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ENERGY CONSERVATION
IN
ELECTROSTATIC FABRIC FILTRATION
OF
INDUSTRIAL DUST

MASTER

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by

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ABSTRACT

Conservation in energy consumption in industrial fabric filtration systems has become very important due to the substantial increase in energy costs. Recently, an external electric field was utilized in the industrial dust control by fabric filters with very promising initial results. A substantial decrease in the pressure drop and an increase in collection efficiency were observed. In this final report the detailed outcome of the experimental research program in electrostatic fabric filtration was presented. The results show that pressure drop decreases substantially with the increased electrostatic field strength for all relevant parameters. Furthermore, the data of the experimental program was utilized to develop a semi-empirical model for the determination of the pressure drop and to establish an Energy - Optimized Design Criteria.

1. INTRODUCTION

Conservation in energy consumption in industrial fabric filtration systems has become very important due to the substantial increase in energy costs since 1973. The energy consumption in an industrial bag house is a function of the pressure drop across the fabric-dust cake combination and of the work required to remove collected dust from the fabric filter.

In a survey of operational systems in the field [1] it is noted that the average pressure drop across a fabric filter is approximately 6 inches of water. It has been estimated that in 1979 flue gas passed through the industrial fabric filter systems in this country is about 361×10^6 cfm¹. It is also generally accepted that energy required for cleaning of fabric filter bags is about 30 percent of the energy used for the operation of bag houses. Then with a fan efficiency of 50 percent² and an average electric energy cost of 4.75¢/kw-hr., approximately 300 million dollars were spent nationally to cover the energy cost for fabric filtration systems. Furthermore, it is estimated that a typical expenditure of 60¢/cfm a year is required for materials and labor to replace fabrics which typically last for a year. Therefore the total cost of the operation of the conventional bag houses was more than 500 million dollars in 1979.

¹McIlvaine Company, Oakbrook, IL

²Apitron Division, American Precision Industries, Charlotte, NC

In the completed experimental and bench scale research program for a new method of electrostatically enhanced fabric filtration of industrial dust; a pressure drop decrease between 20-80 percent was obtained in comparison to the conventional filtration [2-4]. The additional energy utilized in the bench scale experiments for the charging of particles was very little (in the order of one milliamperere). Therefore based on these somewhat limited findings of the experimental research program, it appears that this new method has a potential for substantial savings in the energy consumption in industrial fabric bag houses.

Furthermore with a substantial decrease in pressure drop, considerably less frequent bag cleaning could be employed with a resulting additional conservation in energy for cleaning and also an extension of fabric bag life. It could be assumed that the cleaning interval and the life of fabric bags would be doubled with the electrostatic enhancement. Therefore a potential savings of 78-216 million dollars in a year in the energy consumption appears to be possible in the operation of industrial bag houses. Furthermore, when the cost of fabric bags is included a potential total savings of 191-324 million dollars in a year could be obtained for a total air flow of 361×10^6 cfm.

Moreover, it is observed that presently there is a substantial increase in the use of fabric bag houses at coal fired utility boilers, incinerators and in the high temperature particulate control processes with the use of high temperature resistant bags (teflon, metal fibre bags). Also due to ever rising costs in energy, labor and

materials it is estimated that by 1985, over one billion dollars will be spent for conventional fabric bag houses. However, the electrostatically enhanced bag filtration may generate a substantial savings of well over one half billion dollars in energy consumption by the same year. Therefore a pilot and full scale testing program with the goal of minimizing the energy consumption coupled with an increase in collection efficiency appears to be well warranted.

2. EXPERIMENTAL PROGRAM

It is widely accepted that an analytical formulation of pressure drop across a dust cake on fabric filter is extremely difficult if not impossible. This is due to a number of factors such as difficulties in formulating the dust cake structure and wide variations in the properties of the particulate matter being filtered, operating conditions, fabric structure, cleaning mechanism, inlet loading etc. It is also known that the pressure drop across a fabric filter is substantially affected by the characteristics of the particulate matter. Furthermore, operating conditions such as filtering velocity, humidity and temperature of flue gas, cleaning mechanism and clean fabric permeability and surface characteristics and fabric weight all affect the pressure drop. Enormous difficulties involved in the identification and representation of all the above stated complicated factors dictate an experimental approach to the described task.

Therefore, in this research, an experimental program was conducted to develop a semi-empirical model for the determination of the pressure drop as a function of such previously untreated variables as

electric field and relative humidity as well as of the more conventional parameters. The proposed semi-empirical model is primarily based on Darcy's law of filtration. Furthermore, it contains a mechanism to take into account the effect of an electrically charged dust and/or fabric structure on pressure drop. It is known that the same dust produces widely different results for different fabrics [5,6], since the interyarn spaces, interfiber spaces, fabric surface, clean fabric permeability, etc., all affect the formation and nature of the dust cake. Finally, operating conditions such as filtering velocity, relative humidity, temperature, and dust cake weight are combined into a semi-empirical model. Within these conditions, the relative humidity as expected showed a considerable effect [7-9] on the pressure drop since the forces of adhesion within the cake, and eventually the structure of the cake, are directly influenced by the relative humidity.

Effects of particle size and, size distribution, gravity and porosity of dust materials are reflected as the input characteristics of the particulate matter. The other inputs are related to the strength of the electric field, clean fabric permeability and dust cake weight.

