Selection of an Optimal Air Pollution Management System for Commercially Operated Spray Driers located in an Industrial Estate

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Abstract

Industrial air pollution is of serious concern in developing countries like India due to inferior ambient air quality. Among various states Gujarat is major hub/contributor for the production of dye and dye-interactive industries. Most of them are using spray driers leading to emission of pollutant air containing various dye particles. These dye particles are causing health problems along with problems related to aesthetics in the nearby residential areas. In the present work we propose a mathematical model for optimal selection of air pollution control equipment. The model is capable to consider multiple pollutants, multiple emission sources and multiple control equipment. Constraints like budget, efficiency of control equipment and regulatory norms are included in the model. We have monitored seventeen commercial spray driers and fourteen process plants located in the Vatva industrial estate in Ahmedabad District in the state of Gujarat. Based on the monitoring results we have identified the industries with inadequate Air Pollution Management Systems (APMS). The proposed optimization model is used to suggest necessary modifications in Process Control (PC) equipment to make the Air Pollution Management system (APMS) adequate. The efficacy of the proposed model is successfully demonstrated.

Keywords: Spray driers; Air pollution; Mixed integer nonlinear programming; Optimization; Air pollution management system

Introduction

The existing air pollution control technologies and future trends are studied extensively [1,2]. Efforts of air pollution control are focused on two important aspects, development of advanced technologies to reduce the emissions and utilization of existing technologies in optimal manner. World Bank group report [3] pointed out that pollution control shall consider both particulate as well as gaseous pollutants. McIlvaine [4] noted that techno-commercial evaluation of technologies to face future challenges of stringent norms is necessary.

Among all air pollutants, particulate matter attracted considerable attention of researchers. The ultrafine particulate matter (PM10) and (PM2.5) are associated with a range of respiratory and cardiovascular diseases [5-7]. Moreover, particulate matter influences many atmospheric processes including cloud formation, visibility, solar radiation and precipitation, and plays a major role in acidification of clouds, rain and fog [8-10]. At present industry uses Cyclone separators, Electrostatic Precipitators (ESP), Fabric Filters (FF) and wet scrubbers for removal of particulate matter and control air pollution.

Cyclone separator applies centrifugal force to separate suspended particles from the flue gas streams. The efficiency of the cyclone separator depends on the size and density of the particle, flue gas inlet velocity and its viscosity, cone length and diameter of the cyclone separator, and flue gas inlet and outlet diameters. Cyclone separators have no moving parts, which results in minimum maintenance and less energy consumption [11-13]. Fabric filters [14,15] have high collection efficiency, no corrosion problems and ability to collect particles with high, as well as low, electrical resistivity. However, it has high maintenance costs, temperature limitations, larger size requirement which makes it difficult to use when space is at a premium. Electrostatic precipitator utilizes an electric field to separate the suspended particles from the dust laden flue gas. The basic principal of operation of an ESP is that the flue gas is forced to pass through an electrical field wherein the suspended particles get electrically charged [11,16]. The Overall collection efficiency of each one of the air pollution control devices depends on particle size distribution (PSD) of inlet stream, mass flow rate and physicochemical characteristic of particles. In the process industry air pollution control devices were used as a single or in series based on requirements.

Mathematical programming and optimization in general, have found extensive use in process system engineering. Extensive reviews of optimization tools are available in the open literature. Biegler and Grossmann [17] provided a general review on optimization, emphasizing the strategies that have been applied or studied more extensively, namely, nonlinear programming (NLP), mixed-integer nonlinear programming (MINLP), dynamic optimization, and optimization under uncertainty.

Optimal selection of pollution control strategies has attracted considerable attention in the recent past. Kuprianov et al. and Zhen et al. [18,19] discussed a linear programming based optimization for minimization of total cost including fuel and environmental cost in terms of emission of gaseous pollutants. Shaban and Gharbi [20] described a mixed integer linear programming model that determines the best investment strategy for control of gaseous air pollutants. Zhang and Huang [21] developed stochastic possibilistic multiobjective programming model for economic and environmental objective for handling greenhouse gaseous emissions from municipal solid waste management facilities.

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To propose an optimal air pollution control and prevention strategy it is necessary to study the source of pollutants and pollutant characteristics. After thorough monitoring sampling and analysis of the results it is necessary to identify Industries with inadequate APMS and propose a model for identification of an optimal air pollution control strategy.

The objective of present work is to propose a generic optimization model for optimal selection of air pollution prevention and pollution control strategies. It shall be generic enough for application for multiple sources and multiple air pollutants. The model shall be able to provide solution to a real time air pollution pertaining issues in the industrial estates. The study also aims at evaluating the existing scenario with respect to environmental implications and includes the same while optimizing along with economic aspects.

