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Flue Gas Flow Dynamics and Deposition of Particulate Matter In-side an Air Sampler Thimble: A Suggestive Study

Anindya Das Gupta*

Department of Environmental Engineer, West Bengal Pollution Control Board, State of West Bengal, India

Corresponding Author: Anindya Das Gupta, Department of Environmental Engineer, West Bengal Pollution Control Board, West Bengal, India, Tel: 09748434946; E-mail: anindyadasgup20@gmail.com

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Abstract

Flue gas, generated by combustion of fuel particularly solid fuel is usually rich with Particulate Matter (PM) which is a major pollutant for the air pollution issue. The Particulate Matter content may be generated by (a) unburnt carbon particle (b) ash particle (c) condensed gas vapour, particularly if existing below dew point. The flue gas is sampled using a Particulate Matter Collector thimble placed inside a sampling probe tube with a Collector Nozzle attached to a S shaped bent section at the tip of the Probe tube. The probe arrangement is inserted through a sampling hole into a stack and subjected to negative suction pressure generating an induced flue under iso-kinetic condition through the thimble by an external vacuum pump suction. The thimble serves as a screen allowing only flue gas through its pores while obstructing and collecting the Particulate Matter over its internal surface. The following mathematical model investigates the flue gas dynamics through the Thimble and corresponding various forces generated that may contribute for Particulate Matter arrest and deposition inside the thimble.

The thimble is basically a cylinder with one end sealed as a hemisphere, the other end open. The surface of the thimble is serrated and spread with micro-pores having characteristic temperature and acid resistance.

Keywords: Particulate matter; Bernoulli's equation; Navier Stokes equation; Laminar flow; Turbulent flow; Boundary layer ;Impaction; Interception; Attraction; Diffusion

Introduction

Particulate matter collector thimbles and accessories (Fig. 1) are used for sampling flue gas flow being dissipated through stacks by mounting a thimble in a sampling probe mechanism with a nozzle attached to a bend at the top of the probe tube. The entire mechanism is a hollow suction arrangement to draw in a part of stack bound flue gas by using a vacuum pump, under iso-kinetic condition. The thimble is marked for its initial weight under desiccated condition and also marked for its final weight after the sampling process is complete. The thimble collects the flue gas borne particles through any combination of four processes that may include a mechanical force dominated process like interception, impaction, diffusion or an electrical force dominated process like electrostatic attraction.

Aim and Objective

The paper aims to provide a fundamental study of the various forces generated by the fluid dynamics inside the thimble for generating the particulate matter arrest and deposition over the thimble. The study is expressed in an open ematical

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model with further scopes for improvement as indicated implicitly by the broad conclusions implying both theoretical experimental further studies.

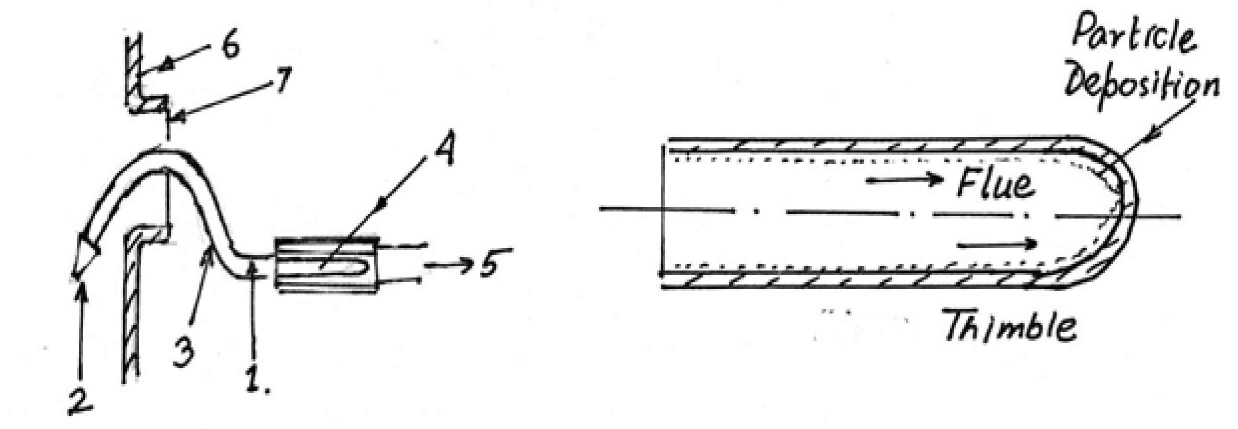


FIG. 1. Thimble and pitot tube. 1) Probe Rod; 2) Nozzle; 3) Bend; 4) Thimble; 5) Pump; 6) Stack; 7) Sampling hole

Mathematical model of the phenomenon involving momentum, energy and force distribution for particulate matter deposition inside the thimble.

