**HOT-GAS CLEANUP SYSTEM
MODEL DEVELOPMENT**

Volume II

Final Report

**By
K. Ushimaru
A. Bennett
P. J. Bekowies**

November 1982

Work Performed Under Contract No.: DE-AC21-81MC16049

**For
U. S. Department of Energy
Office of Fossil Energy
Morgantown Energy Technology Center
Morgantown, West Virginia**

**By
Flow Industries, Inc.
Research and Technology Division
Kent, Washington**

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Foreword

This study of Hot-Gas Cleanup System Model Development was conducted under Contract No. DE-AC21-81MC16049 for Morgantown Energy Technology Center of the United States Department of Energy. The direction and valuable comments from the past and present project officers, Dr. L. E. Graham and Ms. R. A. Bajura, respectively, have been greatly appreciated.

The authors are grateful for the cooperation and dedicated effort of the individuals who have been actively involved in this study of Hot-Gas Cleanup System Model Development. The authors are particularly indebted to Dr. G. D. Case of Resource Technologies Group, Inc., and Dr. H. Huynh and Ms. M. L. Johnson of Flow Industries, Inc., for their technical assistance.

Cost Models

The detailed discussion of cost models has been deleted from this report. HTHP gas cleanup devices are in various states of development. Some devices have been developed to the point of being included in conceptual designs of a reference power plant. Other devices are still operating at the bench or subpilot scale. The degree of confidence to be placed in the cost information available for a device parallels the device developmental status to a great extent.

Since the cost models were developed using existing data, cost comparisons among the various devices may not be valid because of the differences in developmental status. Therefore, based on a Department of Energy review, the decision was made to delete the detailed discussion of cost models from this report.

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INTRODUCTION

Under Contract to the Department of Energy (DOE) through the Morgantown Energy Technology Center (METC), Flow Industries, Inc., has developed computer models to simulate the physical performance of five hot-gas cleanup devices for pressurized, fluidized-bed combustion (PFBC), combined-cycle power plants. Separate cost models have also been developed to estimate the cost of each device. The work leading to the development of these models is described in Volume I of this report. This volume contains the user's manuals for both the physical and cost models. The manuals for the physical models are given first followed by those for the cost models. Each manual is a complete and separate document. A list of the model names and devices and their respective sub-routine names is given as Table 1.

Table 1. Hot-Gas Cleanup Models

	<u>Subroutine Name</u>	
	<u>Physical Model</u>	<u>Cost Model</u>
Moving Granular Bed Filter by Combustion Power Company	USRCGB	QFCOST
Ceramic Bag Filter by Acurex	USRACB	QDCOST
Electrostatic Granular Bed Filter by General Electric	USRGGB	QACOST
Electrostatic Precipitator by Research Cottrell	USRCEP	QECOST
Electrocyclone by General Electric	USRGCY	QBCOST

Computer Methodology

All the codes were developed specifically for inclusion in the Advanced System Process Engineering (ASPEN) simulation code developed for DOE by the Massachusetts Institute of Technology (MIT). The ASPEN computer code is the most comprehensive, flexible, but complex computerized process simulation system ever developed. The code contains over 375,000 lines of code and over 1400 subroutines. ASPEN has a very strict naming convention for its sub-routines, COMMON blocks, and variables. It also has an elaborate semaphore

system for controlling execution of various components of the process. It is imperative that the deliverable code interfaces properly with ASPEN and is consistent with its standards. The following sections discuss the work performed in meeting the standards set by the original designers of ASPEN.

ASPEN Interface Algorithm

Considerable time was spent in the development of a common ASPEN interface algorithm sufficient to handle all of the physical models developed as part of this effort. The final pseudocoded algorithm for the user interface sub-routines is as follows:

```
Begin procedure;
  if this is an initialization pass, then;
    set pointers;
    get user input from REAL array;
  end if;
  define simulation and/or report pass;
  if this is a simulation pass, then;
    calculate input flow and pressure drop;
    determine auxiliary power requirement;
    if data correct, then;
      apply filter model;
    end if;
  end if;
  transfer results to output stream;
  if this is a report pass, then;
    write to the HISTORY file;
  end if;
  return to ASPEN;
end of procedure.
```

During the development of the codes, this algorithm proved to be very stable. It should provide a good framework for maintaining the codes over their life-cycle.

Coding Standards

Our design philosophy was to separate, as much as possible, the process of physical model coding from the ASPEN interface coding requirements and to modularize our code whenever possible. Following is a list of the standards set for code development.

1. The names of all subroutines and COMMON blocks must conform to the convention developed by Flow and approved by METC.

2. Only ASPEN variables and arrays are listed in subroutine argument lists. Internal model variables and arrays are listed in appropriate COMMON blocks created especially for communication purposes.
3. The International System of Units (SI) is used in communications between modules of the physical models. Data entering the user interface module from user-defined arrays (REAL) are converted and verified before being passed on to the other physical model subroutines.
4. All cross-sectional dimensions of spherical and cylindrical sections (including particle sizes) are entered as diameters.
5. The algorithm for each procedure is contained within the source coding of each model and is easily stripped out by eliminating the executable statements.

