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Project Summary

Cost and Performance Models for Electrostatically Stimulated Fabric Filtration

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A survey of the literature on performance models for pulse-cleaned fabric filters is presented. Each model is evaluated for its ability to predict average pressure drop from pilot plant data. The best model is chosen and used in conjunction with pressure drop reduction data from an electrostatically stimulated fabric filter (ESFF) pilot plant to produce a model of ESFF performance. The accuracy of the models is limited by their primitive nature and the size of the pulse-jet performance data base. Where the baghouse, dust, and fabric to be modeled are very similar to the pilot plant from which the model was developed, the model should perform adequately for comparison between ESFF and non-ESFF baghouses.

Published correlations relating equipment size and cost are used in a model for predicting the capital and operating costs of conventional pulse-jet baghouses. A comparison between predicted capital costs and independently obtained esitmates shows that the baghouse cost model is capable of ±20% accuracy. A prototype design for ESFF hardware is developed and cost quotes from vendors are incorporated into a predictive equation for ESFF costs. Because there are no pulse-jet ESFF baghouses, the prototype design is subject to revision. This lack of certainty in the hardware design restricts the accuracy of ESFF cost predictions to ± 30%. The cost model is best used in comparing cost estimate of ESFF and non-ESFF pulse-jet baghouses and in comparisons of different sizes of conventional pulse-jet baghouses.

The performance and cost models are incorporated into a computer program for two different computers: the Tektronix series 4050 computers and the TRS-80 Model 1, III, and 4 microcomputers. The program requires pulse-jet design data as input and predicts average pressure drop, capital cost, operating cost, and net present value. Complete program documentation is also included.

This Project Summary was developed by EPA's Industrial Environmental Research Laboratory, Research Triangle Park, NC, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).

Introduction

Electrostatic stimulation of fabric filtration (ESFF) involves applying an electric field to the surface of a fabric filter to enhance the collection of particulate matter. An added benefit of ESFF is a reduction of the pressure drop across the filter. This technology has been successfully demonstrated in the laboratory on a pilot scale pulse-jet fabric filter. Preliminary estimates show that this technology may also be economically feasible.

This report summarizes work done for the U.S. Navy and the U.S. Environmental Protection Agency to develop a computerized model of pulse-jet ESFF performance with the ability to predict capital and operating costs as well.

Performance Model

Design of a pulse-jet fabric filter requires predicting the maximum and average pressure drops for the filter and for the gas flow through the entire system, and determining the maximum penentration of particles and agglomerates through the filter. Predicting the cost of a fabric filter is usually more sensitive to the pressure drop calculations since the collection efficiency is generally greater than 99 percent. Thus, for the performance model in this cost analysis, only the pressure drop is considered.

The state of the theoretical and empirical models for predicting pressure drops in conventional pulse-jet fabric filters is not well developed. The empirical models are limited to the conditions under which they were developed. The theoretical, or quasitheoretical, models have not been well tested for conditions other than those used by their authors; furthermore, they require some data for determining unknown constants. Thus it is necessary to rely primarily on full-scale and pilot-plant experience for designing new systems.

As with the theory of pulse-jet filter pressure drops, the theory of the effect of electric fields on fabric filter pressure drop is limited to rationalizations of pilot-plant observations. The laboratory studies that have been done do not yield sufficient information to extend the results to full-scale baghouses. Of the pilot-plant studies reported in the literature, that referred to earlier is the most applicable for this study. Consequently, the models of baghouse performance will rely on user experience for the prediction of conventional baghouse pressure drop and on the referenced operating experience for the electrostatic enhancement effect. The data requirements for each model are described below.

Figure 1 shows how pressure drop increases as the amount of dust on the fabric (W) increases for a typical pulse-jet filter. The pressure drop increases rapidly just after a bag has been cleaned. After a dust cake becomes established on the filter, the pressure increases linearly with time. The slope of the linear portion of the curve is called K_2, the specific resistance coefficient. There is no satisfactory way to predict *a priori* the nonlinear portion of the pressure drop curve. The simplest way to predict the overall performance is to postulate an effective residual pressure drop P_e (i.e., the pressure drop just after cleaning) and assume that the pressure drop increases linearly for the entire filtering time. The pressure drop across the bag can then be written:

$$P = P_e + K_2VW \qquad (1)$$

where V is the filtration velocity. To develop a pressure drop model independent of filtration velocity, it is necessary to define the drag: S = P/V. Substituting into Equation (1):

$$S = S_e + K_2W \qquad (2)$$

where S_e is the "effective" residual drag just after cleaning: $S_e = P_e/V$. There is no satisfactory way to predict S_e.