A functional form of the proposed equation for pressure drop is given by:

$$\Delta p = F(V, \epsilon_p, D_p, \rho_p, H, T, P_f, W_f, W_c, E_o)$$

Where

$$\Delta p = \text{Pressure drop}$$

V = Air cloth ratio
 ϵ_p = Porosity of dust material
 D_p = Mass mean diameter of particles
 ϵ_p = Specific gravity of particles
 H = Relative humidity
 T = Temperature
 P_f = Clean fabric permeability
 W_f = Fabric weight
 W_c = Dust cake weight
 E_o = Electrical field strength

It should be indicated that a simpler form of the semi-empirical pressure drop equation without the effect of an electric field has been successfully determined by Ariman [7]. It is based on an extensive bench scale testing without an electric field and on a statistical analysis of the bench scale data.

In the selection of the Darcy's filtration law as the starting point of the model, it is assumed that gas flow through a fabric is viscous at typical filtration velocities, incompressible and steady. As an outcome of these assumptions, the resistance to flow is determined primarily by viscous and secondarily by inertial effects. The parameters in the semi-empirical model of the pressure drop are determined through the use of data from an experimental program with a bench-scale filter system.

The basic apparatus which was employed in the experimental program is shown schematically in Figure 1. Primarily, it consists of

Figure: 1

a means for creating a representative dust cake on a fabric sample under varying conditions of relative humidity and charge levels. At constant face velocity, suspended dust particles were filtered by an initially clean fabric filter. The particles were charged prior to deposition by means of passage through a corona discharge (Fig. 2). Degree of charge was controlled by the magnitude of the field strength, and pressure drop was recorded after a specified weight of dust has been deposited. Then the similar testing is performed for different dust/fabric type combinations.

Air flow rate through the system is measured with the aid of a laminar flow element and a pressure gauge. Relative humidity is sensed with an electric hygrometer and the temperature in the sample holder is monitored with the aid of a thermocouple system. Pressure drop across the filter is measured by an inclined manometer. The system permits a variation in the flow rate over a range such that a filtering velocity range of 0-15 ft/min can be obtained and that relative humidity can be controlled over the range of 15-80 percent. The electric field strength is varied between 0-12 KV/in.

Nine industrial dust samples were utilized in the bench-scale tests. The resulting extensive data were used in the formulation of the effects of electric field strength, flow rate, dust type, fabric types, etc. on pressure drop. The dust samples were:

- a. Electric Furnace Fume
- b. Limestone
- c. Asphalt Plant Rock Dust
- d. Phosphate

Figure: 2

- e. Gypsum
- f. Calcium Carbide
- g. Asbestos
- h. Wedron Silica
- i. Fly Ash

Some selected results are presented in the following section.

Bench Scale Test Results

In Figure 3, pressure drop values in inches of water are presented as a function of the filtering velocity (ft/min) for charged and non charged gypsum. Fabric type was wool felt with a weight of 16 ounces per square yard and relative humidity and temperature were kept at 36% and 81°F respectively during the test runs. Three tests were performed at 5, 10 and 15 ft/min filtering velocity with approximately the same amount of gypsum. Thus, in the graph CW represents the cake weight and is determined by weighing the initially clean flat fabric filter sample (9" x 11.5") before and after the test. Then the fabric filter sample was cleaned for each test by a brush. It is seen that in all tests electric charge on particles causes particularly for $U=15$ ft/min. a considerable decrease in pressure drop or filter resistance. Similar situation is observed in Figure 4 for the Orlon felt fabric sample. It appears that the majority of the decrease takes place for $V = 7$ KV/in case with little additional decrease with $V = 10$ KV/in. This situation more or less was valid for all dust samples tested.

In Figure 5, the pressure drop variation for gypsum is presented for a sample of Fiberglas Teflon B. Again pressure drop decreases as the degree of particle charging increases. The effect of fabric type

Figure: 3

Figure: 4

Figure: 5

GYPSUM

T = 80° F

V = 7 KV/in.

FIBERGLASS TEFLON B (26 oz.)

RH = 34%

POLYESTER FELT (22 oz.)

RH = 57%

WOOL FELT (16 oz.)

RH = 36%

ORLON FELT (16 oz.)

RH = 38%

Figure: 6

on pressure drop for the charged case of $V = 7$ KV/in is demonstrated in Figure 6. Orlon felt, wool felt, fiberglas teflon B and Polyester felt fabric samples were utilized in the tests. It appears that under the similar operating conditions orlon felt (16 oz) and wool felt (16 oz) were the best performers and fiberglas teflon (26 oz) was the worst one from the pressure drop point of view.

Figures 7 and 8 represent the pressure drop variations for limestone and for non charged and charged cases. Four fabric samples namely polypropylene, Orlon, Dacron and Nomex were utilized in tests at the filtering velocities of 5, 10 and 15 ft/min. For all tests it is observed that electric charge on limestone particles causes an important amount of decrease particularly for higher filtering velocity values of 10 and 15 ft/min. As stated earlier the degree of charge was controlled by the magnitude of the field strength, namely through the voltage values of $V = 7, 10$ and 12 KV/in. The tests were performed for a dust cake weight of 30 grams. It is remarkable to notice that for the Orlon 16 oz filter sample and noncharged case pressure drop is 8.2 inches of water while for the charged case of 7 KV/in the corresponding pressure drop value is substantially lower namely 2.1 inches of water. It is therefore, estimated that by charging particles, the filtration rate per unit fabric area of a given fabric can be increased by a factor of up to four. This implies that with the aid of electrostatics it might reasonably be expected that fabric filters can be reduced in size by a factor of four, while achieving better collection efficiency.