Background and Scope of the Study

The industrial estate of Ahemdabad district region is having more than 500 small, medium and large scale industries. They are situated within a radius of about 10-15 km from the city centre. Most of these industries are in operation since last three decades. Due to increase in population in last decade, the city has started growing in all directions. Presently in some regions it becomes difficult to distinguish between the industrial estate and residential plots. As shown in Figure 1 the Vatav industrial estate is located in South-Eastern part of the Ahmedabad city. Around seventy five of the industries located in this industrial estate producing dyes and dye intermediates. Pollution control board has carried out careful inspection and monitoring to follow up complaints from residential areas about deposition of colored particles in terrace of their buildings. It has also been observed that the seasonal temperature changes cause inversions which make these suspended colored particles and other toxic gases to remain at the ground level. The regulatory authority found that dye and dye- intermediate industries in the area are responsible for such colored SPM emissions. Industrial Associations tried to identify the problem and conclude the same. We in collaboration with the Industrial association conducted a detailed study of APMS of the dye and dye- intermediate industries located in Vatva industrial Estate.

Scope of the study is limited to evaluation of APMS and to suggest suitable additional mitigation measures required to make the APMS adequate. In this study spray drying units along with particulate collection devices as part of APMS are considered. Various parameters of spray drier and air pollution control devices influencing the emission of air pollutants are considered. These parameters include design capacity of drier, diameter & height of drier, concentration of slurry, air flow rate, and inlet outlet air temperature. Specifications of control devices like cyclone, scrubber and bag house were also considered. Moreover, velocity and flow rate of air pollutants through stationary emission sources are evaluated.

The study has paid special attention to the followings

1. Evaluate the status of air pollution scenario in the industries.

![Figure 1: Map of Ahmedabad city enclosed by outer ring road.](image)
2. Monitoring of stack gases quality and checking the adequacy of air pollution control measures.
3. Suggesting additional measures required to improve overall APMS.

Methodology Adopted for the Study

In view of the scope of the work presented above following methodology has been adapted while evaluating adequacy of APMS.

1. The basis for evaluation is taken as consolidated consent and authorization granted by the regulatory agency to the company to operate the process plant.
2. Emission norms for all industries are taken as same. Special attention is paid to emission of particulate matter as the nature of the industrial operation demands the same.
3. In the present study the air pollutants emitted from the stacks attached to the spray dryers are only considered as the scope of the work demands the same. Detailed design data regarding the spray dryers and pollution control measures attached to them are collected from the industries in a specified format.
4. Operating capacity of the plant is one of the major factors influencing the quantum of pollution generated in a process plant. Hence design capacity of the spray dryer is considered.
5. The air pollutants are sampled and analyzed from the stationary sources using standard test methods as mentioned in Table 1.
6. The analysis results are used to identify plants, exceeding standard emission norms. The proposed mathematical model is applied for such industries to suggest optimal air pollution control strategy.
7. Effect of stringent regulatory norms on selection of optimal air pollution control strategy is evaluated with the help of simulation study.
8. Various industries are adopting air pollution control measures in addition to the general air pollution control measures presented in Figure 2. Overall observations made regarding each component of APMS are also reported.

Brief Description of the Process and Equipment Involved in the Study

Spray drying technology is highly energy intensive, yet it is widely used in dye and dye intermediate industries. This is due to rapid and non-contact drying, and can handle higher initial temperature, and provide high evaporation rates and thermal efficiencies. Figure 2 illustrated a typical process flow diagram of spray drying unit. Spray drying includes atomization of feed solution into drying chamber in which small droplets are converted into powder. The dye powder produced is collected from drying chamber. Spray dryers are equipped with high efficiency dust collectors. The operation of spray drying is largely affected by particle size and bulk density requirements of the dried product.

In general the feed solution is atomized using feed devices like (1) single fluid nozzle or pressure type, (2) two-fluid nozzle or pneumatic type, and (3) centrifugal (spinning disc). Single fluid nozzle is used.

| S.no | Parameter            | Standard code followed |
|------|----------------------|------------------------|
| 1    | Particulate Matter   | IS: 5182 (part 15) 1974 |
| 2    | Sulphur Dioxide      | IS: 5182 (part 02) 2001 |
| 3    | Oxides of Nitrogen   | IS: 5182 (part 06) 1975 |

Table 1: Standard methods for monitoring of air pollutants.
to produce a narrow spray of fine particles. Two fluid nozzles or multiplicity of nozzles are used to obtain the desired feed rate, due to the high pressure employed. In centrifugal atomizers the feed solution is pumped through spinning disc where dispersion is achieved by centrifugal force. This system is generally used for larger productions. The nature and chamber geometry depends on atomization used. The product collection systems attached with spray dryers requires substantial capital investment. However, the cost per kg of dry product is significantly lower for higher capacity dryers.