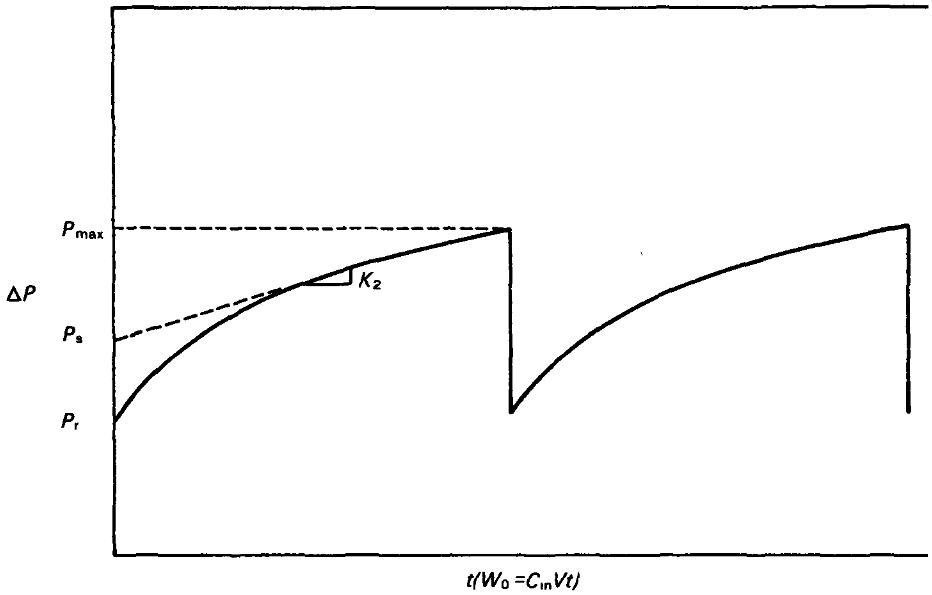

Figure 1. *Pressure drop versus cycle time for pulse-jet fabric filters.*

Thus, to design a conventional fabric filter for a given set of inlet conditions (including inlet dust concentration, velocity, and cycle time), either (1) P_e (S_e) and K_2, or (2) P_r (S_r) and the nonlinear behavior of P (S) with loading must be measured and used as input to the model.

To extend the conventional pulse-jet model to the ESFF pulse-jet, the change in these parameters with the applied field must be predicted. Since few data are available to predict these effects, rough approximations must be made based on available data.

Experimental data from ESFF units are reported in terms of the pressure drop ratio (PDR) defined as:

$$PDR = (P_{max}-P_r)_{ESFF}/(P_{max}-P_r)_{conventional} \qquad (3)$$

where P_{max} is the maximum pressure drop (see Figure 1) that is reached in one cycle of filtration and P_r is the true residual pressure drop. If PDR is known as a function of applied voltage and (P_{max}-P_r) conventional is known, then $(P_{max}-P_r)_{ESFF}$ can be calculated. To find $(P_{max})_{ESFF}$ the $(P_r)_{ESFF}$ must be known.

The residual pressure drop (P_r) has been found to be significantly affected by the presence of an applied field; however, due to limited testing and scatter in available data, a correlation could not be developed between applied field strength and the reduction in P_r. An average reduction in residual pressure drop of 0.42 with a standard deviation of 0.27 was found for a wide range of operating conditions. The reduction in residual pressure drop is defined as:

$$r = (P_{r\ conventional} - P_{r}\ ESFF)/P_{r\ conventional}. \qquad (4)$$

Lacking further information, the model for this program uses a reduction in residual pressure drop of 0.42 when comparing the ESFF to the conventional pulse jet. Thus given r and $(P_r)_{conventional}$, then $(P_r)_{ESFF}$ can be predicted from Equation 4 and thus $(P_{max})_{ESFF}$ can be found from Equation 3.

Using the earlier observed dependence of PDR on the applied field, the data were empirically fit to give:

$$PDR = 0.77 \exp(-0.25f) \quad 5 > f \geq 0.75 \qquad (5)$$

$$PDR = 1.0-0.63f + 0.21f^2-0.024f^3 \quad f < 0.75 \qquad (6)$$

where $PDR = (P - P_r)_{ESFF}/(P - P_r)_{conventional}$, and (7)

f is the applied field in kV/cm.