The thimble for collection of particulate matter during an air sampling process acts according to a principle similar to that of collection of particulate dust by bags in an air pollution controlling bag filter device. Accordingly, the operation is guided by four parallel collection principles determined by four categories of forces [1].

Impaction Force (F1)

Impaction force F1 or mechanical adhesion to the thimble surface by loss of kinetic energy and corresponding penetration work generation by particulate matter in a forced convection flow with corresponding momentum loss. The fundamental governing equation is

ρVπ(4/3 πr^3)

Where r: Radius of the particle, V: Velocity the particle, ρ: Density of the particle

Velocity of the particle may be inferred by Maxwell Boltzmann velocity distribution function which is represented by

$$f(v)\,d^3v = \left(\frac{m}{2\pi KT}\right)^{\frac{3}{2}} e^{\frac{(-mv)}{2kT}}\, d^3v$$

Where,

v: Velocity

d3v: Velocity space

m: Particulate Matter mass

K: Boltzmann's Constant

T: Temperature

Interception Force (F2)

Interception force (F2) or mechanical adhesion to the thimble surface by obstruction which may be considered a cognate phenomenon of impaction.

The energy distribution leading to the field potential distribution in the system which in turn determines the momentum and force distribution is provided by the Bernoulli's equation for an Open thermodynamic system as the given case is [2]:

$$\left(H+\frac{v^2}{2g}+z\right)m+W=Q$$

H: Enthalpy

v: Velocity

Z: Potential head

m=mf+mp: Mass of flue gas (control volume)+mass of particulate matter

W: Work done =0 for this case

Q: Thermal input from combustion in the process

So, total fluid energy input generated for the process

= Q+Δ P

Where ΔP: Pressure differential of the stack

=Δ P1+Δ P2

Where Δ P1: Induced pressure head by ID fan

Δ P2: Pressure head generated by natural draught

Assuming the flue gas flow adiabatic and compressible

$$P=C'g^k(K\rho^{(k-2)}/K-2)+C=f(\rho)$$

Where k: Adiabatic exponent. C, C': Constant

Assuming W=0, Z=0

$$(u=PV+V^2/2g+z)\text{m}+\text{W}=\text{Q}$$

Translates to

$$\text{u}+[C'g^k(K\rho^{(k-2)}/K-2)+C]V+V^2/2g+z=Q'$$

Which is the transformed original equation of the open thermodynamic system?

Assuming Z=0 The energy the equation translate into Navier Stokes Equation which ultimately results into impaction force (F1) interception force and (F2) for the particulate matter by momentum transfer through fluid solid interface (flue gas and solid interface) as per the mentioned logic of field potential difference as [3]

P (DU/Dt) =-∇ p+∇.Γ+ρg

Assuming P=f (H, v2 /2g)

P (DU/Dt) =-∇f (H, v2 /2g) +∇.Γ+ρg

What might be of further interest may be the exact nature of viscosity as a function of temperature. It is assumed that the flue gas has characteristics of Newtonian fluid flue which may need further observation [4]. The pressure differential ΔP in the Navier Stoke's equation is one of the causes of impaction force that generates deposition directly or indirectly.

Attraction Force (F3)

Attraction force (F3) which may be due to electrostatic attraction which in turn may be generated by ionisation of the particulate matter in an acidic or alkaline environment and subsequent electrostatic charging by induction of the thimble surface by deposition [5]. However the particulate matter deposition will generate a repulsion layer similar to zeta potential unless the induced or flue gas laden particulate charges have an alternating nature.

The attraction force in expressed by as

$F=K^* Mm/d^2$

Where

K: Permittivity of the free space

M: Deposited mass in the thimble Surface

m: Particulate matter mass

d: Distance between Thimble Surface and gas borne particulate matter

Diffusion Force (F4)

Diffusion force (F4) governed by Fick's law (1st and 2nd). This fourth force will be a functions of concentration expressed as [6].

$$J = -D\nabla\psi \; \ldots.(1)$$

$$\partial \psi / \partial t = \nabla(D\nabla\psi) \ldots.(2)$$

Where, J: Diffusion flux

∇: Del operator

ψ: Concentration

D: Diffusion Coefficient

The diffusion force generation is expressed by

J= (D/RT) ∇ f

Where

R: Universal gas constant

T: Temperature

f: Frugality/population of particulate matter of species/diameter

However we may consider diffusion force if the corresponding Peclet Number Pe->LU/D>>1

Where

L: Characteristic length

U: Fluid velocity

D: Diffusion Coefficient

Self-repulsion between charged Particulate matters in the flue gas may further contribute to deposition force distribution.