It is further seen from the Figures 7 and 8 that there was no

LIMESTONE

Figure: 7

LIMESTONE

Figure: 8

noticeable difference for the cases of 10 KV/in and 12 KV/in. Again the majority of the decrease in the pressure drop takes place for $V = \text{KV/in}$ case.

The effect of fabric type on pressure drop for the non-charged and charged limestone dust samples ($V=7 \text{ KV/in}$) is demonstrated in Figures 9 and 10 respectively. For the non-charged case, wool felt (16 oz), Nomex (14 oz), Dacron (15 oz), felt (15 oz), Orlon (16 oz) and Dacron (22 oz) fabric samples were utilized in the tests. It appears that under the same operating conditions such as relative humidity level of 42%, 85°F temperature and a dust cake weight of 30 gram, the wool felt nomex were the best performers while the Dacron (22 oz) was the worst one for the pressure drop values particularly at the higher face velocities of 10 and 15 ft. min. Note that the Dacron (22 oz) fabric sample causes higher pressure drop in comparison to the lighter Dacron (15 oz) sample. Therefore, it appears that the fabric weight is another factor to be considered in the formulation of the pressure drop in fabric filtration.

A similar comparison is provided in Figure 10 for the charged case with the utilization of the same fabric samples. While Dacron (22 oz) remains the worst performer by causing the highest pressure drop. Orlon (16 oz) and Polypropylene (15 oz) provide the lowest pressure drop values.

The effect of relative humidity on pressure drop is demonstrated for charged and non-charged cases in Figure 11 for limestone dust and Dacron (15 oz) and Nomex (14 oz) fabrics. As expected, increase in relative humidity causes decrease in pressure drop. While this

Figure: 9

LIMESTONE

$V = 7 \text{ KV/in.}$
 $T = 82^\circ \text{F}$

Figure: 10

LIMESTONE

Figure: 11

decrease is quite small for the charged case. The variation is linear which is in accordance with the previous findings of an earlier research project at Notre Dame for the non-charged case pressure drop investigations [7,8].

Figure 12 presents pressure drop results for phosphate and for Nomex (9 oz) and Spun Nomex (9 oz) fabrics again for two different face velocities of 10 and 15 ft/min for charged (7 KV/in) and non-charged cases. In accordance with the test results of the previously stated dust samples, a tremendous decrease in pressure drop is observed due to the effect of electric charge on particles. Similar results were obtained with the utilization of the Polyester felt and Nomex fabric samples in Figure 13. The effect of fabric type on pressure drop is demonstrated for the charged case ($V=7$ KV/in) for the fabric samples of Orlon (16 oz) Dacron (15 oz) Spun Nomex (9 oz), Spun Glass and Spun Nomex (10 oz) in Figure 14. While Figure 15 represents the similar effect for the fabric samples of Nomex (9 oz), Dacron (22 oz), Nomex (14 oz), Spun Nomex (5.4 oz), all filament glass (8.5/9 oz) and Nomex (5.4 oz). From the comparison of the curves in Figures 14 and 15 it appears that all glass filament gives rise to the largest pressure drop for the similar operating conditions and the cake weight. While Nomex causes the least pressure drop. The effect of relative humidity for Phosphate and for Orlon (16 oz) and Wool felt (16 oz) fabric samples is demonstrated in Figure 16. Similar to the previous observation, relative humidity does not appear to have a considerable effect on pressure drop for the charged case.

Pressure drop - face velocity relation is presented in Figures 17

PHOSPHATE

Figure: 12

PHOSPHATE

Figure: 13

PHOSPHATE

Figure: 14

PHOSPHATE

Figure: 15

PHOSPHATE

Figure: 16

and 18 for electric furnace fume and for four fabric samples. In accordance with the procedure of the previous tests no charge and charged (7 KV/in) cases were investigated. Nomex (14 oz) and Spun Nomex (10 oz) were utilized for the tests of Figure 17. As expected a considerable decrease took place in pressure drop for the charged case. It is further noted that for the similar operating conditions Spun Nomex fabric filter causes somewhat higher pressure drop as compared to that for Nomex fabric filter. Namely 3.6 inches of water for Spun Nomex versus 3.2 inches for non charged limestone particles and 1.6 inches versus 1.3 inches for the charged case. Note that this interesting observation was made despite the fact that Nomex (14 oz) filter is heavier than the Nomex (10 oz) one. Therefore, it appears that in addition to the fabric weight, fabric characteristics need also to be considered in the pressure drop formulation.