Field data indicate that an optimum PDR is achieved at field voltages of 2.5 - 3.0 kV/cm. Operation at applied fields greater than this would not result in much better performance.

In summary, due to a lack of a well-developed theory on the performance of conventional pulse-jet filters, a simple model of baghouse pressure drop (Equations 1 and 2), requiring user input of critical parameters, is used in the performance model for predicting baghouse pressure drop. If the baghouse is to be operated as an ESFF unit, the user-supplied value of the residual pressure drop for the conventional baghouse is adjusted to account for the presence of the electric field (Equation 4). The rise of the pressure drop over the filtration cycle is also adjusted, using the estimated PDR (Equations 5-7) to yield an estimate of pressure drop performance of the ESFF baghouse. This method is summarized in Table 1.

Note that the performance model given here is based on a limited amount of data. The quality of the predictions obtained from this model will depend on the quality of the user-supplied inputs and on the similarity of the coal and fabric type used to those employed during the ESFF pilot-plant evaluation. Laboratory and theoretical studies are in progress to improve the understanding of the ESFF mechanism and its effects on pressure drop.

Economic Measures of Merit

Before the construction of a pulse-jet baghouse can begin, the optimum design must be determined. Is a small baghouse with a large pressure drop better than a large baghouse with a low pressure drop? Is the added expense of electrostatic stimulation worthwhile? An objective criterion is needed to answer these questions. For this reason several economic measures of merit have been established. The three measures of merit—savings-to-investment ratio, payback period, and net present value—are the objective criteria needed for such an evaluation.

A measure of merit describes the economic feasibility of a project. For the Navy, the evaluation of a baghouse falls under the category of a Fundamental Planning Analysis (FPA). There are two kinds of FPAs: Types I and II. A project to retrofit a baghouse with ESFF hardware to reduce its pressure drop and therefore lower operating costs requries a Type I FPA. The construction of a new baghouse, either with or without ESFF, requires a Type II FPA. A Type I FPA results in a value of the Savings/Investment Ratio (SIR), which is similar to the Return on Investment (ROI) indicator discussed by other analysts. Another measure of merit that can be used to describe a Type I FPA is the payback period. Either measure of merit (SIR or payback period) can be used to determine the economic feasibility of a project under both Navy and EPA guidelines.

The SIR gives a direct measure of the "profitability" of a proposed modification in current operations. Before the savings gained by retrofitting a baghouse with ESFF are calculated, the annual operating and maintenance (O&M) costs for the ESFF baghouse must be computed, then substracted from the current annual O&M costs to determine annual savings in current dollars. This difference must be positive if ESFF is to offer an economic advantage over the status quo. Before determining the economic benefit of an ESFF retrofit over the remaining life of the baghouse, the cumulative savings must be computed, using the cumulative uniform series factor. This factor, which discounts the value of money that is to be paid out in the future to the value at the present time, is calculated as:

$$b_n = \frac{\exp(n\cdot\ln(1+R)) - 1}{\ln(1+R)\cdot\exp(n\cdot\ln(1+R))} \qquad (8)$$

where

n = the number of years the annual payments are to be made, and

R = the effective annual discount rate.

Table 1. Performance Model

Input:

Option 1—$P_r(S_r)\ P_e(S_e),\ C_{in},\ t,\ V,\ K_2,$ *applied field*

Option 2—Data set of $P_{max},\ P_r(S_r)\ P_e(S_e),\ C_{in},\ t,\ V,$ *applied field f; the program will calculate* $K_2=(P_{max}-P_e)/((C_{in}Vt)V)$

Pressure drop calculation:

(1) $W = C_{in}Vt$

(2) (P_{max}) *conventional* $= S_eV + K_2\ VW$

(3) $(P_r)_{ESFF} = (P_r)$ *conventional* $(1-r),\ r=0.42,\ P_r=S_r\cdot V$

(4) *PDR = f(applied field), by Equations 5-7*

(5) $(P_{max})_{ESFF} = P_r\ ESFF + ((P_{max})_{conventional} - P_r) \times PDR$

(6) $P_{ave}ESFF = ((P_{max})\ ESFF + P_r\ ESFF)/2$

Output:

$(P_{max})_{ESFF},\ (P_{ave})_{ESFF},\ PDR,\ (P_r)_{ESFF},\ K_2$

The present value of a series of uniform annual payments is then calculated as:

$$SPV = A_pb_n \qquad (9)$$

where

A_p = the uniform annual payment.

