Optimal Air Pollution Control Strategy Based on Particle Size Distribution

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Abstract: **Air pollution prevention and control is one of the key factors for sustainable Environmental Management System. Among all air pollutants, particulate matter attracted considerable attention of researchers. Particles smaller than 10 µm (PM10) & 2.5 µm (PM2.5) are associated with a range of respiratory and cardiovascular diseases. Overall collection efficiency of each one of the air pollution control devices depends on particle size distribution (PSD) of inlet stream. Existing air pollution control strategies does not consider PSD of particulate matter emitted into atmosphere and its impact on the environment. In the present work a Mixed Integer Non Linear model has been presented for selection of optimal air pollution control strategy. Collection efficiency of control equipments based on PSD has been considered. The Optimization model presented minimizes total cost of air pollution control strategy including economical and environmental cost meeting prescribed emission norms. The efficacy of the model has been successfully evaluated using a case study of typical process plant. The model presented can be used for selection of optimal emission norms with minimum social cost**

Keywords: **economic cost, environmental cost, particulate matter, optimization, mixed integer Non linear programming.**

I. INTRODUCTION:

In recent past looking at adverse health impacts of particulate matter, governments all over the world imposed stringent norms for both stationary and ambient air quality standards. Particular attention is paid to revise emission norms with respect to $PM_{2.5}$ and PM_{10} in the ambient air (NAAQM Notification GOI 2009). The increased level of ultra-fine particulate matter ($PM_{2.5}$) is associated with respiratory and cardiovascular diseases (Donaldson et al. 1998). The health effect of ultrafine particulate emission has been reviewed and analysed extensively (Lekkas et al. 2008; Oberdorster 2001; Brown et al. 2001; Renwick L. C. et al. 2001). These studies focused mainly on health effect associated due to Ultra fine particles. Ultrafine particles in general deposit in all regions of the respiratory tract and also escape detection and clearance by macrophages (Oberdorster 2001; Brown et al. 2001). Renwick L. C. et al. (2001) investigated whether this slowed clearance after exposure to ultrafine particles was due to a failure in alveolar macrophage phagocyte. The toxicity study of ultrafine particulate especially with traces of metals has also been carried out by Zhang Q. et al. (2003). The effect of ultrafine concentration in the ambient air has been studied using mixed effect model which includes measurement of changes in heart rate, blood pressure and heart rate variability due to exposure to ambient air particles (Cheng et al. 2003).

Despite this, exact quantification of health cost due to air pollutant emission is a challenging task. Akbar et al. (2003) proposed a method that assess and value the adverse health impacts of exposure to air pollutants. Method of medical costing using pollutant tracing (Friedrich et al. 2001) involves dispersion studies of the air pollutants right from the source till its final impact. Filliger et al. (1999) proposed the 'at least' approach that includes emission inventories and receptor studies for health cost estimation of air pollution due to road-traffic. Economic health impact due to air pollution by' value of statistical life' approach (Lvovsky et al. 1998) includes capacity of money trading by people using the terms like willingness to pay (WTP) and value of a statistical life (VOSL) to avoid a statistical premature death. The age effects, underlying health conditions and social cost have also been taken into consideration. The VOSL is also linked with fractions of years of healthy life lost as a result of illness or disability which is reported as Disability-Adjusted Life Years (DALY). However, effect of the ultrafine and respective health cost has not been considered yet for optimal selection of air pollution control strategy.

The best way of reducing the health effect of air pollutants is use of efficient air pollution control strategy. In recent past considerable efforts have been made for designing of air pollution control devices considering variety of operating parameters. Existing scenario in general uses control devices like, electrostatic precipitator (ESP), cyclone separator, fabric filter (FF) etc. (Rao 1994; Jiao and Zheng 2007; Shanthakumar et al. 2008) for collection of particulate matter from stationary sources in industries. The methodologies have been proposed for estimation of collection efficiencies of control devices for ultrafine particulate matter ($PM_{2.5}$) (Falaguasta et al. 2008).

The mathematical equation for evaluation of collection efficiency of particulate matter of various particle ranges is in use since last five decades (White 1963). The collection efficiency of cyclone separator has been presented with semi empirical model, Lagrange approach, Algebraic Slip Mixture Model (ASMM) & Reynolds stress model for prediction of grade efficiencies (Zhang and Basu 2004; Wan et al. 2008;Qian et al. 2007;Wang et al. 2003). Recent studies also reported with multi-region separation model and boundary layer separation theory (Jiao and Zheng 2007; Zhao 2005) for determining the cyclone efficiency. Moreover, open literature available with three-dimensional, time-dependent Eulerian–Lagrangian simulations of the turbulent gas–solid flow in a cyclone separator (Derksen et al.2006; Raoufi et al. 2008). Ji et al (2009) investigated performance of cyclone sepeartor and grade efficiency for extermly low particle concentration. The study of removal of PM2.5 in ESP has also been reported in the recent past. (Falaguasta et al. 2008; Jedrusik et al. 2006; Choi and Fletcher 1997). Studies on particulate removal efficiencies of bagfilters (Cora MG and Hung YT 2002; Shanthakumar et al. 2008) and scrubbers (Keshavarz P et al 2008; Li S et al. 2008; Bozorgi Y et al. 2006) were also extensively reported.