Over 40 subroutines were developed as part of the contract work and, to the best of our knowledge, the code names do not conflict with any of the other 1400 subroutines contained in ASPEN. ASPEN requires that user interface routine names begin with the prefix USR. The hot-gas cleanup user interface subroutines and the naming convention approved by METC for subordinate routines are listed in Table 2.

Table 2. ASPEN Conventions for Naming Subroutines

<u>Cleanup Device</u>	<u>User Interface</u>	<u>Subordinate Routines</u>
Moving Granular Bed Filter	USRCGB	QFxxxx
Ceramic Bag Filter	USRACB	QDxxxx
Electrostatic Granular Bed Filter	USRGGB	QAxxxx
Electrostatic Precipitator	USRCEP	QExxxx
Electrocyclone	USRGCY	QBxxxx

The prefix QQ was reserved for any subordinate routines common to more than one of the above user interface routines. There are two such routines, namely, QQPNTN and QQFLOT. The first routine, QQPNTN, determines the stream pointers (subscripts) required to locate stream data. The second routine, QQFLOT, transfers the output stream data to ASPEN. Both of these routines are common to all of the user interface subroutines. Table 3 is a list of routines developed as part of this effort.

Table 3. List of FORTRAN Subroutines Used in Cleanup Models

	Electro- cyclone	Moving Granular Bed Filter	Electro- static Granular Bed Filter	Ceramic Bag Filter	Electro- static Precipitator
Dummy Driver	HOTGCY	HOTCGB	HOTGGB	HOTACB	HOTCEP
Interface	USRGCY	USRCGB	USRGGB	USRACB	USRCEP
Auxiliary Power	QBAUXP	QFAUXP	QAAUXP	QDAUXP	QEAUXP
Error	QBERRW	QFERRW	QAERRW	QDERRW	QEERRW
Filter Model	QBFILT	QFFILT QFFLO1 QFFLO2 QFFLO3 QFFLO4 QFFLO5 QFFLO6	QAFILT	QDFILT	QEFILT
Read Input Stream	QBFLIN	QFFLIN	QAFLIN	QDFLIN	QEFLIN
Read REAL Array	QBRDRL	QFRDRL	QARDRL	QDRDRL	QERDRL
Write Output	QBWRIT	QFWRIT	QAWRIT	QDWRIT	QEWRT

Global Procedures

Get the pointers	QQPNTR
Calculate electric power	QQELEC
Write errors	QQERRW
Transfer output data	QQFLOT

Only COMMON blocks are used for internal variable communication so that the ASPEN and model variables can be kept separately and not mixed in calling lists. During code development and later during the maintenance period, the names and quantities of variables often change, and having a separate list enables these changes to be accomplished much faster and with greater assurance that ASPEN variables are not altered inadvertently.

Practically none of the gas cleanup models obtained from the vendors had a consistent set of units. But, since ASPEN uses only SI units internally, our codes are designed to conform to that standard. During the initialization pass, the QARDRL subroutine reads the ASPEN user REAL array and performs the necessary unit conversions.

The six auxiliary subroutines that are needed by each model are listed below. When any of these routines becomes too large, it is split and the subprocedure is given a similar name using the same first two letters and a trailing number. All models contain at least these six subroutines. The second letter (i.e., A, B, D, E or F) identifies the specific model.

- QARDRL - Reads the REAL array and converts data to SI units for further processing.
- QAERRW - Checks the REAL array and the inlet material stream for errors.
- QAAUXP - Determines the auxiliary power requirement.
- QAFLIN - Fetches needed variables from the inlet material stream, SIN1, to determine temperature, pressure, viscosity, volumetric flow rate, superficial gas velocity, and gas density.
- QAFILT - Filters the solid particles from the inlet material stream in the manner determined by the mathematical model for the device. All substreams are processed.
- QAWRIT - Writes the History file for the model.

Each physical model may have two user COMMON blocks which contain the variables needed by other subroutines. The COMMONs are QA003 and QA004. Only ASPEN variables appear as subroutine arguments.

The two general subroutines that are called by all models are

- QQPNTR - Determines the pointers needed for processing the inlet material stream.

QQFLOT - Returns the stream data to ASPEN.

A general subroutine that is called by the models using electrostatics is

QQELEC - Calculates electrostatic properties.

The universal COMMONs are:

```
COMMON /QQ001/ IDXFLO(13) , IDXP3D(13) , IDXCIP , IDXEND ,
1          IDXMIX      , IDXNCP
C  END COMMON /QQ001/
C
REAL*8 MFRCIN , MFRCOU
COMMON /QQ002/ DP(30)      , DELP      , DELT      ,
1          GRADE(30) , EFFNET      , FRCVAP      ,
2          MFRCIN(30) , MFRCOU(30) , NPSD      ,
3          RHO      , SUMIN      , SUMOUT
C  END COMMON /QQ002/
C
COMMON /QQ003/ DELTA , DPIPE , DWE , EC , PJL ,
+          SJL , SR , VCORN , VOLTO , WCL
C  END COMMON /QQ003/
C
COMMON /QQ004/ IERR , CORRCT
C  END COMMON /QQ004/
C
```

PERFORMANCE MODEL

Moving Granular Bed Filter

Model Name: Moving Granular Bed Filter (USRCGB)

Function

This procedure calculates the particle capture efficiency of a granular bed filter in high-temperature, high-pressure (HTHP) applications. The model is based on the steady-state equations developed by Combustion Power Company (CPC) (see Goren, 1979).