In general most of the spray drying units in dye and dye intermediate industry uses cyclone separators, venture scrubber and bag filters as particulate collection devices. However in most of the industrial units under consideration in the study cyclone separator and venture scrubber is used. In a rare case cyclone separator followed by bag filter is used in parallel to venture scrubber is used.

The collection of particles in cyclone separators is based on the action of the inertial or centrifugal forces upon particles. Various forces acting during operation of Cyclone Separator are centrifugal force, drag force and gravitational force. The particulate matter laden with dirty air particles move downwards and are removed from the walls, the dirty air particles move downwards and are removed from the central exhaust pipe to produce an inner vortex. After reaching the cyclone portion, the air stream changes direction and moves upwards towards the exhaust pipe to produce an inner vortex. After reaching the cyclone walls, the dirty air particles move downwards and are removed from the cyclone through the draw-off pipe.

Similarly, varieties of scrubbers are used as air pollution control devices to remove particles and/or gases from industrial exhaust streams. A typical ventury scrubber consists of converging diverging cross section flow channel. In this type of system the cross-sectional area of the channel decreases then increases along the length of the channel. The narrowest cross section area is referred as “throat”. In the converging section, the decrease in cross section area increases the waste gas velocity. The scrubbing liquid is injected into the scrubber slightly upstream of the throat or directly into the throat section. The scrubbing liquid is atomized by the turbulence in the throat, improving gas-liquid contact. The gas-liquid mixture then decelerates as it moves through the diverging section, causing additional particle-droplet impacts and agglomeration of the droplets. The liquid droplets are then separated from the gas stream in an entrainment section, usually consisting of a droplet/mist eliminator.

**Monitoring and Analysis of Results**

As per the methodology illustrated in above section, seventy five spray dryers installed in dye and dye intermediate industries are monitored and analyzed to evaluate their APMS. The analysis report of such monitoring is depicted in Table 2. The detailed specifications of

| S.no | Name of industry | Temp °C | Velocity m/s | PM mg/Nm³ | SO₂ ppm | NOₓ ppm |
|------|------------------|---------|--------------|------------|---------|---------|
| 1.   | Balaji           | 50      | 10.27        | 85         | 6.52    | 0.92    |
| 2.   | Bhavin           | 52      | 11.69        | 108        | 3.92    | 13.98   |
| 3.   | Apex dyestuff    | 56      | 9.43         | 42         | 2.61    | 13.96   |
| 4.   | Shree hari       | 52      | 11.48        | 114        | 5.26    | 27.02   |
| 5.   | Tapsheer         | 43      | 13.69        | 86         | 1.31    | 14.51   |
| 6.   | Jagson industries| 52      | 12.97        | 98         | 5.25    | 12.49   |
| 7.   | Shivcare         | 47      | 9.74         | 83         | 2.61    | 11.91   |
| 8.   | Aryes organic    | 46      | 15.55        | 112        | 5.26    | 7.85    |
| 9.   | Amin enterprise  | 46      | 10.83        | 90         | 1.31    | 17.42   |
| 10.  | Kiri             | 46      | 11.37        | 142        | 6.54    | 14.39   |
| 11.  | Amtex            | 57      | 11.35        | 89         | 5.23    | 26.45   |
| 12.  | Meghnani 1       | 47      | 9.98         | 107        | 5.26    | 23.14   |
| 13.  | Nichem           | 54      | 9.78         | 208        | 6.56    | 18.04   |
| 14.  | Bodal 4          | 56      | 13.97        | 146        | 1.31    | 17.55   |
| 15.  | Parshwanath      | 55      | 20.9         | 88         | 10.45   | 15.01   |
| 16.  | Multi colourcheem| 50      | 16.4         | 196        | 9.16    | 15.42   |
| 17.  | Gayatri          | 43      | 8.22         | 146        | 5.23    | 15.39   |
| 18.  | Khayti 3         | 60      | 12.89        | 136        | 5.23    | 21.73   |
| 19.  | Khayti 2         | 75      | 11.76        | 114        | 3.94    | 14.06   |
| 20.  | Khayti 1         | 62      | 10.4         | 13         | 7.88    | 40.82   |
| 21.  | Jagson           | 55      | 11.74        | 77         | 5.25    | 14.68   |
| 22.  | Uma              | 56      | 14.18        | 132        | 5.23    | 14.75   |
| 23.  | Appollo          | 50      | 13.3         | 181        | 2.63    | 10.58   |
| 24.  | Mayur            | 54      | 9.53         | 131        | 7.87    | 12.87   |
| 25.  | Indocoal 3       | 50      | 8.94         | 96         | 6.6     | 14.11   |
| 26.  | Indocoal 2       | 52      | 8.97         | 55         | 2.62    | 16.7    |
| 27.  | Indocoal 1       | 47      | 8.05         | 12         | 2.63    | 21.2    |
| 28.  | Sagar            | 90      | 5.72         | 77.72      | 3.93    | 13.61   |
| 29.  | Macfl 1          | 50      | 5.83         | 77.34      | 5.25    | 16.75   |
| 30.  | Macfl 2          | 52      | 6.53         | 110.37     | 10.51   | 14.06   |
the spray drying units with inadequate APMS are presented in Table 3. The other observations made regarding APMS have been presented in the following section.