Optimization has become a major enabling area and evolved from a methodology of academic interest into a technology that has and continues to make significant impact in industry (Biegler and Grossmann 2004). Since mid of 20th century efforts are been made to apply mathematical programming for air pollution control. Kohn (1969) has described a linear programming based optimisation procedure for reduction of pollutant to prescribed norms with available control devices and varying production rate. The recent studies take into account economic as well as environmental impact into consideration (Azapagic and Clift 1995, 1999). An optimization model for selection of suitable control option to minimize pollution load and maximize the profits has been described by Shaban et al. (1997). The mixed integer linear programming (MILP) model combines the minimization of costs with minimization of environmental impact that is assessed in terms of life cycle (Papandreou and Shang 2008). Chandra et al. (2009) proposed a mathematical model that described cost analysis of power generation from coal based power plant. The model considered quality of coal fed, installation cost, energy cost and environmental cost in terms of ESP efficiency. However the models reported neither considered health cost for optimal selection of control options nor they incorporated reduction efficiency of air pollution control equipment for ultrafine.

In this paper a MINLP based optimisation program for selection of optimal air pollution control devices considering particle size collection efficiency is presented. The objective of the program is minimization of total cost consisting of economics cost & health cost due to emissions of particulate matter including ultrafine ($PM_{2.5}$ & PM_{10}). Effect of regulatory norms on the total cost is presented after taking various constraints like available budget and maximum reduction efficiency of control equipments. The efficacy of the proposed model is illustrated by considering case studies of a typical dye intermediate industry. The model proposed is generic enough for application for selection of optimal air pollution control strategies. The model presented has following salient features:

- It considers collection efficiencies of control devices with respect to particle size distribution with a special emphasis on respirable particulate matter.
- It takes into consideration of multiple pollutants emitted from multiple emission sources and multiple control equipments to reduce the emissions to desired levels.
- It considers environmental cost due to the emission of the pollutant into atmosphere while minimizing total cost of the alternatives.

II. THEORIES

In general air pollution control strategies are selected to meet the norms prescribed by regulator. Recently looking at adverse health hazards of respirable particulate matter, the removal efficiency of control devices for various ranges of particles became necessary. Regulatory authorities all over the world also stared prescribing norms including PM2.5 & PM10. The present work includes the modelling and simulations of air pollution control device to evaluate the fractional efficiency of particulate matter. These simulated efficiencies of control devices for various ranges of particles were considered for optimal selection of air pollution control strategy.

A. Modelling and simulations of air pollution control devices:

The commercial software's Aspen plus®, MATLAB® and CAMCAD® were used for modelling and simulation of major air pollution control devices presented in this paper. The simulations have been done to evaluate collection efficiencies of control devices for various particle size diameters. The application of single air pollution control device has been simulated for collection efficiency with changing particle size. The collection efficiencies of Cyclone separator, Bag filter and Electrostatic precipitator for various particle diameters are shown in Fig. 1. It can be observed that as particle diameter increases the collection efficiencies of all the control devices increase. Collection efficiencies of these control devises becomes a limiting factor while selecting the control devise for removal of ultrafine particulate matter. Pollution control devises are used in series if single control equipment is not sufficient enough to remove pollutants to required levels.