The model is designed to receive one inlet material stream:

1. The product of combustion (POC) stream, SIN1
 - a. Substream MIXED
 - b. Substream CIPSD
 - c. Substream NCPSD

The substreams are not required to be in any fixed order.

The model produces two outlet material streams:

1. The POC stream, SOUT1
2. The ASH stream, SOUT2

The model will handle any number of conventional and nonconventional components and up to thirty (30) particle sizes. The number of particle sizes and chemical analyses are listed in the user ASPEN input file INT.

Principles

Granular bed filters have been used in several industrial installations: for the removal of particulate matter from the effluents from waste boilers in the forest products industry; in the cleaning of gases from clinker coolers in the cement industry; and in the cleaning of lime kiln effluents. Experimental studies have also been conducted for a wide variety of potential applications,

including the removal of radioactive particles from the air in ventilation systems, the cleaning of waste gases from open hearth furnaces, and the simultaneous desulfurization and particulate removal from the gas from coal-fired boilers.

Granular bed filters consist of closely packed granules of river stone, alumina, or other materials that are capable of withstanding the environment of the flue gases to be cleaned. The sizes of the granules vary with the application, the usual sizes ranging from around 1.5 to 8 mm in diameter.

The physical arrangements of granular bed filters include a wide range of designs that permit the gas to flow through the filter medium and provide a means for removing the collected dust. Two basic methods of cleaning the filter medium are used. Fixed bed filters generally employ back flushing or mechanical agitation to dislodge the collected particulate matter and permit it to fall into a hopper for removal.

In moving bed filters, as that illustrated in the accompanying figure, the filter medium and the collected dust are removed from the filter and the dust separated from the medium externally. The filter medium is cleaned in a disengagement chamber, where the dust and the granules are separated. The granules are reintroduced to the moving bed, and the dust falls into an ash hopper.

The performance model of the moving granular bed filter takes into account the following particle collection mechanisms:

- . Inertial impaction
- . Direct interception
- . Gravitational sedimentation
- . Random diffusion

The efficiency of particle collection by granular bed filters is influenced by the temperature and pressure of gases as they alter the collection mechanisms. Inertial impaction depends upon the particle separation from a gas stream which is diverted around a collecting body. The efficiency of collection by impaction is a function of the particle mass, velocity, the resistance of the gas to particle motion, and the frontal diameter of the collecting body. The resistance of the gas to particle motion increases with increasing temperature for relatively large particles due to the increase in gas viscosity.

Sketch of CPC Moving Granular Bed Filter

Increases in pressure would have a similar influence on viscosity; hence, a reduction in collection efficiency of large particles would be expected with increase in pressure. Collection of small particles, on the other hand, would be enhanced by increasing temperature, as a result of the increased Brownian motion.

Steady-state equations for a one-dimensional moving granular bed have been developed by CPC (Goren, 1979). The method takes into account the dominant parameters of particle collection as identified above. These equations contain three terms that relate collection efficiency and pressure drop to operating conditions such as gas velocity, granule media characteristics, particle size, and local loading of suspended and captured dust.

Mathematical Model

The mathematical model used is that developed by Goren (1979) for a one-dimensional moving granular bed filter. The model requires prior knowledge of the device configuration.

The model has been developed for (1) the cocurrent configuration, in which the collector granules in the moving bed and the particle-laden gas flow in the same direction, and (2) the countercurrent configuration, in which the granule media and the gas stream flow in opposite directions. The equations are based on mass balance on the sum of suspended and captured particles,

$$\frac{d(Un + U_G N_G)}{dz} = 0, \quad (1)$$

mass balance on suspended particles alone,

$$\frac{d(Un)}{dz} = -J N_G + R N_G, \quad (2)$$

and momentum balance on the gas,

$$\frac{dp}{dz} = -F N_G. \quad (3)$$

The variables are summarized as

z = filter depth, m

U = superficial gas velocity, m/s

- $n(z)$ = local concentration of suspended particles at depth, $1/m^3$
 U_G = superficial grain velocity, m/s
 N_G = number of grains per unit volume of bed, $1/m^3$
 $N(z)$ = local number of dust particles adhering to a single grain at depth z
 $p(z)$ = gas pressure, N/m^2
 J = rate of deposit onto a single grain including deposition onto its adhering dust particles, fraction
 R = rate of reentrainment, fraction
 F = drag force on a single grain including its adhering dust particles, N .