Similar test results were provided by Figure 18 for the fabric filter samples of Spun Nomex and Spun Glass. Once again the pressure drop decrease was certainly main feature of the results. It is further noticed that Spun Glass fabric filter caused the largest pressure drop values within the stated four fabric samples for the corresponding cases. This outcome is also seen in Figure 19 which combines all the results for the non-charged tests of the Figures 17 and 18. The effect of fabric type on pressure drop for electric furnace fume dust sample is shown in Figure 20. Finally, the effect of relative humidity for the same dust and for Polypropylene (15 oz) and Nomex (14 oz) fabric filters is demonstrated in Figure 21 with the previously stated basic character.

ELECTRIC FURNACE FUME

Figure: 17

ELECTRIC FURNACE FUME

Figure: 18

ELECTRIC FURNACE FUME

Figure: 19

Figure: 20

ELECTRIC FURNACE FUME

Figure: 21

Figure 22 represents the pressure drop results of the tests with Asphalt Plant Rock Dust sample and for Orlon (16 oz) and Nomex (14 oz) fabric filter samples. The tests were performed for the face velocities of 10 ft/min and 15 ft/min and for charged and non-charged cases. It is interesting to note that although the expected decrease in the pressure drop took place for the charged case, Nomex fabric filter sample provided pressure drop values which are considerably lower than those of Orlon.

Pressure drop - face velocity results are shown in Figures 23 and 24 for fly ash and for four fabric filter samples of Dacron (22 oz), Wool (16 oz), Orlon (16 oz) and Polypropylene (15 oz). The tests were performed with non-charged and charged (7 KV/in) and 10 KV/in) fly ash and three face velocities of 5, 10 and 15 ft/min. It should be noted due to the considerable difficulties in the charging of fly ash particles, several tests were performed in order to obtain acceptable results. It appears that for the case of Dacron fabric filter sample, an increase in the applied voltage from 7 KV/in to 10 KV/in causes further important decrease in the pressure drop. This outcome is somewhat different than the previously stated results. Within the four fabric samples Dacron caused the highest and Polypropylene produced the lowest pressure drop values.

The effect of relative humidity on pressure drop is shown in Figures 25 and 26 for Asbestos and in Figure 27 for Calcium Carbide. The tests with Asbestos were performed with Dacron (22 oz), Nomex, Wool and Dacron (15 oz) fabric filter samples. The results are basically in agreement with the previously stated ones.

ASPHALT PLANT ROCK DUST

Figure: 22

FLY ASH

Figure: 23

Figure: 24

ASBESTOS

Figure: 25

ASBESTOS

Figure: 26

CALCIUM CARBIDE

Figure: 27

In order to investigate the effect of the increase in the charge on particles in a continuous form, a series of tests were performed with Wedron Silica by using Orlon (16 oz) fabric filter sample at the face velocities of 10 and 15 ft/min and with no charge, 5, 6 and 7 KV/in cases. For the higher face velocity between $V=0$ and $V=5$ KV/in no noticeable change took place in the pressure drop (Fig. 28). However, following the formation of the corona discharge around 5.3 KV/in, a sudden decrease in the pressure drop was observed. Namely from 3.8 to 2.1 inches of water for $V=6$ KV/in. A further decrease with less magnitude also took place when V was increased to 7 KV/in. A continuous decrease in pressure drop with an increased rate was observed with higher V values for the face velocity of $U = 10$ ft/min. A similar continuous variation is also displayed for Asphalt Plant Rock Dust with Orlon felt fabric in Figure 29.

Finally, the effect of the charge of the sign of corona discharge field was also investigated for an Asphalt Plant Rock Dust and Orlon (16 oz) filter (Fig. 30). It is quite interesting to note that for both filtration velocities of 10 and 15 ft/min there is no noticeable difference on pressure drop with the change of the sign of the electric field.

3. PRESSURE DROP FORMULATION

As stated in this report, analytical formulation of pressure drop across a dust cake on fabric filter is extremely difficult if not impossible. This is due to a number of factors such as difficulties in formulating the dust cake structure and wide variations in the properties of the particulate matter being filtered, operating con-

Figure: 28

ASPHALT PLANT ROCK DUST

Figure: 29

ASPHALT PLANT ROCK DUST

Figure: 30

ditions, fabric structure, cleaning mechanism, inlet loading etc. It is known that the properties of the particulate matter, which are not completely defined or understood at present, include the size, size distribution, shape, porosity, specific gravity, surface characteristics, electrostatics, chemical reactivity, adhesiveness and hygroscopicity of the particles. It is also known that the pressure drop across a fabric filter is substantially affected by the characteristics of the particulate matter. Furthermore, operating conditions such as filtering velocity, humidity and temperature of flue gas, cleaning mechanism and its characteristics, inlet loading, gaseous properties such as viscosity and density, clean fabric permeability and surface characteristics and fabric weight all affect the pressure drop. Enormous difficulties involved in the identification and representation of all the above stated complicated factors have dictated an experimental type of approach and a semi-empirical pressure drop model based on the experimental results.

Pressure Drop Model by the Analysis of Multiple Regression

It is known that regression analysis is used to determine the functional relationship between variables, while correlation analysis is used to determine the degree of association between variables. In regression analysis, once a functional relationship between the dependent and the independent variable is established, it can be used to determine how the dependent variable changes with the independent variable. The regression can be applied to all distributions (normal, Weibull, exponential, etc.); however, the regression method assumes that the error of the dependent variable is normally distributed, and

it requires no assumption about the distribution of the independent variable.