The total force on a gas laden particulate matter element may be expressed as [7].

$$F = F_{1x}i + F_{1y}j + F_{1z}k$$

$$F_2 = F_{2x}i + F_{2y}j + F_{2z}k$$

$$F_3 = F_{3x}i + F_{3y}j + F_{3z}k$$

$$F_4 = F_{4x}i + F_{4y}j + F_{4z}k$$

Which can be represented as the corresponding matrix?

$$\sum F = \begin{bmatrix} F_1 \\ F_2 \\ F_3 \\ F_4 \end{bmatrix} = \begin{bmatrix} F_{1X} & F_{1y} & F_{1z} \\ F_{2X} & F_{2y} & F_{2z} \\ F_{3X} & F_{3y} & F_{3y} \\ F_{4X} & F_{4y} & F_{4z} \end{bmatrix}$$

∑F is thus the total settling force for deposition over thimble surface.

The arresting forces for particulate matter may also include

The caking and adhering properties of the particulate matter which is a function of temperature or formation of weakly adhering chars

The adhering adsorptive properties expressed by the adsorptive potential which is basically change in free energy of adsorption that represents the work done for transfer of the adsorbed molecule [8].

$$G_{ads} = RT\ ln\left(P_u\ /\ P \right)$$

Where, G: Adsorptive potential

Pu: Vapour pressure/Dalton's partial pressure

In addition to the four (04) mentioned major forces and other mentioned factors and the Bernoulli's equation governing energy distribution, additional forces and their possible combinations that may contribute for the force, energy, momentum distribution in the discussed phenomenon contributing further to particulate matter deposition are related to the flow of the particulate matters as a part of the mixed binary phase fluid flow (Fig. 2). These may be:

- The drag force or flow resistance force F=CD (V2 /2g) where CD is the drag coefficient which is a function of particulate shape factor.
- Buoyant or upward body force generated by displaced fluid F=ρfgVpg ρfg-Density of fluid/flue gas replaced Vp particulate matter volume g: Gravitational const.
- The lift force or upward force generated by kinetic head of flowing fluid F=CL(V2 /2g) Where CL: Lift coefficient as a function of particular shape factor.
- Gravity force or downward body force F=ρVg ρ: Density of particle, V: Particle volume, g: Gravitational const.
- Thrust force or forwarding force F=Kinetic head+pressure head.

The characteristic Cunningham correction factor for correcting this drag force subjected to Knudsen number (Kn)

Kn=λ/L λ: Mean free path for particulate matter flow

As a parallel expression $K_n = K_B T\ /\ \left(\sqrt{2}\ \pi\ d^2 \right)$ PL where

KB: Boltzmann Constant

T: Thermodynamic temperature

d: Hard shell diameter of particle

P: Total pressure

L: Characteristic length of the system

The Cunningham correction factor being expressed as

$$C = 1 + 2\lambda / d\left(A_1 + A_2 e^{-A3\ d/\ \lambda} \right) = f\left(\lambda,\ d\right)$$

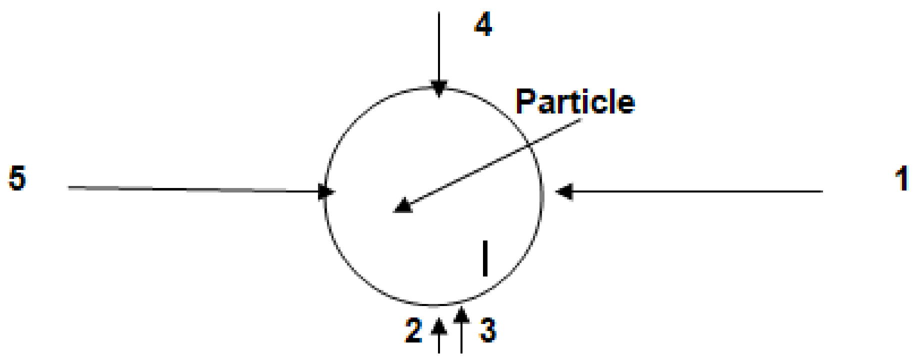


FIG. 2. Aerodynamic forces on a floating particulate matter. 1) The drag force/ resistance force; 2) Buoyant/upward body force; 3) The lift force/upward force; 4) Gravity force/downward body force; 5) Thrust force /forwarding force.