The SIR is then computed as the ratio of the present value of the annual savings to the investment cost of retrofitting the baghouse with ESFF hardware.

According to the Navy, the "discounted payback occurs when the present value of accumulated savings equals the present value of the investment." Mathematically this is expressed:

$$\text{Payback period} = \frac{-\ln(1 - \ln(1+R)\cdot I/A_p)}{\ln(1+R)} \qquad (10)$$

where

I = the amount invested,

A_p = the uniform annual payment in current dollars, and

R = the effective annual discount rate.

Here it is assumed that no lead time is involved in realizing the benefits of the ESFF retrofit. The payback period thus represents the length of time a baghouse that has been retrofitted with ESFF hardware must operate before breaking even.

The measure of merit that characterizes a Type II FPA is the equivalent uniform annual cost. This measure of merit standardizes cost estimates of different particulate control strategies, allowing direct comparison of the costs. For this study, the other possible particulate control alternatives are unknown; therefore, it may not be possible to calculate the equivalent annual cost. It is possible to calculate the Net Present Value (NPV), which can be used to determine the equivalent annual cost when all alternatives have been established. Therefore, the NPV will be the result of the Type II FPA reported by the computer program

The NPV is the sum of the present values of the annual costs for each year of equipment life. It is assumed that the payment schedule for capital and operating costs is on an annual basis and that the project requires no lead time. If the annual cost is constant, as is assumed here, the NPV of the annual payments can be calculated from the cumulative uniform series factor. The capital cost must be added to the annual cost to determine the total NPV. It is assumed that no capital recovery costs are associated with the purchase of the equipment.

A rigorous evaluation of a project's measure of merit would incorporate the effects of depreciation, tax credits, inflation, and other indirect costs on the annual payment. Consideration of these factors is beyond the scope of this project, though it is still desired to estimate the appropriate measures of merit. Therefore, the reported measures of merit, described under *Computer Program*, below, are based only on the capital, operation, and maintenance costs. As such, the reported values are "before-tax" estimates of the measures of merit. For those who wish to pursue a more rigorous evaluation of the measure of merit, the capital cost and operation and maintenance costs are also reported.

Pulse-jet Baghouse Cost Estimation

Each measure of merit discussed above requires a knowledge of the initial investment in equipment and the annual cost of operating the equipment. The initial investment is the capital cost of the project, including the cost of purchasing and installing the baghouse system. The method for estimating the costs used in this project is based on obtaining costs for the major items in the plant (e.g., baghouse, ducting, fan), based on the net cloth area available for flow. Then Lang factors are used to estimate the installation charges and the indirect costs as percentages of the cost of the major plant items.

The annual operating and maintenance costs are calculated based on the size of the equipment (net cloth area) and the flow rate of gas. The indirect annual costs are based on the capital cost of the equipment.

The procedures used for estimation of capital and operating costs are too lengthy to be described here.

Correlations for predicting the cost of equipment were developed from vendor quotes. One subtask of this contract was to develop an independent check of the accuracy of those correlations. Unfortunately, very little data have been published in the literature on the cost of pulse-jet baghouses. As a result, a consultant was hired to obtain new vendor quotes for pulse-jet baghouses.

Three different sizes of baghouses were priced: 26, 85, and 165 acms (55, 180, and 350 k acfm). The equipment includes the baghouse, its insulation, woven glass bags and cages, inlet and outlet manifolds and dampers, hopper heaters, controls, and structural supports. The baghouses were specified with air-to-cloth ratios of 0.02 m/s (4 ft/min). With this information, earlier correlations were used to develop the costs in Table 2. *A rigorous effort was made to guarantee* that the vendor quotes were directly comparable with the predicted numbers.

The agreement between the predicted values and the reported values is surprising because both are based on vendor quotes. Typically such price quotes can vary by a factor of 2 between different vendors. Note that the cost modeling equations are based on design standards that are at least 7 years old, so that changes since then are not included in the costs reported in the table. Note also that this comparison does *not* include the price of ducting, ash conveying systems, ash ponds, or installation. Also, at the time of this writing, data were not available to validate the ESFF costs.