For cocurrent flow of gas and granular media, the + sign is used, and for countercurrent flow, the - sign is used in Equation (1). Expressions for J , R and F are complex functions of the operating conditions and geometrical variables. The remaining terms are interpreted as follows:

- Term $J N_G$: Rate of particle deposition per unit volume of bed
 Term $R N_G$: Rate of particle reentrainment per unit volume of bed
 Term $F N_G$: Drag force per unit volume of bed

The particle capture occurs on both the grain surface and on adhering dust particles. This effect is written as,

$$J = J_G + N J_1, \quad (4)$$

where J_G is the rate of particle capture due to clean single grains and J_1 is the rate of particle capture due to all adhering particles. The present model expresses J_G and J_1 in terms of single grain capture efficiency, η_G , and single dust particle capture efficiency, η_1 , defined by the following equations:

$$J_G = \pi a_G^2 U n \eta_G \quad (5)$$

$$J_1 = (4\pi a_p^2) (3A_G U a_p / 2a_G) n \eta_1, \quad (6)$$

where a_G = collector granule radius, m
 a_p = particle radius, m
 n = number concentration of dust particles, $1/m^3$

η_G and η_1 are empirical correction factors which account for the realistic aerodynamics of the particles, including bounce-off and influence of the neighboring particles.

The assumption made here is that the gas flow rate must be much greater than the granule flow rate in the moving bed, i.e.,

$$U \gg U_G .$$

Wigton (1978) and Goren (1979) introduced an expression for the collection efficiency due to a clean single grain, η_G . The model is an addition of four terms representing the collection by impaction, interception, diffusion, and sedimentation mechanisms,

$$\eta_G = f \left(\epsilon, K_{II}, K_I, K_D, K_{GS} \right) \quad (7)$$

This equation corresponds to the experimentally determined values of η_G for clean granular media for a wide range of gas velocities and particle diameters.

The terms are described as:

ϵ = void fraction of the granular bed

$$K_{II} \text{ , Inertial Impaction Parameter } = \frac{C_S \rho_p d_p^2 U_G}{9 \mu_G d_G}$$

$$K_I \text{ , Interception Parameter } = \frac{d_p}{d_G}$$

$$K_D \text{ , Diffusion Parameter } = \frac{C_S K_T}{3\pi \mu_G d_p U_G}$$

$$K_S \text{ , Gravitational Sedimentation } = \frac{C_S \rho_p d_p^2 g}{18 \mu_G U_G} ,$$

where C_S = Cunningham slip correction factor, nondimensional
 d_p = particle diameter, m
 ρ_p = particle density, kg/m^3

d_G	=	granule diameter, m
K	=	Boltzmann's constant, J/°K
T	=	absolute temperature, °K
μ	=	gas viscosity at temperature and pressure, N-s/m ²
g	=	acceleration due to gravity, 9.8 m/s ²

These parameters are summarized and discussed in detail in Goren (1979).

Equation (6) defines the particle capture efficiency due to a single adhering particle, η , in a manner analogous to the definition of η_G in Equation (5). However, the cross section available for capture $4\pi a_p^2$ is based on the dust particle size, and the local gas velocity, $3A_G U a_p / 2a_G$, is evaluated at a distance a_p away from the no-slip grain surface. The factor A_G is a hydrodynamic factor relating the velocity gradient near the granule surface to the void fraction of the bed. For low-speed flows, A_G can be computed from simple hydrodynamic models of granular media. For example, Happel's model predicts $A_G = 38$ for a bed of spheres with solid fraction $(1-\epsilon) = 0.6$. For Reynolds numbers encountered in typical granular bed operations, fluid inertia plays a significant role in determining A_G . In the absence of detailed theoretical and experimental analyses, Goren (1979) recommends that A_G be scaled with Reynolds number:

$$A_G = 38 (1 + 0.0194 \text{ Re}) \quad , \quad (8)$$

where Re is the Reynolds number based on granule diameter $= \frac{d_G \rho u}{\mu}$.

The drag force, F , in Equation (3) can be approximated in a similar way. The drag force acts on both granules and dust particles, thus we may write

$$F = F_G + F_1 \quad (9)$$

and evaluate F_G and F_1 as follows:

$$F_G = 6\pi\mu a_G U B_G \quad (10)$$

$$F_1 = (6\pi\mu a_p) \left(\frac{3 A_G U a_p}{2 a_G} \right) B_1 \quad , \quad (11)$$

where $6\pi\mu a_p$ is the drag force that would be exerted on a single isolated grain

according to Stokes' law, B_G is a hydrodynamic factor that accounts for influence of neighboring particles, and B_1 is a correction factor known from theory to be 1.7 for creeping flow past a sphere on a flat wall. For low speed flow, B_G can be computed from simple hydrodynamic models. For example, Happel's model gives the value of 85 for creeping flow past packed granules as Re approaches zero. To account for fluid inertia, Goren (1979) scales B_G to the Ergun equation, viz,

$$B_G = 85 (1 + 0.0194 Re) \quad (12)$$

To compute the mathematical model, the boundary conditions are formulated as follows:

for cocurrent flow

$$n(0) = n_{in} \quad \text{and} \quad N(0) = N_{in} \quad (13)$$

for countercurrent flow

$$n(0) = n_{in} \quad \text{and} \quad N(L) = N_{in} \quad (14)$$

where L is the total depth of the bed.