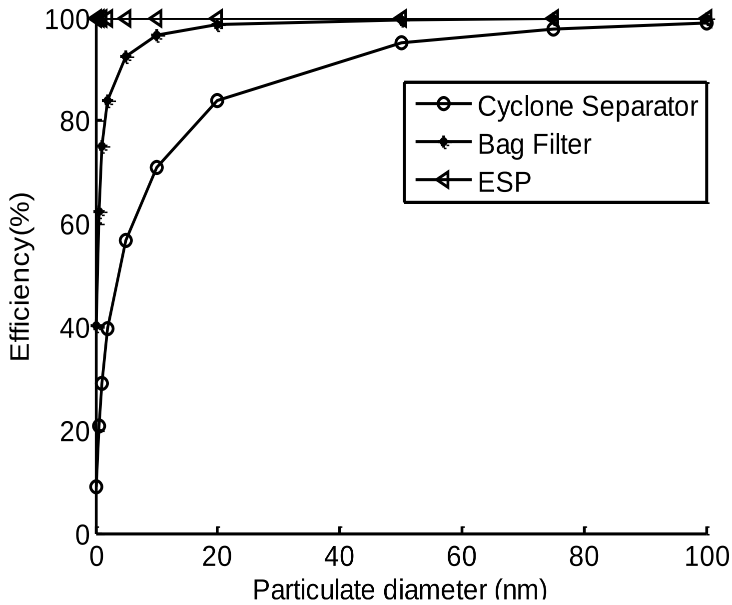

Figure (1): Particulate Matter Collection Efficiency of typical air pollution control devices.

Collection efficiencies of two air pollution control devises arranged in series are presented in Fig. 2. Similarly Collection efficiencies of three air pollution control devises arranged in series are presented in Fig. 3. From Fig. 2 & 3 it can be observed that when control devises are used in combination their overall particulate collection efficiency is better. It is to be noted that pollutants emitted from the sources consists of particulate matter of different size. More over these pollutant gases consist of gaseous pollutants along with particulate matter. Hence, it is necessary to evolve optimal control strategy that removes pollutants to achieve regulatory norms.

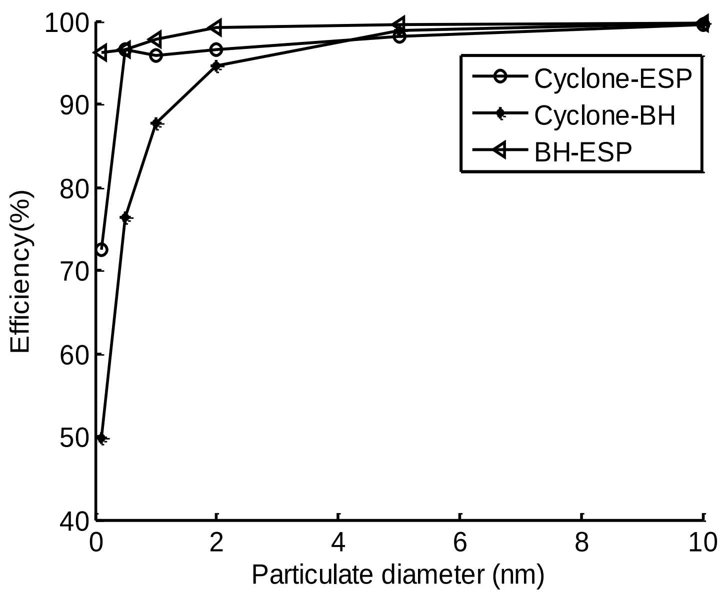

Figure (2): Particulate Matter Collection Efficiency of two air pollution control devices in series.

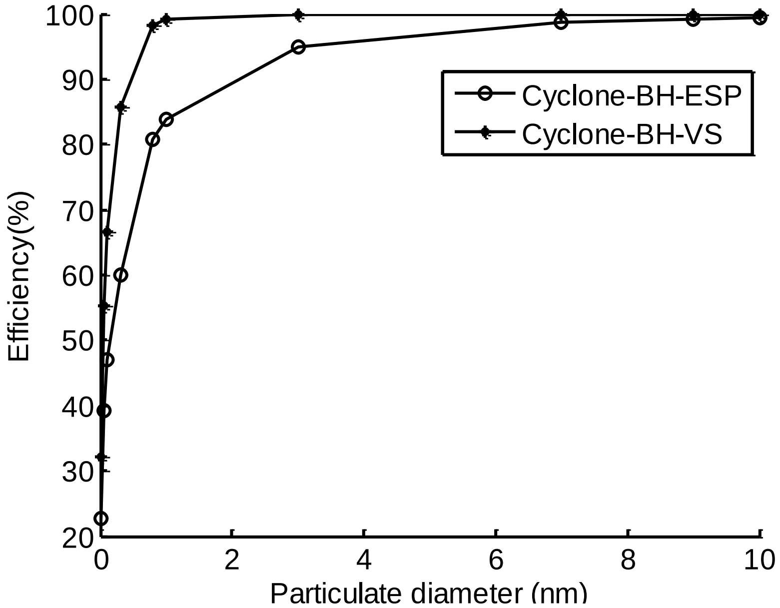

Figure (3): Particulate Matter Collection Efficiency of two air pollution control devices in series.