Observations made during the Study

This section deals with overall observations made during the study. These observations are classified into two categories namely a) pollution control aspects and b) effect of APMS on the behavior of these pollutants once they are emitted into the atmosphere. Problems identified in the above said categories are presented below.

Observation related to pollution control

Pollution control measures used

It is noted that the pollution control equipment provided in the industries are generally consisting of cyclone separators, venturi scrubbers, followed by water tanks. Some of the industries have installed bag filter in place of cyclone separator and venturi scrubber.

Separation of particulate matter in the spray chamber

In most of the cases around 40% of the particulate are collected in

Table 2: Analysis report for the stationary emission source for various spray drier units.

| No. | Name               | Particulate | Pressure | Temperature | Flow Rate | Efficiency |
|-----|--------------------|-------------|----------|-------------|-----------|------------|
| 31  | Choksi pigment     | 54          | 14.65    | 80.29       | 5.24      | 15.44      |
| 32  | Shivanand polymer  | 53          | 8.71     | 199.21      | 5.28      | 20.48      |
| 33  | Pranav             | 45          | 16.78    | 36.6        | 7.87      | 14.81      |
| 34  | Jay chemical       | 52          | 10.42    | 87.13       | 3.93      | 13.23      |
| 35  | Amardeep           | 60          | 14.83    | 135.57      | 6.55      | 12.34      |
| 36  | Chemistar          | 50          | 8.88     | 77.78       | 7.88      | 15.48      |
| 37  | Bluemorn           | 56          | 19.34    | 97.13       | 5.23      | 14.39      |
| 38  | Ushanti            | 50          | 10.62    | 66.6        | 3.96      | 15.15      |
| 39  | Choksi colourchem  | 45          | 19.78    | 5.76        | 2.64      | 6.58       |
| 40  | Choksi organic     | 46          | 8.82     | 9.39        | 2.63      | 4.75       |
| 41  | Ornet              | 46          | 14.05    | 62.1        | 5.27      | 12.67      |
| 42  | Dynamic            | 62          | 12.02    | 162.4       | 2.63      | 11.99      |
| 43  | Bansari            | 40          | 5.63     | 33.7        | 9.2       | 4.53       |
| 44  | Aerodyning         | 56          | 7.45     | 54.19       | 3.93      | 5.42       |
| 45  | Oba speciality     | 75          | 7.49     | 13.39       | 5.23      | 7.6        |
| 46  | Aris dyechem 2     | 60          | 8.06     | 85.4        | 3.94      | 13.45      |
| 47  | aabis dyechem 1    | 47          | 8.97     | 75.02       | 10.51     | 8.53       |
| 48  | Alfa               | 65          | 12.02    | 155.02      | 5.26      | 8.03       |
| 49  | Denim colourchem   | 42          | 15.57    | 59.66       | 7.88      | 8.41       |
| 50  | Comacolourchem     | 50          | 8.88     | 86.05       | 5.26      | 16.29      |
| 51  | MAC                | 46          | 7.09     | 164.07      | 5.26      | 10.31      |
| 52  | sSar dyes          | 55          | 7.99     | 88          | 2.62      | 6.83       |
| 53  | Rohan dyes 2       | 60          | 7.69     | 28          | 3.15      | 13.45      |
| 54  | Rohan dyes 1       | 52          | 13.6     | 50          | 4.05      | 11.96      |
| 55  | Orjet              | 48          | 21.78    | 42          | 8.11      | 7.21       |
| 56  | Prince industry    | 34          | 13.22    | 65          | 6.58      | 5.96       |
| 57  | Ambica industry 1  | 33          | 7.19     | 144         | 5.22      | 7.45       |
| 58  | Ambica Industry 2  | 53          | 7.74     | 88          | 2.61      | 9.9        |
| 59  | Bhagwesh Industries| 55          | 15.13    | 124         | 7.05      | 8.35       |
| 60  | Ambuja Intermediate| 55          | 10.88    | 73          | 6.83      | 7.63       |
| 61  | Silver Industries  | 45          | 13.88    | 63          | 1.57      | 13.38      |
| 62  | Shanghai Industries| 45          | 10.64    | 62          | 2.76      | 7.23       |
| 63  | Bhagwati Chemicals | 56          | 11.72    | 114         | 4.72      | 12.01      |
| 64  | Arham Industries   | 56          | 8.32     | 122         | 3.68      | 9.45       |
| 65  | Kiridyes 3         | 45          | 8.42     | 103         | 5.9       | 7.48       |
| 66  | Shivanand Polymer 2| 56          | 11.77    | 136         | 8.54      | 11.64      |
| 67  | Shanti Industries  | 52          | 9.82     | 72          | 5.52      | 12.03      |
| 68  | J D Chem           | 54          | 8.87     | 86          | 1.57      | 9.9        |
| 69  | Alps Industries 2  | 52          | 8.4      | 133         | 3.27      | 7.08       |
| 70  | Alps Industries 1  | 52          | 13.93    | 45          | 6.81      | 13.41      |
| 71  | Shreenathji Industries| 56          | 11.63    | 97          | 1.96      | 9.39       |
| 72  | Kiridyes – 1       | 50          | 16.14    | 71          | 2.49      | 7.47       |
| 73  | Kiridyes - 2       | 55          | 7.83     | 86          | 2.48      | 14.02      |
| 74  | Bhagwati Dyesstuf  | 45          | 8.16     | 136         | 3.17      | 14.54      |
| 75  | National Industries| 46          | 10.2     | 90          | 6.29      | 11.99      |
the spray chamber itself. At some locations outlet of cyclone separator is connected to the bottom of the spray chamber making it possible to collect the product at a single collection point. The principle aim of the spray chamber is drying of the material and removal of water from the product. Hence it is not expected to give 100% separation of particles from the flue gas. The outlet temperatures of the chambers are around 80 to 90°C.