Linear multiple regression analysis is a method for establishing a linear functional relationship between one dependent and two or more independent variables. Many engineering experiments involve more than one independent variable which affects the dependent variable. It may then become necessary to isolate the effect of one independent variable from the effects of the others and to determine the contribution of each variable to the total effect. The general form of the linear function with multiple variables is

$$y = a_0 + a_1x + a_2z + \dots \quad (1)$$

where y = dependent variable which varies partially due to variation in x and partially due to variation in z .

x, z = independent variables

a_0, a_1, a_2 = multiple regression parameters

This equation is called the linear multiple regression equation of y on x, z , etc. Then, the method of least squares is employed in determining the parameters a_0, a_1 , and a_2 from the experimental data. When a set of experimental data points (x, y, z) is given by a least-squares plane on a three dimensional plot, the sum of squares E of the deviations of the data points from the most probable plane is

$$E = \sum_{i=1}^n (y - a_0 + a_1x_i - a_2z_i)^2 \quad (2)$$

The best estimate of the parameters a_0, a_1 , and a_2 is the one which

minimizes the sum of squares E. This is done by first partially differentiating the linear multiple regression equation with respect to a_0 , a_1 , a_2 and then setting the results equal to zero. Thus, a set of three simultaneous equations is obtained:

$$\begin{aligned}\sum y &= na_0 + a_1 \sum x + a_2 \sum z \\ \sum yx &= a_0 \sum x + a_1 \sum x^2 + a_2 \sum xz \\ \sum yz &= a_0 \sum z + a_1 \sum xz + a_2 \sum z^2\end{aligned}\tag{3}$$

These are called the "normal" equations. By simultaneously solving these equations, parameters a_0 , a_1 , and a_2 are computed. After the multiple regression parameters are determined, the equation that represents the data best is known. The next step is then to establish how well this equation of plane fits the data.

However, in many experiments the relationship between two variables may not be linear. Instead, the underlying functional relationship can be logarithmic $y = ax^b$ which falls under the category having non-linear parameters. In order to apply the principles of least squares, the equations should be reduced to a linear form. $y = ax^b$ can be transformed into a linear form by

$$\ln y = \ln a + b \ln x$$

or

$$Y = a_0 + bX\tag{4}$$

where

$$\begin{aligned}Y &= \ln y \\ a_0 &= \ln a \\ X &= \ln x\end{aligned}\tag{5}$$

The last equation has a linear form; therefore, all the equations of the method of least squares discussed previously apply here to determine a_0 and b .

Based on the bench-scale experimental program the following semi-empirical pressure drop model has been proposed:

$$\Delta p = \beta U^{\alpha_1} H^{\alpha_2} \left(\frac{P_f}{7.5}\right)^{\alpha_3} \left(\frac{W_f}{22}\right)^{\alpha_4} \left(\frac{1}{\epsilon}\right)^{\alpha_5} \left(\frac{D_p}{7}\right)^{\alpha_6} \cdot \left(\frac{\rho_p}{2.8}\right)^{\alpha_7} \left(1 + \frac{V}{7}\right)^{\alpha_8} \left(\frac{W_c}{25}\right)^{\alpha_9} \quad (6)$$

where

- Δp = Pressure drop, inches of water
- U = Air cloth ratio, ft/min
- H = Relative humidity %
- P_f = Clean fabric permeability
- W_f = Fabric weight, oz. per sq. yard
- ϵ = Porosity of dust material
- D_p = Mass mean diameter of dust material, micron
- ρ_p = Specific gravity of dust material, gm/cm³
- V = Voltage of the applied electric field, KV/in
- W_c = Dust cake weight, gr.

and $\beta, \alpha_1 - \alpha_9$ are unknown coefficients to be determined from the experimental testing results. It is seen that the proposed semi-empirical model is a non-linear one and can be transformed into a linear form by

$$\begin{aligned} \ln \Delta p = \ln \beta + \alpha_1 \ln U + \alpha_2 \ln H + \alpha_3 \ln \left(\frac{P_f}{7.5} \right) + \alpha_4 \ln \left(\frac{W_f}{22} \right) + \alpha_5 \ln \left(\frac{1}{\epsilon} \right) + \alpha_6 \ln \left(\frac{D_p}{7} \right) \\ + \alpha_7 \ln \left(\frac{\rho_p}{2.8} \right) + \alpha_8 \ln \left(1 + \frac{V}{7} \right) + \alpha_9 \ln \left(\frac{W_c}{25} \right). \end{aligned} \quad (7)$$

This equation has a linear form, therefore all the equations of the method of multiple linear regression and of the method of least squares discussed previously apply here to determine intercept β and regression coefficients $\alpha_1 - \alpha_9$. By using a computer program which is given in the appendix and by utilizing the results of the bench-scale testing, the unknown coefficients $\alpha_1 - \alpha_9$ were determined and the pressure drop model is given as:

$$\begin{aligned} \Delta p = .18 U^{1.87} H^{-.45} \left(\frac{P_f}{7.5} \right)^{-.11} \left(\frac{W_f}{22} \right)^{1.83} \left(\frac{1}{\epsilon} \right)^{.66} \\ \left(\frac{D_p}{7} \right)^{-.37} \left(\frac{\rho_p}{2.8} \right)^{.48} \left(1 + \frac{V}{7} \right)^{-.66} \left(\frac{W_c}{25} \right)^{.71} \end{aligned} \quad (8)$$

Note that negative powers in this formulation indicate as expected a decrease in pressure drop with increased voltage, relative humidity, clean fabric filter permeability and mass mean diameter of particles. A qualitative comparison of the results of the developed semi-empirical pressure drop model with those of the single bag simulator [10] was reasonably good. It is further noted that the described pressure model also compares basically rather well with that of the previous research program for non-charged case.