B. Development of Model

The model developed includes emission of particulate matter as well as gaseous emissions from multiple pollution sources. Multiple air pollution control devices were considered to control emissions from each source. The collection efficiencies of the control devices with respect to particle diameter simulated in above section is considered. Cost associated with control devices like set-up and operating cost are considered. Moreover, pollutants emitted into the atmosphere have their impact on human health. The model also considers health cost due to emission of pollutants. Therefore the total cost includes set up and operating cost of air pollution control devices together with health cost. The objective of the model is optimal selection of the control devices so as to reduce the total cost, meeting prescribed regulatory norms. The mixed integer non linear programming model is presented with an objective function to minimize the total cost for the selection. The indices, variables and parameters used in developing the model are presented prior to the model development.

Sets

i pollution source.

j air pollution control devices.

n multiple pollutants.

Variables

X_{ij} = binary variable indicating whether control equipment j is selected on source i (X_{ij} =1) or not (X_{ij} = 0)

Parameters

C_j Installation cost of control device *j*.

P_{ij} Operating cost of control *j* when applied over source *i*.

HC_n Health cost of the pollutant *p* in INR per kg of pollutants emitted.

B Budget available for the air pollution control system.

L Length of time horizon, for which, the control device is applied.

Q_i Flow rate of the flue gas through sources *i* in m^3/s.

C_{in} Emission concentrations of pollutant *p* from source *i* in mg/m^3.

R_{ijn} Reduction capacities for control devices j operated over source *i* for pollutants *p*.

$C1_{in}$ Allowable emissions of pollutant *p* from source *i* in mg/m^3.

C. Economic cost consideration:

Evaluation of economical cost associated with air pollution control devices is a crucial task. In general economic cost is broadly classified as Installation/set up cost and operation cost. The installation cost includes cost of material procurement, erection & commissioning etc. Whereas cost incurred during operation like labour cost, maintenance, power consumption etc. are considers as operational cost. Based on this classification the installation and operational cost of air pollution control devices are presented using equation 1 & 2.

$$\text{Installation cost} = \sum_i \sum_j C_j X_{ij} \tag{1}$$

$$\text{Operating cost} = \sum_i \sum_j P_{ij} X_{ij} \left[(1+i_{com})^n - 1 \Big/ (1+i_{com}) * i_{com} \right] \tag{2}$$

The term i_{com} indicates the combination of local interest rate and inflation effect, whereas n is number of years of operations which control device, j is operated over source i.
In the equations 1 & 2 for operating and installation cost, if a control option j is not selected for application over any particular sources i then $X_{ij} = 0$ and becomes 1 when control equipment is selected.

D. Environmental cost consideration:

The uncontrolled air pollutants emitted into atmosphere affect environment and human health. Such health effect associated with pollutant emissions are taken as cost to environment. The method based on dispersion model (Friedrich et al. 2001) has been considered in the present paper to value the adverse effect of the uncontrolled emission. Friedrich et al. (2001) used numbers based on year of life lost (YOLL) thus significantly lower than value of statistical (VSL) for same dose response function. VSL is the collective willingness to pay for avoiding a small risk of an anonymous premature death. Friedrich et al. (2001) has therefore calculated the value of a YOLL on theoretical grounds by considering VSL as the net present value of a series of discounted annual values. The ratio of VSL and the value of a YOLL thus obtained depend on the discount rate. Also Nonfatal and fatal cancers (depending on the YOLL for each cancer type) has been considered.

The health impact associated with emission of pollutant n is expressed here as Indian rupees per unit amount of pollutant released into atmosphere, HC_n. The concentration of pollutant n generated from source i is C_{in}. While the concentration of the pollutant n emitted into atmosphere through stationary source i is $C1_{in}$. The pollutants are emitted through sources i with flow rate Q_i. The total length of time for which air pollution control equipments j operates over sources i is $(L - T_{inst})$.
Therefore the health cost associated with emission of the pollutants from the outlets of the air pollution control devices is

$$\text{Health cost} = \sum_i \sum_p HC_n C1_{in} Q_i (L - T_{inst}) \tag{3}$$

Objective function is to minimize the total cost which includes operating, installation and health cost.