Separation of particulate matter in cyclone separators

This is the major pollution control equipment. Most of the particles are collected here up to 55% to 60% from the air. The outlet of the cyclone separator consists of less than 3% of the total product quantity. It is noted that in general the separation efficiency of cyclone separators are varying between 90% to 96%. It is observed that most of the industries have installed tangential entry type cyclones. The observations made with respect to cyclone separators are as follows.

1. Most of the existing cyclones are working with satisfactory efficiency.
2. Most of the product is collected at the bottom of the separator.
3. It is noted that in some of the industries series of two cyclones having same dimensions are arranged to improve the efficiency. When cyclones are arranged in series the amount of particles collected by the second cyclone become very limited. It advisable to improve the efficiency nozzle for water injection.

Problems related to venturi scrubber

Venturi scrubbers of various types are installed subsequent to the cyclone separators. These scrubbers installed by various industries differ in the throat, converging and diverging section dimensions. Another major difference observed is location of water injection. It is also noted that nozzle designs location of water injection makes major difference in gas liquid contact. Improvement in the contact between particles and water is expected to improve the particle removal efficiency.

1. It is noted that various industries are adapting different scrubber dimensions. It is beneficial to standardize the most efficient design for overall improvement in the pollution in the industrial zone.
2. One of the major scopes for the improvement is design of high efficiency nozzle for water injection.
3. Improvement in the dimensions of ventury is expected to improve pressure drop and reduce the energy consumption.

Issues related to droplet removal

A separate cylindrical drums are provided to remove droplets from the gases. In many of these cases strainer or mist eliminator is provided to improve the droplet removal efficiency.

1. It is observed that the some of these drums are fitted with baffles to improve efficiency.
2. In some cases it is noted that droplet eliminators are removed unintentionally for ease of cleaning. It is advised to keep proper mist eliminating/droplet removing mechanism to improve particulate removal.

Problems related to water chamber

Some of the industries have installed a water tank between droplet remover of the scrubber and the stack. These tanks are typically of 1-2