The above set of equations can be expressed more compactly in dimensionless terms.

$$d(n^* + N^*)/dz^* = 0$$

$$dn^*/dz^* = -n^*(1 + \zeta N^*) + \xi N^*$$

$$d\bar{p}^*/dz^* = -(1 + \zeta \beta N^*)$$

$$n^*(0) = 1 \quad (15)$$

$$N^*(0) = N_{in}^* \quad \text{for cocurrent flow}$$

or

$$N^*(L^*) = N_{in}^* \quad \text{for countercurrent flow.}$$

The dimensionless terms appearing in these equations are defined as follows:

$$\begin{aligned}
 n^* &= n/n_{in} \quad , \quad P = n_{out}/n_{in} \\
 N^* &= U_G N_G N / U n_{in} \quad , \quad N_{in}^* = U_G N_G n_{in} / U n_{in} \\
 z^* &= z \pi a_G^2 \eta_G N_G \quad , \quad L^* = L \pi a_G^2 \eta_G N_G \\
 p^* &= p a_G \eta_G / 6 \mu U B_G \quad , \quad \Delta p^* = \Delta p a_G \eta_G / 6 \mu U B_G \\
 \zeta &= J_1 U n_{in} / J_G U N_G = 6 A_G a_p^3 \eta_1 U n_{in} / a_G^3 \eta_G U N_G \\
 \xi &= k / \pi a_G^2 N_G U \eta_G \quad \beta = F_1 J_G / F_G J_1 = B_1 \eta_G a_G / 4 \eta_1 B_G a_p
 \end{aligned} \tag{16}$$

By solving the above set of equations we may express the penetration, P , and pressure drop, Δp^* , as functions of L_x^* , ζ , ξ , N_{in}^* and β . These are written as

$$\begin{aligned}
 P &= f_1(L_x^*, \zeta, \xi, N_{in}^*) \quad \text{and} \\
 \Delta p^* &= L_x^* + \beta f_2(L_x^*, \zeta, \xi, N_{in}^*) \quad .
 \end{aligned}$$

Explicit formulas relating these groups are given below.

For countercurrent flow define

$$\begin{aligned}
 A &= (1 - \zeta P + \zeta N_{in}^* - \xi) / 2\zeta \quad \text{and} \\
 B &= \xi(P - N_{in}^*) / \zeta \quad .
 \end{aligned}$$

Then, the solution to Equation (15) has one of the following three forms:

If $C^2 = A^2 - B > 0$, then

$$\begin{aligned}
 L_x^* &= \frac{1}{2C\zeta} \left\{ \ln \left(\frac{1+A-C}{P+A-C} \right) - \ln \left(\frac{1+A+C}{P+A+C} \right) \right\} \\
 (\Delta p^* - L_x^*) / \beta &= \zeta [N_{in}^* - A - P] L_x^* + \frac{1}{2} \ln \left(\frac{1+A-C}{P+A-C} \right) + \frac{1}{2} \ln \left(\frac{1+A+C}{P+A+C} \right)
 \end{aligned}$$

If $A^2 - B = 0$, then

$$\begin{aligned}
 L_x^* &= \frac{1}{\zeta} \left(\frac{1}{P+A} - \frac{1}{1+A} \right) \\
 (\Delta p^* - L_x^*) / \beta &= \zeta [N_{in}^* - A - P] L_x^* + \ln \left(\frac{1+A}{P+A} \right)
 \end{aligned}$$

If $-D^2 = A^2 - B < 0$, then

$$L_x^* = -\frac{1}{D\zeta} \arctan \left(\frac{D(1-P)}{(1+A)(P+A)+D^2} \right)$$

$$(\Delta p^* - L_x^*)/\beta = \zeta [N_{in}^* - A - P] L_x^* + \frac{1}{2} \ln \left(\frac{(1+A)^2 + D^2}{(P+A)^2 + D^2} \right).$$

For cocurrent flow define

$$A = (1 + \zeta + \zeta N_{in}^* + \xi)/2\zeta \quad \text{and}$$

$$B = \xi(1 + N_{in}^*)/\zeta.$$

Then, the solution to Equation (15) has one of the following three forms:

If $C^2 = A^2 - B > 0$, then

$$L_x^* = \frac{1}{2C\zeta} \left\{ \ln \left(\frac{1-A+C}{P-A+C} \right) - \ln \left(\frac{1-A-C}{P-A-C} \right) \right\}$$

$$(\Delta p^* - L_x^*)/\beta = \zeta(1 + N_{in}^* - A)L_x^* + \frac{1}{2} \ln \left(\frac{1-A+C}{P-A+C} \right) + \frac{1}{2} \ln \left(\frac{1-A-C}{P-A-C} \right).$$