Minimize

$$\left[\sum_i \sum_j P_{ij} X_{ij} \left((1+i_{com})^n - 1 \Big/ (1+i_{com}) * i_{com} \right) + \sum_i \sum_j C_j X_{ij} + \sum_i \sum_p HC_n C1_{in} Q_i (L - T_{inst}) \right] \tag{4}$$

E. Constraints:

1. The inlet concentrations of pollutant n through source i (Cin) shall be reduced to outlet emission standards concentrations (C1in). This in general is decided by regulatory authority. However, each air pollution control equipment j is associated with limited collection efficiency (Rijp) to remove pollutant n generated from source i.

$$C_{ip} * \prod_j ((1 - R_{ijn}/100) * X_{ij}) \le C1_{in} \quad (5)$$

2. Non negativity constraints.

$$L \geq 0 \quad (6)$$

$$X_{ij} = 0 \text{ or } 1$$

3. As per the need of regulatory compliance at least one pollution control device has to be installed on each one of the sources. The constraint given in equation 5 ensures that for each source *i* there will be at least one control equipment *j* installed. However, this can be relaxed with affecting the performance of the model.

$$\sum_j X_{ij} \ge 1 \quad (7)$$

4. The total cost includes installation, operation & health cost, which shall not exceed the allotted budget. This constraint also can be relaxed without affecting the performance of model in case where budgetary limit does not exist.

$$\left[\sum_i \sum_j P_{ij} X_{ij} (L - T_{inst}) + \sum_i \sum_j C_j^0 X_{ij} + \sum_i \sum_p HC_p K1_{ip} Q_i (L - T_{inst})\right] \le B \quad (8)$$

III. MIXED INTEGER NON LINEAR PROGRAMMING SOLUTION:

The objective function indicated in equation 4 minimizes total cost subjected to constraints given in equations 5 through 8. This mixed integer non linear programme can be solved using suitable commercial software. In the present work General Algebraic Modelling System (GAMS®) software has been used for simulation. The detailed program starts with definition of indices, sets, parameters, variables, tables and equations in the required syntax. The software then compiles the model developed using Discrete and Continuous optimizer program (DICOPT) for solving MINLP problem.

IV. A CASE STUDY: OPTIMAL SELECTION OF AIR POLLUTION CONTROL STRATEGY:

The model presented can be used for optimal selection of air pollution control strategy. The multiple pollutant sources were considered which emits multiple pollutants. Each of the sources has an option of multiple control options. It is generic enough for application to select optimal air pollution control option by minimizing total cost including economic and environmental cost. The effect of variations in particle size diameters on collection efficiencies of control devices has been simulated in previous section. The model utilizes these data for optimal selection of air pollution control devices to satisfy the outlet norms.

To check the efficacy of the proposed model a case study has been presented. The typical sources of emission from a pharmaceutical plant have been considered which includes utility section, process emissions and an incineration operation. The actual data have been collected from four commercially operated pharmaceutical plants in state of Gujarat state India. thrice a year for four years. The stationary sources considered are monitored for three times a year for four years to cover seasonal as well as production variations. The other supporting data collected include dimensions of stationary sources like diameter and height of stacks. The pollutants concentration and flow rates from the stacks are monitored using 'Vayubodhan' make stack monitoring kit and velocity meter VVM1 respectively. The cost associated with commissioning and operation of the control equipments was also collected as actual. The data presented in this paper are average of the actual data obtained from process plants.

The air pollution control devices considered include cyclone separator, scrubber and electrostatic precipitator. The single electrostatic precipitator with options of selecting single or multiple electric fields is also considered as a special case. The installation and operating cost of these devises are presented in Table 1 and Table 2 respectively. Whereas flow rate and emission load of air pollutants from stationary source are illustrated in Table 3 & 4 respectively. The pollutants emitted include Particulate matter of size 2.5, 10 and above 10 microns with sulphur dioxide and oxides of nitrogen. Details of the health cost due to these pollutant emissions as reported in the literature are presented in Table 5.The collection efficiency of the control devices for various particulate diameters was simulated using commercial software. The reduction capabilities of these control devices are presented in Table 6. The health effects of these pollutants have been considered with set up and operational cost of the control devices for the selection of the optimal air pollution control strategy.

Table No.1 Installation cost for the control devices.

Control Devices	Installation cost in Millions USD
Cyclone	0.1
ESP1	0.16
ESP2	0.18
ESP3	0.2
ESP4	0.3
Scrubber	0.08

Table No.2 Operating cost of control devices in Millions USD per annum.

Sources	Control devices					
	Cyclone	ESP1	ESP2	ESP3	ESP4	Scrubber
Incinerator	0.04	0.04	0.05	0.1	0.36	0.05
Drier	0.036	0.042	0.044	0.1	0.36	0.05
Boiler	0.044	0.044	0.05	0.12	0.38	0.05

Table No.3 Flow rate of the gas from sources

Stack attached to	Flow rate (m^3/s)
Incinerator	18
Drier	24
Boiler	22

Table No 4 Concentrations of the pollutants at the inlet of the control device in $mg/m.^3$

Sources	Pollutants concentration in mg/m^3				
	PM2.5	PM10	SPM	SO_2	NO_X
Incinerator	800	1200	1500	800	500
Drier	650	1000	1150	750	550
Boiler	850	1300	1300	680	670

Table No.5 Details of the health cost due to pollutant emission as reported in the literature (Friedrich et al. 2001).