4. ENERGY-OPTIMIZED DESIGN CRITERIA

As indicated in the introduction, the energy consumption of an industrial fabric filter system is a function of the pressure drop across the fabric-dust cake combination and of the work required to remove collected dust from the fabric. It is noted that [1] the average pressure drop across a fabric filter approximately 6 inches of water. Assuming a charge rate of 4.5¢/kw-hr the stated pressure drop requires an electrical cost of 45¢ cfm-year. The cost of energy for cleaning of fabric filter bags varies depending upon the cleaning technique and other variables; however, for pulse jet systems the electrical energy consumed in compressing the cleaning air is at least 30% of that spent in overcoming the pressure drop. It has been estimated that in 1979 about 361×10^6 cfm of dust laden gas was passed through fabric systems. As stated in the introduction of this report, more than 500 million dollars was spent nationally to cover energy costs in industrial fabric filtration in 1979. Therefore it is very clear that the development of an energy-optimized design criteria for filtration systems is well warranted.

The pressure drop model for electrostatic fabric filtration, equation (8), indicates that increased voltage, relative humidity, clean fabric permeability and mass mean diameter of particles causes a decrease in pressure drop and therefore in energy consumption. Among these parameters, the results of the experimental program indicate that the voltage is the dominant one. However, a substantial part of the decrease takes place upon the formation of the corona discharge (Figures 28 and 29). A further decrease with less magnitude occurs

until the particles are charged at the saturation level. Beyond that, there is no noticeable decrease in pressure drop. The very similar phenomenon was also observed in the testing of an electrostatically augmented single bag unit [10].

An increase in relative humidity also reduces the energy consumption by causing the reagglomeration of particles, (and therefore an increase in particle size), prior to the filtration. It was observed that [3] the increase in the relative humidity and particularly an external charge on particles lead to the formation of more porous and fluffy dust cakes and therefore a smaller resistance against the dust laden gas flow. Note that the increase in voltage, relative humidity and mass mean diameter (MMD) of particles also provide an increase in the collection efficiency of fabric filters. The effect of external charge on the efficiency becomes more pronounced for fine particulates, namely $0.3\text{ }\mu\text{m}$ and smaller in MMD.

Based on these and all other observations in the bench scale and the single bag unit testing, an energy-optimized design criteria in industrial fabric filtration is established as given below:

Criteria

1. The utilization of an external high voltage electric field to charge particles is strongly recommended. In order to keep the additional energy consumption due to the field to a minimum, it is further recommended that the voltage value should not exceed the one necessary for the formation of the corona discharge.

2. The relative humidity of dust laden gas should be increased with the use of atomized droplet sprayers prior to the filtration process. The results indicate that relative humidity could be increased up to 85 per cent without causing the dust cake to become muddy. An increase in relative humidity also lowers the temperature of hot gases (350°F and over); thus it makes possible the use of fabric filters in the control of industrial dust.
3. It is recommended that the use of Nomex is preferred for fabric of filters whenever possible due to more favorable pressure drop results. The use of glass bag filter should be avoided unless the operating conditions do not permit any other alternative.
4. Fabric weight should be kept at a minimum whenever possible. The increased weight causes an increase in pressure drop and therefore in energy consumption.
5. Prior to the electrostatic filtration design the resistivity of an industrial dust should be examined with respect to the charge on particles. The changes in temperature and relative humidity should be considered in order to lower the resistivity of particulates and energy consumption required for charging of particles.

The developed criteria and the pressure drop model given by equation (8) should provide a qualitative understanding of the energy use

in an industrial fabric filter system. However, due to the restrictions on the bench scale experimental program, the presented energy-optimized design criteria and the pressure drop formula should not be considered in the final form and they are subjected to future revisions. It should be further noted that the completed research program is based on the charged particles only. The investigation of the case in which an electrostatic field across the fabric filter is applied with charged or non-charged particles is essential for the completion of the optimization of energy consumption in industrial fabric filter systems. It is planned that this case as well as the use of a pilot scale electrostatic single bag simulator will be proposed as the continuation of the research program.

5. CONCLUDING REMARKS

An experimental program was carried out for the development of a semi-empirical model for the determination of the pressure drop in electrostatic fabric filtration. The model is formed as a function of a previously untreated and important parameter, namely, the applied electric field voltage and other variables such as relative humidity, dust cake weight, fabric and dust characteristics and operating conditions. The model looks reasonable good and promising. However, due to the certainly limited nature of the experimental program, the presented pressure drop formula may not be considered in its final form and it may be subjected to future modifications.

The results of the experimental program clearly indicate that filter and dust cake resistance or pressure drop decreases with the

electrostatic charge on particles. Although there are quantitative differences in the magnitude of the effect of charging dusts prior to filtration, the effect is qualitatively identical for all dusts tested. Fabric type and relative humidity level exert some influence on the pressure drop in the electrostatic filtration process and pressure drop increases with face velocity as expected, and it can be seen that particle charging results in a substantial reduction of pressure drop, regardless of fabric types and relative humidity level.