In summary, the equations for predicting the cost of the baghouse, insulation, dampers, and fabric seem to be in good agreement with expected values. The cost predictions of ESFF hardware, other auxiliary equipment, and operating and maintenance costs have not been validated. An earlier report, that cost equations (except the ESFF hardware) should be accurate to ±20 percent, is consistent with the results given here.

The reliability of ESFF hardware-cost predictions is unknown. The earlier prototype system is quite simple, and it is likely that some items have been overlooked. In situations such as this, it is common to specify the accuracy of the estimate as ±30 percent. Likewise, for lack of reliable data, it is assumed that annual operating and maintenance cost predictions should be accurate to within ±30 percent.

Computer Program

A computer program has been written that incorporates the performance and cost models described above. The program allows the user to predict pulse-jet baghouse performance, and then use the air-to-cloth ratio, air flow rate, and predicted pressure drop to predict the capital and annual operating costs. The appropriate measure of merit (NPV for new baghouses and SIR and payback period for baghouses retrofit with ESFF hardware) is calculated from the predicted values.

The computer program (PULSEJET) was developed for two different types of microcomputers: the Tektronix® series 4050 computers and the TRS-80® Models I, III, and 4. For the PULSEJET program to run successfully on a Tektronix® 4051, 4052, or 4054, the computer must have a minimum of 32 kilobytes of available memory (RAM). Floppy disk drives are not required for program operation. The program can provide hard copies of the program input and output on a Tektronix® Hard Copy Unit.

Table 2. *Comparison Between Predicted Values and Vendor Quotes*

	Cost ($)		
Item	*$Q = 26\ m^3/s$* *$A = 1{,}275\ m^2$*	*$Q = 85\ m^3/s$* *$A = 4{,}274\ m^2$*	*$Q = 165\ m^3/s$* *$A = 8{,}194\ m^3$*
Baghouse	*109,870*	*354,970*	*675,690*
Insulation	*37,910*	*115,310*	*216,590*
Bags	*11,380*	*31,192*	*57,034*
Dampers	*2,783*	*6,608*	*11,810*
Total	*161,943*	*508,080*	*961,124*
Instruments and controls (10%)	*16,194*	*50,808*	*96,112*
Purchased Equipment Cost	*178,137*	*558,888*	*1,057,236*
Foundation and Supports (4%)	*7,125*	*22,356*	*42,289*
Capital Cost (December 1977)	*185,262*	*581,244*	*1,099,525*
Purchased Equipment Cost (CE Plant Cost Index) (mid-1983)	*281,526*	*883,263*	*1,670,847*
Predicted Unit Cost ($\$/m^2$ fabric)	*221*	*207*	*204*
Vendor Quote ($\$/m^2$ fabric)	*258*	*215*	*183*
Ratio: Predicted Unit Cost/Vendor Quote	*0.857*	*0.963*	*1.115*

The minimum system required to run the TRS-80® version of the program includes a TRS-80® Model I, III, or 4 microcomputer with 32 kilobytes of available memory and one 5-1/4-in. floppy disk drive. The program requires either the TRSDOS® or NEWDOS® Disk Operating System (DOS) or any other DOS that can run Microsoft Disk Basic and is file-compatible with TRSDOS. The pulse-jet program is also required to list results on a line printer.

The PULSEJET program is menu-driven in both operation and data entry; it includes default values if input values are unknown. English and metric units are available and program execution is very fast. Complete instructions on program operation and helpful information are available for programmers who wish to modify the code.

Summary

A simple model of pulse-jet baghouse performance has been adapted for prediction of ESFF performance. The model predicts maximum and average pressure drops across the baghouse based on user-supplied parameters. Pilot plant data have been used to estimate the reduction in pressure drop that results from applying an electric field to the fabric surface. This model of an electrostatically enhanced pulse-jet baghouse has been incorporated into a computer program, along with a model for predicting capital and operating costs. The program predicts the performance of a conventional or ESFF baghouse, along with capital and operating costs. The program also reports the appropriate measure of merit (depending on whether the equipment is new or retrofit). Complete documentation of the performance model, the cost model, and the computer program are available.

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The complete report, entitled "Cost and Performance Models for Electrostatically Stimulated Fabric Filtration," (Order No. PB 84-207 828; Cost: $13.00, subject to change) will be available only from:

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