Type of pollutants	Health cost (USD per Kg of pollutant)
PM2.5	0.09
PM10	0.08

SPM	0.06
SO_2	0.06
NO_x	0.056

Table No. 6 Details of efficiencies of air pollution control devices.

Description	**Reduction capacities of the control devices in % for the given pollutants**				
	PM2.5	**PM10**	**SPM**	**SO_2**	**NO_X**
Incinerator. Cyclone	0.04258	0.06459	0.5025	0.2	0.2
Incinerator.ESP1	0.92134	0.98770	0.9889	0.25	0.25
Incinerator.ESP2	0.98105	0.98890	0.9899	0.25	0.25
Incinerator.ESP3	0.99870	0.99890	0.9998	0.3	0.3
Incinerator.ESP4	0.99980	0.99990	0.9999	0.3	0.3
Incinerator.Scrubber	0.7500	0.8600	0.9500	0.85	0.80
Drier.cyclone	0.04258	0.06459	0.5025	0.2	0.2
Drier.ESP1	0.92134	0.98770	0.9889	0.25	0.25
Drier.ESP2	0.98105	0.98890	0.9899	0.25	0.25
Drier.ESP3	0.99870	0.99890	0.9998	0.3	0.3
Drier.ESP4	0.99980	0.99990	0.9999	0.3	0.3
Drier.Scrubber	0.7500	0.8600	0.9500	0.85	0.80
Boiler.cyclone	0.04258	0.06459	0.5025	0.2	0.2
Boiler.ESP1	0.92134	0.98770	0.9889	0.25	0.25
Boiler.ESP2	0.98105	0.98890	0.9899	0.25	0.25
Boiler.ESP3	0.99870	0.99890	0.9998	0.3	0.3
Boiler.ESP4	0.99980	0.99990	0.9999	0.3	0.3
Boiler.Scrubber	0.7500	0.8600	0.9500	0.85	0.80

V. RESULT AND DISCUSSION:

Three scenarios are considered for simulation study are I) considering specific emission standards for respirable particulate matter as well as total suspended particulate matter II) considering emission norms for only respirable particulate matter III) considering regulatory norms for total suspended particulate matter. The MINLP problem has been solved using commercial solver GAMS and the results obtained are presented in Table 7. Installation cost, operating cost and health cost changes with change in regulatory norms are evaluated and presented in Fig.4. The health cost due to emission of ultrafine particles is plotted in Fig.5. The total cost of each control strategy is presented in Fig.6.

From Fig.4 and Table 7 it has been observed that in the operating cost, health cost and installation cost is relatively higher for respirable particulate matter. Similarly the total cost is also relatively higher for repirable particulate matter. This is due to selection of optimal air pollution control devices to capture fine particles to prescribed level. It can also be observed that as the emission norms become stringent all the equipments are selected to reduce the emissions to required levels. Stringent emission norms lead to high installation and operating cost. On the other hand as expected the health cost decreases as norms becomes stringent. As the emission norms relaxed beyond 65 mg/m^3 for total suspended particulate matter the installation cost changes abruptly. This can be attributed to change in the selection of control equipments. From Fig. 6 it can be noted that total cost decreased and attains minimum before increasing continuously. The increasing trend is due to increase in health cost due to relaxed norms. The minimum for the total cost indicates optimal emission norms with minimum social cost.

From Table 7 it can be observed that as the norms are related only for suspended particulate matter relatively low collection efficiency devices are selected. As expected, when norms are prescribed both on ultrafine particulate matter and total suspended particulate matter emissions high efficiency control devices are selected. Hence the efficacy of the model is demonstrated using the simulation case study for selection of optimal control strategy based on the particle size distribution.

Table No. 7 Optimal Selection of air pollution control devices & variation in the cost with changing outlet emission norms keeping operating years constant.