It is shown in this research program that the electrostatics appears to have a profound effect on the flow resistance of fabric filters. For example, it is shown that by simply charging particles, the filtration rate per unit fabric area of a given fabric filter can be increased by a factor of four. This implies that with the aid of electrostatics it might reasonably be expected that fabric filters can be reduced in size by a factor of four, while achieving better collection efficiency.

6. PROPOSED RESEARCH PROGRAM

Based on the important outcome of the completed research program, a field verification task with the use of electrostatic single bag simulator is well warranted. As a continuation of the present effort, a pilot scale testing program for collection efficiency and pressure drop will be proposed. In this program the simulator which is already constructed, calibrated and tested in the laboratory [10] will be utilized in the particulate collection from effluent gases in a number of industrial processes.

As stated previously, due to the restrictions on the bench scale experimental program, the presented energy optimized design criteria and the pressure drop formula should not be considered in final form. The use of flat fabric rather than a cylindrical bag, non-existence of a periodic cleaning mechanism, and inlet loading level and control of it are considered to be the restrictions in the completed bench scale research program. Furthermore, the investigation of the case in which an electrostatic field across the filter is applied (with charged or non-charged particles) is essential for a complete understanding of the optimization of energy consumption in industrial fabric filter systems.

Therefore, the proposed use of the field-operational electrostatic single bag simulator at a variety of industrial plants is expected to stress the energy conservation with a higher collection efficiency in industrial fabric filter systems.