If $A^2 - B = 0$, then

$$L_x^* = \frac{1}{\zeta} \frac{1}{P-A} - \frac{1}{1-A}$$

$$(\Delta p^* - L_x^*)/\beta = \zeta(1 + N_{in}^* - A)L_x^* + \ln \left(\frac{1-A}{P-A} \right).$$

If $-D^2 = A^2 - B < 0$, then

$$L_x^* = \frac{1}{\zeta D} \arctan \left(\frac{D(P-1)}{(1-A)(P-A)+D^2} \right)$$

$$(\Delta p^* - L_x^*)/\beta = \zeta(1 + N_{in}^* - A)L_x^* + \frac{1}{2} \ln \left(\frac{(1-A)^2 + D^2}{(P-A)^2 + D^2} \right).$$

The above set of equations is very complex and the problem of obtaining a set of solutions is compounded by the several computation paths that occur during the calculation process. The first step in formulating an algorithm

for solving the problem is to categorize the equations and their terms as shown in Table 1. In the table, an invariant equation is defined as one that produces a constant value once the particle size is chosen whereas a variant is an iterative loop equation that produces changing values until a final solution is obtained.

The iteration control parameter is the penetration parameter, P. Researchers at CPC have found that a bisection technique is sufficient to obtain a set of solutions. A final solution is reached for each particle size when L_x^* converges to L^* . At that point, it is a trivial calculation to obtain the pressure drop and collection efficiency by using the following equations.

$$\Delta p_i = 6\mu U B_G \Delta p_i^* / a_G n_G$$

$$\eta_i = 1 - P_i .$$

These equations provide solutions for a given particle size (i) and are sufficient for the collection efficiency. At present, however, there is no basic physical model available to obtain a bed pressure drop for multiple particle sizes except by averaging the particulate pressure drops. The researchers at CPC indicate that the technique is adequate for particle sizes less than 10 μm but could be inaccurate when used to evaluate device performance for HTHP streams with larger particle sizes.

Physical Properties Required

The CPC moving granular bed filter requires gas density, solid density, and gas viscosity.

User-Supplied Information

The device information is supplied to the user model via the ASPEN secondary keywords PARAM, INT, and REAL. The elements of each of these are defined in the following sections.

Table 1
Moving Granular Bed Model Equations and Parameters

<u>User-Defined Constants</u>		<u>ASPEN Inputs</u>	
a_G	N_G	P	U
L	n_{in}	T	μ
U_G	N_G		
<u>User Variable</u>			
a_p			
<u>Iterative Invariants</u>		<u>Iterative Variants</u>	
N_G		P iteration control parameters	
B_G		$A(P)$	
L^*		$B(P)$	
A_G		$C(P)$	
n_1		$D(P)$	
B_1		L^*	
B_1		$L_x^* (P, A, C \text{ or } D)$	
β		$\Delta p^* (P, A, C \text{ or } D, L_x^*)$	
ζ			
ξ			
N_{in}^*			

Input Required

PARAM NINT, NREAL, NIW, NW

NINT - Length of INT array
NREAL - Length of REAL array
NIW - Length of IW array
NW - Length of W array

INT(i), i=1, NINT

INT(1) - NPSD, Number of particle size intervals.
INT(2) - NCC, Number of chemical analyses for conventional components.
INT(3) - NNCC, Number of chemical analyses for nonconventional components.
INT(4) - Switch for bed direction and state (one value per simulation).
INT(4) = 0, dirty bed, countercurrent flow
INT(4) = 1, dirty bed, cocurrent flow
INT(4) = 2, clean bed, countercurrent flow
INT(4) = 3, clean bed, cocurrent flow
INT(5) - Debug print switch.
INT(5) = 0, no debug output
INT(5) = 1, debug output

REAL(i), i=1, NREAL

REAL(1)	Particle size distribution
.	" " "
.	" " "
.	" " "
REAL(NPSD+1)	Last particle size
REAL(NPSD+2)	Diameter of collector granules (mm)
REAL(NPSD+3)	Bed void fraction (nondimensional)
REAL(NPSD+4)	Collector velocity (mm/min)
REAL(NPSD+5)	Collector dust loading (fraction)

REAL(NPSD+6) Density of collector (g/cm^3)
REAL(NPSD+7) Sphericity of collector granules (0.0-1.0)
REAL(NPSD+8) Bed depth (cm)
REAL(NPSD+9) Reentrainment frequency (dimensionless)
REAL(NPSD+10) Diameter of inlet (cm)
REAL(NOSD+11) Diameter of granular bed (cm)
REAL(NPSD+12) Fraction of vapor entrained in solid underflow
REAL(NREAL) Temperature loss expected (degrees F)

Error Messages

Substream is not MIXED, CIPSD or NCPSP. Block is bypassed.

Not enough particle sizes are specified in the REAL array. At least two are required. Block is bypassed.

Gas temperature is zero. Block is bypassed.

Gas pressure is zero. Block is bypassed.

The particle size delimiters are not in ascending order or a mean particle size is less than or equal to zero. Block is bypassed.