| S.no | Specification                        | Unit        | Multicolourchem Ltd. | Nichem Ltd. | Appolo Ltd. | Shivanand Ltd. | Alfa industries | MAC Ltd. | Dynamic Ltd. |
|------|--------------------------------------|-------------|-----------------------|-------------|-------------|----------------|----------------|-----------|--------------|
| 1    | Design load (Liquid flow rate)       | Lt/Hr       | 650                   | 500         | 770         | 700            | 400            | 715       | 700          |
| 2    | Concentration of the dye in inlet    | Kg/Kg       | 25                    | 25-30       | 35          | 35             | 30             | 30        | 20-30        |
| 3    | Air flow rate                         | m3/Hr       | 11000                 | 8000        | 10000       | 21000          | 7000           | 17500     | 10000        |
| 4    | Spray Chamber height                  | mt          | 10                    | 3.36        | 4.5         | 12.5           | 3.5            | 5.5       | 12           |
| 5    | Spray Chamber diameter                | mt          | 4.5                   | 4.2         | 4.5         | 4.5            | 4              | 4.4       | 2.7          |
| 6    | Conical section height                | mt          | 4                     | 3           | 4.5         | 4.5            | 2.87           | 4.75      | 5.5          |
| 7    | Gas temperature at dryer outlet       | C           | 90-95                 | 80          | 90          | 40-50          | 80             | 105       | 85-90        |
| 8    | Chamber pressure                      | kpa         | -10                   | -10         | -10         | -16            | -10 to -15     | -15 to -20 | -10          |
| 9    | Cyclone diameter                      | mt          | 1.2                   | 1.2         | 1.2         | 1.4            | 1.1            | 1400      | 1.6          |
| 10   | Cyclone conical section height        | mt          | 1.5                   | 3.06        | 3.7         | 3.5            | 2.5            | 3250      | 4.5          |
| 11   | Cyclone efficiency                    | %           | 95                    | 97%         | 95          | 80-95%         | 95-98%         | 99        | 99%          |
| 12   | Ventury inlet diameter                | mt          | 500 mm                | 585         | 0.5         | 700            | 0.35           | 600 mm     | Tangential   |
| 13   | Ventury thoat diameter                | mt          | 350 mm                | 390         | 0.3         | 350            | 0.97           | 375 mm     | 0.3          |
| 14   | Converging section length             | mt          | 500 mm                | 585         | 0.6 approx  | 0.2            | 1.61           | --        | 0.3          |
| 15   | Diverging section length              | mt          | 1000 mm               | -           | 0.45 approx | 0.3            | 1.61           | --        | 2.5          |
| 16   | Liquid flow rate at the ventury       | Lt/Hr       | 10 m3/hr              | 15000       | 7500        | 10000          | 3000           | 5000      | 12000        |
| 17   | Drum height                           | mt          | 5000 mm               | 2800        | 40          | 1.5            | -              | 3.5       | --           |
| 18   | Mist eliminator type                  | --          | --                    | Denister    | NA          | --             | Nil            | --        | 1.25         |
| 19   | Pressure drop across ventrity section| kpa         | 100 mmwc              | -           | 0.5         | 40-60          | 50             | 70 mmwc    | --           |
| 20   | Mist Eliminator packing type          | --          | --                    | Mesh Type   | NA          | --             | --             | --        | --           |
| 21   | Type of blower                        | --          | centrifuge            | Centrifugal| Induced Draft| Centrifugal    | Centrifugal    | Centrifuge | Centrifuge   |
| 22   | Capacity of the blower                | m3/Hr       | 14000                 | 15000       | 11500       | 28000          | 8000           | 11000     | 12000        |
| 23   | Blower motor capacity in HP           | H.P         | 30                    | 40          | 30          | 40             | 30             | 30        | 40           |

Table 3: Detailed specification of spray drying.
m in width and length and 1-2 m in height. These tanks are more than half filled with water. The reason to install these tanks is to remove particulate matter. It was noted that the water in these tanks are seldom replaced at regular interval.

Such installations were not mentioned in the open literature for removal of particulate matter. Our study revealed that these tanks may help in removal of particulate matter of considerable size. However most of the industries are installing these tanks after ventury scrubber and droplet removal. The space available for the air flow is sufficient within the water chamber. Particle ridden air comes in contact with water only at the upper surface of water. The inertial force of bigger particles may be sufficient to hit the surface of the water and get trapped.

**Problems related to stack and monitoring facilities**

It is noted that all of the industries considered for study have installed stacks for atmospheric entry of polluted gases. The following problems related stacks are noted by the expert team

1. The height of the stack is not based on proper pollution load and dispersion study. It is necessary to evaluate proper stack height for better air pollutant dispersion.
2. It is noted that safety of the installation of the stacks are compromised at many locations. It is to be corrected based on suitable mechanical design of the base, support and stack.
3. Leakages of gases from the stack are as observed at least 15% of the cases.
4. Location of the stack is not considered based on the wind direction and dispersion. However, this cannot be corrected for industrial estate having many small scale industries.

**Effect of rooms constructed at the top of the stack**

It is noted that some of the industries have constructed rooms at the top of the stack. These rooms are typically of cubical of 10 ft in dimension. The outlet is through a cloth arranged at the door of these rooms. This cloth works like a bag filter of limited area. This leads to exit of gases around the outlet rather than entering into atmosphere reducing the effective stack height. This arrangement has serious consequences with respect to dispersion of the pollutants in the atmosphere. It is also noted that the pollutant concentration nearby area around the stack are expected to increase. These rooms are serving two purposes a) visibility and dispersion. However, this cannot be corrected for industrial estate having many small scale industries.