Few special cases and factors may be noted which may contribute still further interestingly for local and precise distribution of momentum and force resulting in a more precise comprehension for the generation and nature of main impaction forces for particulate matter deposition inside the Thimble . These phenomena may be studied further along with empirical observations.

- The precise nature of momentum transfer occurring from fluid (represented by Bernoulli's equation) to particulate matter as a binary stage fluid flow [7].
- The momentum distribution and the force distribution becomes more noteworthy if the Particulate Matter laden flow becomes rotational at high temperature generating cross sectional velocity gradient demanding rotational kinetic energy (½ mω2) distribution study.
- Distribution of momentum in case there in any slips velocity between the solid and fluid flow. Such cases may be assumed as cases of zone based coquette flow where the particulate matter rotate amidst fluid flow or move irrationally w.r.t fluid flow.
- Energy and consequent momentum/force distribution will also be contributed by viscid fluid flow (flue gas at high temperature) which will result in coquette flow around the gas laden particulate matter and various aerodynamic stresses like skin friction both at the thimble surface and over individual particulate matter. Such forces will also contribute to dissipative work and energy distribution further and momentum distribution between gas (flue gas) and solid (Particulate Matter). We are disregarding here the possibility of any extended phenomenon related to high Mach number that may generate any separation of boundary layer for the particulate matter elements any generation of vortex path akin to Karman Vortex pathway. The mutual collisions between the particulate matters resulting due to momentum transfer from fluid may result in adhesion between particles thus generating some massive particulate matter for easy deposition. The extend of such adhesion will depend on primarily the density of particulate matter in flue gas and temperature [9].
- The flue gas flow suffers head loss and from surface roughness of the thimbles which may be neglected assuming characteristic Reynolds number (Re) less than 2100 for the studied event. Since the flow is assumed laminar, the overall fluid head loss flowing through the thimble may be assumed as according to Darcy Weisbach equation [10]

$$\Delta P(H_L) = f\ (L/D)(V^2/2g)$$

ΔP: Pressure loss

HL: Head loss

f: Darcy friction factor

L: pipe length

D: Hydraulic diameter

V: Fluid flow average velocity

g: Gravitational Constant

The contribution of roughness in the thimble surface may be approximated using any suitable formula for geometrically similar pipe flow acknowledging the roughness as έ: Roughness dimension, d: Pipe diameter.

- If the fluid flow is unsteady/non uniform.
- Formation of vortex (∇ X u=ω) beyond the particulate matter between particulate matter and fluid flow and shedding of the of vortices.
- Growth of the particulate matter deposition on the thimble surface which is time dependant.
- Considering the fluid flow through the thimble as an approximation of fluid through a thin pipe the solutions for the governing equation may be that of a Poiseuille flow as

$$V(r) = \Delta P / 4 \mu L \left(R^2 - r^2 \right)$$

μ: Viscosity

L, R: Pipe’s length and radius

ΔP: Pressure drops

r: Radial position of considered flow along the cross section

The formula assumes

(a) Incompressible fluid flow

(b) Newtonian fluid flow

(c) Time independent /steady flow

(d) Laminar flow

(e) Straight flow

(f) Uniform cross section of flow.

- The solutions will be modified accordingly in case the flow is compressible, unsteady, on Newtonian, turbulent and dimensionally variable [11].
- Another interesting phenomenon may be possible merging of the boundary layers from two opposing surfaces, thus contributing further to velocity and momentum transfer and hence unique pattern of Particulate Matter deposition characteristics.