Diameter of collector is negative or zero. Block is bypassed.

Void fraction is greater than 1.0. Block is bypassed.

Collector velocity is negative or zero. Block is bypassed.

Density of collector is negative or zero. Block is bypassed.

Sphericity is either negative or greater than 1.0. Block is bypassed.

Bed depth is negative or zero. Block is bypassed.

Diameter of inlet is negative or zero. Block is bypassed.

Diameter of granular bed is negative or zero. Block is bypassed.

Inlet diameter is greater than bed diameter. Block is bypassed.

Warnings

Face velocity is too high.

Granular bed is fluidized.

Lower volumetric flow rate or increase bed diameter.

Results

Geometry for the moving granular bed filter from the user REAL array

Diameter of collector (mm)..... : 2.0000D 00
 Collector void fraction : 4.5000D-01
 Collector velocity (mm/min)..... : 1.9400D 00
 Collector dust loading : 0.0000D-01
 Density of collector (g/cm³) : 6.3500D 00
 Sphericity (0.0 - 1.0) : 9.0000D-01
 Bed depth (cm) : 3.0000D 01
 Reentrainment frequency (dimensionless) : 9.0000D-01
 Diameter of inlet (cm) : 3.6000D 01
 Diameter of granular bed (cm) : 1.1500D 02
 Fraction of vapor entrained in solid underflow : 1.0000D-06
 Temperature loss expected (degrees K) : 0.0000D-01
 Gas operating temperature (degrees K) : 1.0610D 03
 Gas operating pressure (Pa) : 5.1782D 05

System Configuration : Countercurrent flow
 Dirty granular bed

Diam. Range (μ m)	Mean Diameter (μ m)	Mass Fract. In (%)	Mass Fract. Out (%)	Cleanup (%)
0.0 - 0.6	0.30	0.67	4.36	92.62
0.6 - 0.8	0.70	3.39	9.91	96.69
0.8 - 1.0	0.90	4.76	11.35	97.30
1.0 - 1.3	1.15	8.05	11.42	98.39
1.3 - 1.6	1.45	11.21	10.99	98.89
1.6 - 2.0	1.80	10.28	10.60	98.83
2.0 - 2.5	2.25	10.61	9.82	98.95
2.5 - 3.2	2.85	10.01	8.58	99.03
3.2 - 4.0	3.60	8.51	7.05	99.06
4.0 - 5.0	4.50	9.57	6.81	99.19
5.0 - 6.4	5.70	8.16	3.85	99.46
6.4 - 8.0	7.20	6.75	2.39	99.60
8.0 - 10.1	9.05	4.21	1.24	99.67
10.1 - 12.7	11.40	2.38	0.47	99.77
12.7 - 16.0	14.35	1.08	0.11	99.89
16.0 - 20.2	18.10	0.29	0.01	99.97
20.2 - 25.4	22.80	0.05	0.00	100.00
25.4 - 32.0	28.70	0.00	0.00	100.00
32.0 - 40.0	36.00	0.00	0.00	100.00

Net efficiency of device (by mass)..... 98.9

Total particle mass flow rate in (kg/s) 6.8474D-03
 Total particle mass flow rate out(kg/s). 7.7672D-05
 Total change in enthalpy (J/kmole) -6.2133D 05
 Viscosity of the gas (centipoise) 4.3542D-02
 Superficial gas velocity (m/s) 5.0004D-01

Fluidizing velocity (m/s) 6.2609D-01
 Gas volumetric flow rate (m³/s) 5.1938D-01
 Pneumatic power required (watts) 4.9239D 02
 Fan power required (watts) 2.4363D 03
 Total auxiliary power required (watts) . 2.9287D 03
 Pressure drop across the bed (Pa) 1.8763D 03
 Pressure drop across the bed (in. H₂O) . 7.5326D 00

Pointers to the start of the substreams

Start of the MIXED substream : IDXMIX = 1
 Start of the CIPSD substream : IDXCIP = 21
 Start of the NCPSD substream : IDXNCP = 60
 End of input stream SIN1 : IDXEND = 142

Pointers to the substreams in their order of occurrence in the streams

substrm	entry	flow-F	particles
NSUBS	IDXSUB	IDXFLO	IDXPSD
1	1	12	0
2	21	32	41
3	60	63	124

Number of conventional components... : NCC = 11
 Number of nonconventional components : NNCC = 3
 Number of solid particle sizes..... : INT(1) = 19
 Number of CIPSD analysis items..... : INT(2) = 0
 Number of NCPSD analysis items..... : INT(3) = 52
 Switch for BED direction and state.. : INT(4) = 0
 Debug print switch, 0-no debug print.: INT(5) = 0