**Observations related to pollution load**

It is observed that the pollution load is within the permissible limits in most of the cases. From the monitoring results it is noted that the emission concentrations are higher in some of the cases due to two major reasons a) improper operation b) due to reduced efficiencies and due to small defects related to some of the pollution control devices. With suitable minor modifications/improvements to these pollution control equipment overall pollution load can be reduced. For the benefit of the industries detailed discussion on these devises are provided in this report. From the seventy five units monitored with respect to APMS the industrial units with inadequate APMS are identified. The detailed specifications of such units are collected and presented in Table 3. The commercial cost for modification of existing control devices as well as for additional control measure are obtained from the manufacturers of this equipment. The proposed optimization model is applied to suggest optimal air pollution control strategy. The optimization problem formulation for units under consideration is presented in the next section.

**Problem Formulation**

The proposed mathematical model for air pollution control is illustrated herewith. The simulations have been carried out to suggest possible modifications and recommendations in existing air pollution control strategy to achieve prescribed norms. The indices, variables and parameters used are presented prior to the model development.

**Indices**

- $i$ pollution source.
- $j$ control device.
- $p$ pollutant.

**Sets**

- $i$ pollution source.
- $j$ air pollution control devices.
- $p$ particulate matter.
- $f$ types of fuels.

**Variables**

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

**Parameters**

- $C_j^0$ Modification and installation cost of new control $j$.
- $C_t$ Operating cost of control $j$.
- $HC_p$ Health cost of the pollutant $p$ in USD/kg of pollutants.
- $B$ Budget available for the air pollution control system.
- $L$ Length of the time horizon of interest.
- $D_i$ Diameter of the stack in m.
- $H_i$ Height of the stack in m.
- $V_i$ Velocity of the gas through source $i$ in m/s.
- $Q_i$ Flowrate of the flue gas thorough source $i$ in m$^3$/s.
- $A_i$ Cross section area of the stack in m$^2$.
- $K_p$ Emission of pollutant $p$ from sources $i$ in mg/m$^3$.
- $R_{ij}$ Reduction capacities for control devices $j$ operated over source $i$ for pollutant $p$.
- $K_l$ Desired reduction norms for pollutant $p$ from source $i$ in mg/m$^3$. 

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As discussed above the economic cost for the air pollution control equipment like operating cost is taken as actual cost incurred in power consumption maintenance cost, labour cost, utility cost and others.

\[
\text{Operating cost}=\sum\sum C_{ij} X_{ij} \left[ \left( 1 + i_{\text{con}} \right)^n - 1 \right] \left( 1 + i_{\text{in}} \right) X_{ij} \text{ (1)}
\]

Similarly, the cost for modification, revamping of the existing control devices is taken as modification cost. However the cost for erection and setting up the new control devices is also taken into consideration.

\[
\text{Modification and installation cost}=\sum C_{ij} X_{ij} \text{ (2)}
\]

Quantification of the health impact due to particulate matter emission considered is adopted from the impact pathway analysis methodology.

\[
\text{Health cost}=\sum \sum H C_{ip} K_{ip} Q_{ip} (L-T_{\text{con}}) \text{ (3)}
\]

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

\[
\text{Minimize} \left[ \sum \sum C_{ij} X_{ij} \left( (1 + i_{\text{con}})^n - 1 \right) \left( 1 + i_{\text{in}} \right) X_{ij} + \sum \sum \sum C_{ip} H C_{ip} K_{ip} Q_{ip} (L-T_{\text{con}}) \right] \text{ (4)}
\]

**Constraints**

The inlet pollutant load \(K_i\), needs to be minimized to desired outlet emission norms \(K_f\). The reduction of pollution load to desired regulatory norms depends on control equipments with their respective collection efficiencies \(R_{n_{ij}} \), \(K_{ip}(1-\Sigma R_{ij} K_{ij}(100)) \leq K_{ip}\)

Non negativity constraints.

\[
L \geq 0 \text{ (6)}
\]

\[
X_{ij}=0 \text{ or } 1
\]

The present study considers existing pollution control devices namely cyclone separator and venturi scrubber along with option of improvement in existing control devices for selection. The additional control devises are also considered for achieving stringent regulatory norms. The modification cost for existing control devises and installation cost for new control devises are presented in Table 4. The operating costs for these devices are presented in Table 5. For representative calculation of operational cost over the period of equipment lifetime local interest rate of 10% and inflation of 0.07 was considered. Emission concentration from the spray driers from each plant obtained from monitoring and analysis results are presented in Table 6. Details of the health cost due to pollutant emissions as reported in the literature is presented in Table 7. The efficiency of each one of the air pollution control devices was evaluated. The average values of such reduction capabilities of control equipment are mentioned in Table 8.