pollutants						Selection of Air pollution control devices						Pollutants		Selection of Air pollution control devices						pollutants	Selection of Air pollution control devices					
PM 2.5	**PM 10**	**SPM**	**SO_2**	**NO_x**	**Sources**	**Cyc.**	**ESP1**	**ESP2**	**ESP3**	**ESP4**	**scrb.**	**PM 2.5**	**PM 10**	**Cyc.**	**ESP1**	**ESP2**	**ESP3**	**ESP4**	**scrb.**	**SPM**	**Cyc.**	**ESP1**	**ESP2**	**ESP3**	**ESP4**	**scrb.**
10	15	25	30	30	Incinerator	1	1	1	1	1	1	25	25	1	1	1	1	1	1	50	1	1	1	1	1	1
					Drier	1	1	1	1	1	1			1	1	1	1	1	1		1	1	1	1	1	1
					Boiler	1	1	1	1	1	1			1	1	1	1	1	1		1	1	1	1	1	1
15	20	30	35	35	Incinerator	1	1	1	1	1	1	32.5	32.5	1	1	1	1	1	1	65	1	1	1	1	1	1
					Drier	1	X	1	1	1	1			1	X	1	1	1	1		1	X	1	1	1	1
					Boiler	1	1	1	1	1	1			1	1	1	1	1	1		1	1	1	1	1	1
20	25	35	40	40	Incinerator	1	1	1	1	X	1	40	40	1	1	1	1	X	1	80	1	1	1	1	X	1
					Drier	1	1	1	1	X	1			1	1	1	1	X	1		1	1	1	1	X	1
					Boiler	X	1	1	1	1	1			X	1	1	1	1	1		X	1	1	1	1	1
25	30	40	45	45	Incinerator	1	1	1	1	X	1	47.5	47.5	1	1	1	1	X	1	95	1	1	1	1	X	1
					Drier	1	1	1	1	X	1			1	1	1	1	X	1		1	1	1	1	X	1
					Boiler	1	1	1	1	X	1			1	1	1	1	X	1		1	1	1	1	X	1
30	35	45	50	50	Incinerator	1	1	1	1	X	1	55	55	1	1	1	1	X	1	110	1	1	1	1	X	1
					Drier	1	1	1	1	X	1			1	1	1	1	X	1		1	X	1	1	X	1
					Boiler	1	1	1	1	X	1			1	1	1	1	X	1		1	1	1	1	X	1
35	40	50	55	55	Incinerator	1	1	1	X	X	1	62.5	62.5	1	1	1	X	X	1	125	1	1	1	X	X	1
					Drier	1	1	1	X	X	1			1	1	1	X	X	1		1	1	1	X	X	1
					Boiler	1	1	1	1	X	1			1	1	1	1	X	1		1	1	1	1	X	1
45	50	60	70	70	Incinerator	1	1	1	X	X	1	77.5	77.5	X	1	1	X	X	1	155	X	1	1	X	X	1
					Drier	1	X	1	X	X	1			1	X	1	X	X	1		1	X	1	X	X	1
					Boiler	1	1	1	X	X	1			1	1	1	X	X	1		1	1	1	X	X	1
50	55	65	80	80	Incinerator	1	1	X	X	X	1	85	85	1	1	X	X	X	1	170	1	1	X	X	1	1
					Drier	1	1	X	X	X	1			1	1	X	X	X	1		1	1	X	X	X	1
					Boiler	1	1	1	X	X	1			1	1	1	X	X	1		1	1	1	X	X	1

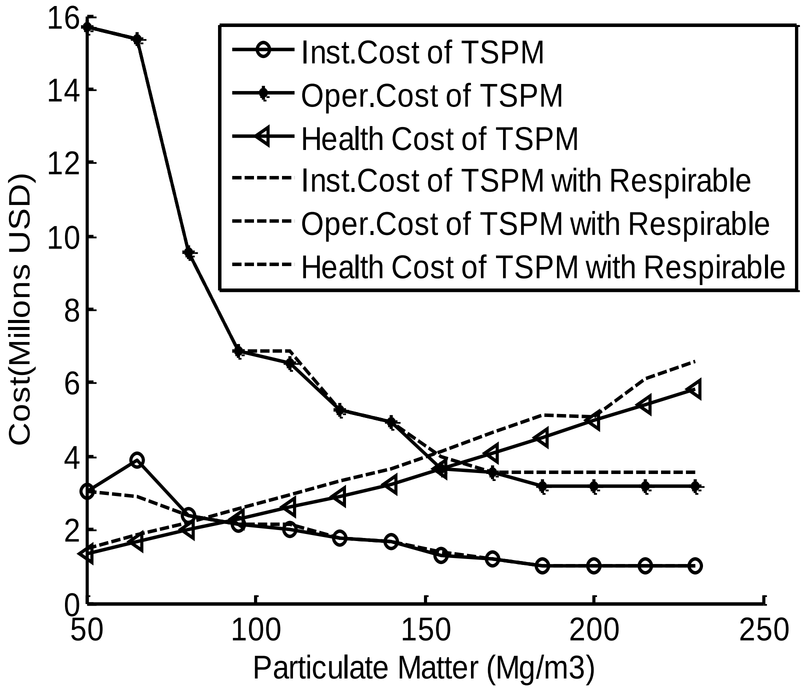

Figure (4): Variations in the cost as a function of particulate matter emission norms.