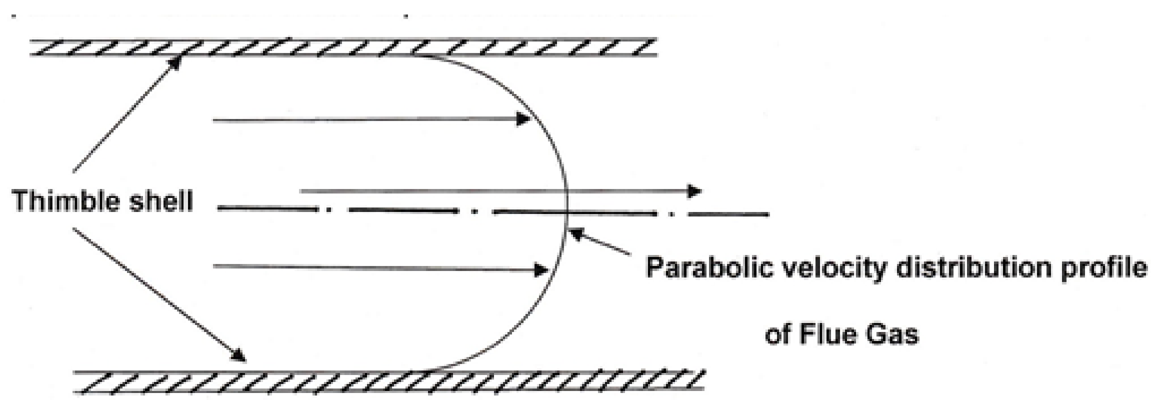


FIG. 3. The velocity distribution profile (V) of the flue gas

The velocity distribution profile of the flue gas flowing through the thimble (Fig. 3) may be considered an approximation of the corresponding equation for any laminar, incompressible fluid flow [12].

It reveals a parabolic velocity distribution function as

$$V_x = R^2/4\mu\ (\Delta P/L)\ \left(1 - r^2/R^2\right)$$

(ΔP/L): Pressure gradient across tube

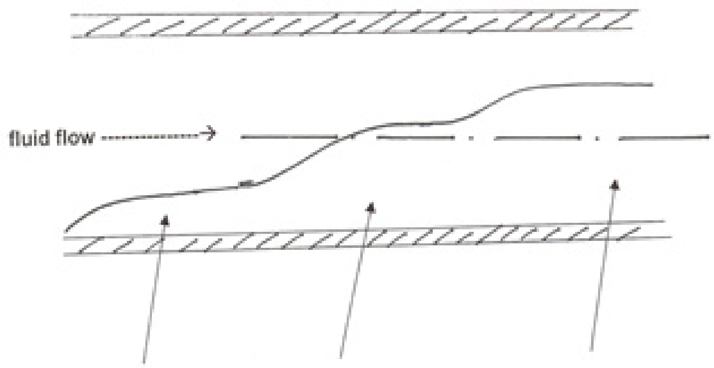
μ: Viscosity

r: Radius/distance of arbitrary velocity calculation

R: Radius of the pipe / Thimble

To modify the equation to accommodate a case of compressible flow the incorporation of Compressibility factor Z=PVm/RT should be considered for further modification of the pressure factor P where Vm: Volume, R: Universal gas Constant T: Temperature.

If the flow becomes turbulent where the momentum transfer and the boundary layer development becomes different and more intense compared to laminar flow (Fig. 4).



Laminar Boundary Layer, Transitional Boundary Layer, Turbulent Boundary Layer

FIG. 4. The momentum transfer and the boundary layer development.

Conclusion

Basically the paper is a suggestive mathematical model that attempts to describe the fundamental principles of flue gas flow dynamics and arresting and deposition of Particulate Matter (PM) contained in the same gas flow while moving through an air flow sampling thimble which may be studied further empirically & through experimentation & field data collection for a more comprehensive picture that may draw conclusions not only for air sampling methodology but also for gaining more insight for the entire field of PM propagation and control in flue gas , the importance of which cannot be exaggerated . Such suggestions have been submitted with three perspectives.

- This paper aims to suggest the various factors generated by the features of the sampler thimble governing such deposition phenomenon that may include impaction forces, interception forces, attraction forces & diffusive forces along with other contribution of the properties of the thimble surface in the process including boundary layer development
- The paper also includes factors generated by the particulate(PM) features the like caking/volumetric & mass changes, adsorption at the thimble surface, Particulate drag forces (shape factor dependent), buoyant force, lift force, gravity force, thrust force which except adsorption are all properties of the flue gas laden particles
- The paper also includes the fluid/flue gas flow characteristics as further contributing factors for the phenomenon that may include momentum and energy transfer suggested by Bernoulli's equations, rotational flow, slip velocity, various possible modes of relative velocities between the moving PMs and gas flow bearing surface , turbulent and laminar flow conditions, steady and unsteady conditions , vortex conditions, head loss at the Thimble surface , boundary layer development, Compressibility of flow and rest. The study produced in the submitted paper is a purely theoretical and a rather loose holistic approach without much supporting observation or data. Nevertheless it should provide a fundamental model with enough space for further studies to improve and also to add further sovereign improvements to it through theoretical and practical case studies, the importance for which may not be exaggerated.

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