ACKNOWLEDGEMENT

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A-1

APPENDIX

COMPUTER PROGRAM FOR

PRESSURE DROP MODEL

PAGE 1 CE-L JPC JOB 1 JAN 24, 1979

// JOB CE-563LJPC

DISK PACK 10 = 1111 MAXIMUM JOB TIME = 120 SECONDS

>>> OCT 25, 1977 SYSTEM UPDATE <<< NOTKE DAME ENGINEERING COMPUTER LABORATORY
// NOFOR

>>> NOTKE DAME FAST FORTRAN/ASSEMBLY SYSTEM V77.3 JAN 21, 1979 UPDATE <<<

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CCCCC
**** MULRG MOUCL OF PRESSURE DRUP W/O PF ****
1ST ENTRY IN OUTPUT IS # OF RUN, THEN OBSERVED PD, THE MODEL'S ESTIMATE,
THE DIFFERENCE BETWEEN THE TWO AND FINALLY THE PERCENT ERROR
10 READ (5,10) RC1, RC2, RC3, RC4, RC5, RC6, RC7, RC8, RC9, BETA
11 FORMAT (10F10.5)
12 READ (5,11) N
13 FORMAT (11)
14 WRITE (6,9) RC1, RC2, RC3, RC4, RC5, RC6, RC7, RC8, RC9, BETA
15 9 FORMAT (110F8.5)
16 TOTER = 0.
17 J10 = 0
18 J5 = 0
19 DO 1000 I = 1, N
20 READ (5,12) X1, X2, X3, X4, X5, X6, X7, X8, X9, PD
21 12 FORMAT (10F10.5)
22 IF (X1.LT. 0.) GO TO 999
23 PMOUL=BETA+RC1*X1+RC2*X2+RC3*X3+RC4*X4+RC5*X5+RC6*X6+RC7*X7+RC8*X
24 8+RC9*X9
25 PD = EXP(PD)
26 PMOUL = EXP(PMOUL)
27 DIFF = PD - PMOUL
28 PCTER = (DIFF/PO) * 100.
29 IF (1.E0.1) BIG = DIFF
30 IF (ABS(DIFF).GT. ABS(BIG)) BIG = DIFF
31 IF (1.E0.1) PMAX = PCTER
32 IF (ABS(PCTER).GT.ABS(PMAX)) PMAX = PCTER
33 WRITE (6,13) 1, PD, PMOUL, DIFF, PCTER
34 13 FORMAT (5X, 13, 5X, F10.5, 5X, F10.5, 5X, F10.5, 5X, F10.5)
35 TOTER = TOTER + ABS(PCTER)
36 IF (ABS(PCTER).LT. 10. ) J10 = J10 + 1
37 IF ( ABS(PCTER) .LT. 5. ) J5 = J5 + 1
38 1000 CONTINUE
39 999 WRITE (6,14) J10
40 14 FORMAT (11H1, 25HTHE MAXIMUM DIFFERENCE IS, F10.6)
41 WRITE (6,15) PMAX
42 15 FORMAT (11H, 20HTHE MAXIMUM ERROR IS, F10.3, 1H%)
43 AVER = TOTER/FL0AT(1)
44 WRITE (6,16) AVER
45 16 FORMAT (11H, 20HTHE AVERAGE ERROR IS, F10.3, 1H%)
46 WRITE (6,17) J10, J5
47 17 FORMAT (11H, 14H# UNDER 10% IS, 14, 7X, 14H# UNDER 5% IS, 14)
48 STOP
49 END
```

// XEQ

REQUESTED LIBRARY SUBPROGRAMS
199L EXP INH

MEMORY USAGE: COMMON 01 DATA 1281 PROGRAM 7861 WORDS UNUSED 10860.

COMPILATION TIME 6.5 SEC

>>> NOFOR FIXED SUBROUTINES V77.2 JAN 03, 1979 UPDATE <<<

>>ERRKOR FA IN LINE 1

EXIT FROM JOB AT LINE 1
EXECUTION TIME 0.5 SEC

>>> EXPLANATION OF ERRORS <<<

FA ATTEMPT TO READ MORE DATA CARDS THAN WERE PROVIDED
// FIN

A-2

*****PRESSURE DROP MODEL FOR FABRIC FILTRATION*****

THIS PROGRAM READS IN THE DATA FROM THE TEST RUNS, PUTS THEM INTO A FORM
SUITABLE FOR MULTIPLE LINEAR REGRESSION, AND PUNCHES THE NEW DATA
THE VARIABLES IN THIS PROGRAM ARE AS FOLLOWS-- PD IS THE DEPENDENT
VARIABLE, THE PRESSURE DROP, AND THE INDEPENDENT VARIABLES ARE H, THE
HUMIDITY, V THE FILTRATION VELOCITY, W, THE WEIGHT OF THE DUST CAKE,
PHI THE APPLIED VOLTAGE, AND THE DUST AND FABRIC PARAMETERS RHO, EPS,
UP, WF, AND PF DEFINED EARLIER.....

DUST CODE # 1 REFERS TO NEOHON SILICA
DUST CODE # 2 REFERS TO PHOSPHATE
DUST CODE # 3 REFERS TO GYPSUM
DUST CODE # 4 REFERS TO CALCIUM CARBIDE
DUST CODE # 5 REFERS TO ELECTRIC FURNACE FUME
DUST CODE # 6 REFERS TO ASBESTOS
DUST CODE # 7 REFERS TO LIMESTONE
DUST CODE # 8 REFERS TO SODA ASH
FILTER CODE # 1472 REFERS TO 16 OZ ORLON FELT
FILTER CODE # 1593 REFERS TO 14 OZ NUMEX FELT
FILTER CODE # 1753 REFERS TO 16 OZ WOOL FELT
FILTER CODE # 1854 REFERS TO 15 OZ POLYPHOPYLENE FELT
FILTER CODE # 1962 REFERS TO 15 OZ POLYESTER (DACRON)
FILTER CODE # 1969 REFERS TO 22 OZ POLYESTER (DACRON)

101 READ (5, 101) N
FORMAT (13)
DO 100 I = 1, N
102 READ (5, 102) IDUST, IFILT, H, PD, W, PHI, V
FORMAT (214, 5F10.0)
IF (IDUST.EQ. 1234) GO TO 999
IF (IDUST.EQ. 1) GO TO 111
IF (IDUST.EQ. 2) GO TO 112
IF (IDUST.EQ. 3) GO TO 113
IF (IDUST.EQ. 4) GO TO 114
IF (IDUST.EQ. 5) GO TO 115
IF (IDUST.EQ. 6) GO TO 116
IF (IDUST.EQ. 7) GO TO 117
IF (IDUST.EQ. 8) GO TO 118

333 IF (IFILT.EQ. 1472) GO TO 472
IF (IFILT.EQ. 1753) GO TO 593
IF (IFILT.EQ. 1854) GO TO 472
IF (IFILT.EQ. 1962) GO TO 593
IF (IFILT.EQ. 1969) GO TO 472

111 EPS = .67
UP = 7.4
RHO = 2.7
GO TO 333
112 EPS = .50
UP = 12.
RHO = 3.2
113 EPS = .40
UP = 5.
GO TO 333
114 EPS = .56
UP = 5.
RHO = 2.26
115 EPS = .70
UP = 8.4
RHO = 2.6
GO TO 333
116 EPS = .84
UP = 3.
RHO = 2.6
GO TO 333
117 EPS = .48
UP = 8.5
RHO = 2.6
GO TO 333
118 EPS = .53
UP = 4.4
RHO = 2.3
GO TO 333
472 PF = 37.5
WF = 16.
GO TO 334
593 PF = 40.
WF = 14.

```

753 GO TO 333
PF = 37.5
PF = 16.
GO TO 334
854 PF = 35.
PF = 15.
GO TO 334
962 PF = 40.
PF = 15.
GO TO 334
969 PF = 7.5
PF = 22.
GO TO 334
334 Y = ALUG (POI
X1 = ALUG (V)
X2 = ALUG (H)
X3 = ALUG (PF/7.5)
X4 = ALUG (WF/22.)
X5 = ALUG (1./EPS)
X6 = ALUG (OP/7.)
X7 = ALUG (KHU/2.8)
X8 = ALUG (1. + PHI/7.)
X9 = ALUG (J/25.)
WRITE (6.5) X1, X2, X3, X4, X5, X6, X7, X8
WRITE (6.15) X9, Y
WRITE (7.5) X1, X2, X3, X4, X5, X6, X7, X8
WRITE (7.15) X9, Y
5 FORMAT (6F10.5)
15 FORMAT (2F10.5)
100 CONTINUE
999 STOP
END

```

// FIN

TOTAL JOB TIME 0:00:15.7 3 TOTAL PAGE(S)