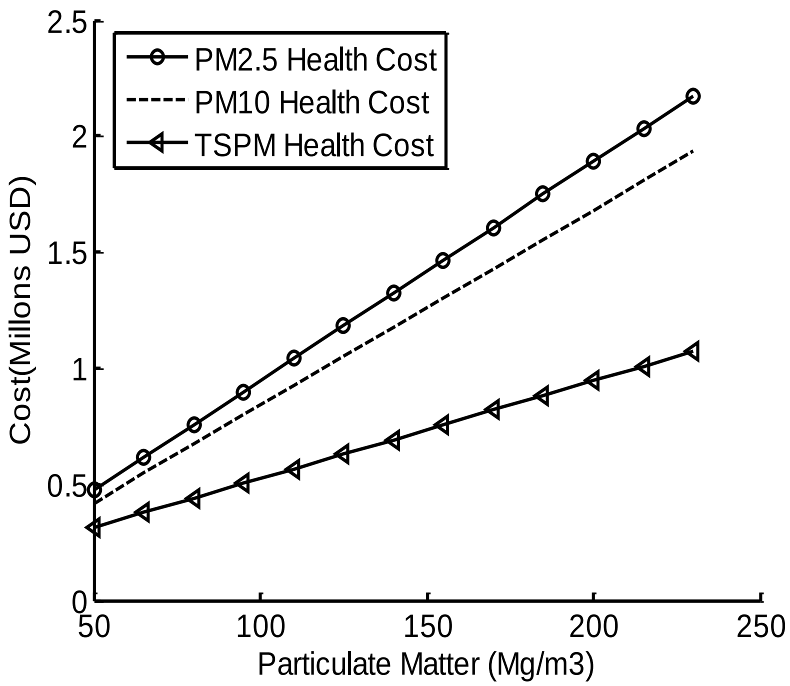

Figure (5): Variations in the health cost due to emission of particulate of various ranges.

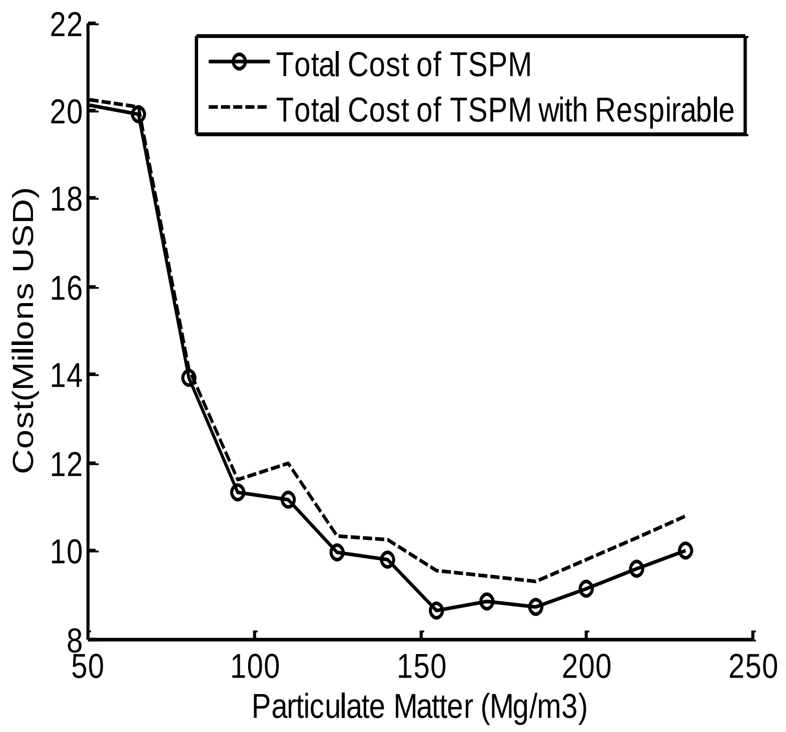

Figure (6): Variations in the total cost as a function of particulate matter emission norms.

VI. CONCLUSIONS:

In the present study air pollution control devices are simulated as single and in series considering effect of ultrafine particulate matter. A mixed integer non linear programming model has been proposed for optimal selection of air pollution control strategy. The model incorporates economical, environmental and health cost for various control options. It considers multiple sources of emission and pollutants with variety in particle sizes. Objective of the model was to minimize the total cost with reduction of pollutants to prescribed level. The best selection strategy for air pollution control which includes operational, installation and health cost has been presented for the given outlet pollution norms. The strategy proposed has been satisfactorily evaluated by considering case study of typically operated process plant. The proposed strategy therefore suggests the optimal emission norms with minimum social cost.

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