**Results and discussion**

The MINLP problem has been solved using commercial GAMS and the results obtained are presented in Table 9. The economic cost in term of Installation cost & operating cost as well as health cost has been evaluated. The data for various outlet emissions are plotted for all industries. The total cost is also plotted against variations in standard emission outlet norms. From the Figures 3-9 it can be concluded that health cost increases continuously as norms are relaxed. Operating and installation costs are more for stringent outlet norms due to selection of modified control devices. However it shows decreasing trend as emission norms are relaxed. The total cost shows increasing behavior initially to meet stringent norms, then decreasing due to relaxed norms and finally increasing. This is due to higher health cost due to higher emission of air pollutants.

**Table 4**: Installation and modification cost (millions USD) of control devices for spray drying system.

| Control devices          | Cost  |
|--------------------------|-------|
| Existing cyclone         | 0     |
| Modified cyclone         | 0.5   |
| Exiting venturi scrubber | 0     |
| Modified venturi scrubber| 0.6   |
| New control device       | 0.56  |

**Table 5**: Operating costs (millions USD per annum) for control devices for spray drying system.

| Spray drier | Existing cyclone | Modified cyclone | Existing venturi | Modified venturi | New control device |
|-------------|------------------|------------------|------------------|------------------|-------------------|
|            | 0.5              | 0.5              | 0.6              | 0.6              | 0.56              |

**Table 6**: Concentration of particulate matter from various dye manufacturing industries in mg/m².

| Type of pollutants | Health cost (USD per Kg of pollutant) |
|--------------------|---------------------------------------|
| PM                 | 0.09                                  |
| SO₂                | 0.063                                 |
| NOₓ                | 0.08                                  |

**Table 7**: Details of the health cost due to pollutant emission as reported in the literature.

**Table 8**: Reduction efficiencies of control devices evaluated for dye manufacturing units.
Table 9: An optimal Selection of air pollution control strategy for standard outlet emission norms for particulate matter (150 mg/Nm$^3$).

| S.no | Name of company       | Cost in millions USD per annum | Control device |
|------|-----------------------|-------------------------------|----------------|
|      |                       | O.C  | I.C.  | H.C.  | T.C  | Existing cyclone | Existing venturi | Modified cyclone | Modified venturi |
| 1    | Nichem Ltd.           | 8.8  | 1.1   | 1.3294| 11.229| X                | X              | 1              | 1              |
| 2    | Multi colourchem Ltd. | 8.8  | 1.1   | 2.1714| 21.971| X                | X              | 1              | 1              |
| 3    | Appollo Ltd.          | 8.8  | 1.1   | 1.7726| 11.672| X                | X              | 1              | 1              |
| 4    | Shivanand polymer Ltd.| 8.8  | 0.6   | 1.1522| 10.552| 1                | X              | X              | 1              |
| 5    | Dynamic Dyes ltd.     | 8.8  | 1.1   | 1.5954| 11.495| X                | X              | 1              | 1              |
| 6    | Alfa industries       | 8.8  | 1.1   | 1.5954| 11.495| X                | X              | 1              | 1              |
| 7    | MAC Ltd.              | 8.8  | 0.6   | 0.9306| 10.33 | 1                | X              | 1              | 1              |

Figure 3: Effect of outlet norms on installation, operating, health cost and total cost for Nichem Ltd.
Figure 4: Effect of outlet norms on installation, operating cost, health cost and total cost for multi colourchem Ltd.

Figure 5: Effect of outlet norms on installation, operating cost, health cost and total cost for Appollo Ltd.
Figure 6: Effect of outlet norms on installation cost, operating cost, health cost and total cost for shivanand polymer Ltd.

Figure 7: Effect of outlet norms on installation, operating cost, health cost and total for dynamic dyes Ltd.
Figure 8: Effect of outlet norms on installation, operating cost, health cost and total for Alfa industries.

Figure 9: Effect of outlet norms on installation, operating cost, health cost and total for MAC Ltd.
Conclusions

The adequacy of APMS is verified for commercially operated process plants located in the Vatva industrial estate of Ahmedabad district, Gujarat. The detailed specifications of the spray drier together with particulate matter collection devices are collected. We have monitored and evaluated collection efficiencies of air pollution control equipment. The monitoring results are reported with identification of unit with inadequate APMS. The proposed model for the air pollution prevention and control is applied to suggest necessary modifications and optimal selection of the air pollution control strategy to achieve the emission standard. Hence, the efficacy of the proposed model to improve APMS is successfully demonstrated.

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