Moving granular bed filter stream data

Index	SIN1	SOUT1	SOUT2
No	POC Stream In	POC Stream Out	ASH Stream
1	2.5850D-03	2.5850D-03	2.5850D-09
2	1.2390D-03	1.2390D-03	1.2390D-09
3	5.6410D-06	5.6410D-06	5.6410D-12
4	0.0000D-01	0.0000D-01	0.0000D-01
5	2.3240D-02	2.3240D-02	2.3240D-08
6	3.6620D-03	3.6620D-03	3.6620D-09
7	0.0000D-01	0.0000D-01	0.0000D-01
8	0.0000D-01	0.0000D-01	0.0000D-01
9	0.0000D-01	0.0000D-01	0.0000D-01
10	0.0000D-01	0.0000D-01	0.0000D-01
11	0.0000D-01	0.0000D-01	0.0000D-01
12	3.0690D-02	3.0690D-02	3.0690D-08

13	1.0610D 03	1.0610D 03	1.0610D 03
14	5.1782D 05	5.1594D 05	5.1594D 05
15	-6.1140D 05	0.0000D-01	0.0000D-01
16	0.0000D-01	0.0000D-01	0.0000D-01
17	0.0000D-01	0.0000D-01	0.0000D-01
18	1.0970D 03	0.0000D-01	0.0000D-01
19	1.7390D 00	1.7390D 00	1.7390D 00
20	2.9430D 01	2.9430D 01	2.9430D 01
21	0.0000D-01	0.0000D-01	0.0000D-01
22	0.0000D-01	0.0000D-01	0.0000D-01
23	0.0000D-01	0.0000D-01	0.0000D-01
24	0.0000D-01	0.0000D-01	0.0000D-01
25	0.0000D-01	0.0000D-01	0.0000D-01
26	0.0000D-01	0.0000D-01	0.0000D-01
27	0.0000D-01	0.0000D-01	0.0000D-01
28	0.0000D-01	0.0000D-01	0.0000D-01
29	3.2140D-05	2.4760D-07	3.1893D-05
30	4.4724D-05	3.4455D-07	4.4380D-05
31	1.7660D-05	1.3605D-07	1.7524D-05
32	9.4524D-05	7.2821D-07	9.3796D-05
33	1.0610D 03	1.0610D 03	1.0610D 03
34	5.1728D 05	5.1540D 05	5.1540D 05
35	-1.1520D 07	0.0000D-01	0.0000D-01
36	0.0000D-01	0.0000D-01	0.0000D-01
37	0.0000D-01	0.0000D-01	0.0000D-01
38	-2.1980D 03	0.0000D-01	0.0000D-01
39	3.2530D 03	3.2530D 03	3.2530D 03
40	6.3570D 01	6.3570D 01	6.3570D 01
41	6.7068D-03	5.1983D-02	6.3553D-03
42	3.3933D-02	1.0644D-01	3.3370D-02
43	4.7620D-02	1.2088D-01	4.7051D-02
44	8.0486D-02	1.1232D-01	8.0239D-02
45	1.1215D-01	1.1182D-01	1.1215D-01
46	1.0279D-01	1.0676D-01	1.0276D-01
47	1.0612D-01	9.7467D-02	1.0619D-01
48	1.0012D-01	8.3677D-02	1.0025D-01
49	8.5065D-02	6.7409D-02	8.5202D-02
50	9.5677D-02	7.2941D-02	9.5853D-02
51	8.1553D-02	3.4411D-02	8.1919D-02
52	6.7584D-02	2.0192D-02	6.7952D-02
53	4.2138D-02	9.6997D-03	4.2390D-02
54	2.3839D-02	3.3185D-03	2.3998D-02
55	1.0781D-02	6.3728D-04	1.0860D-02
56	2.8750D-03	3.5060D-05	2.8970D-03
57	5.2882D-04	2.2981D-07	5.3292D-04
58	3.6115D-05	2.2822D-09	3.6395D-05
59	6.2875D-07	3.9734D-11	6.3363D-07
60	0.0000D-01	0.0000D-01	0.0000D-01
61	7.8189D-04	2.8502D-05	7.5261D-04
62	5.6713D-05	2.0673D-06	5.4589D-05
63	8.3848D-04	3.0565D-05	8.0708D-04

64	1.0610D 03	1.0610D 03	1.0610D 03
65	5.1782D 05	5.1594D 05	5.1594D 05
66	1.3930D 05	0.0000D-01	0.0000D-01
67	0.0000D-01	0.0000D-01	0.0000D-01
68	0.0000D-01	0.0000D-01	0.0000D-01
69	1.0000D 70	0.0000D-01	0.0000D-01
70	1.9770D 03	1.9770D 03	1.9770D 03
71	1.0000D 00	1.0000D 00	1.0000D 00
72	5.3000D 00	5.3000D 00	5.3000D 00
73	5.4000D 01	5.4000D 01	5.4000D 01
74	3.8080D 01	3.8080D 01	3.8080D 01
75	7.9200D 00	7.9200D 00	7.9200D 00
76	7.9200D 00	7.9200D 00	7.9200D 00
77	7.8350D 01	7.8350D 01	7.8350D 01
78	6.0200D 00	6.0200D 00	6.0200D 00
79	1.4800D 00	1.4800D 00	1.4800D 00
80	0.0000D-01	0.0000D-01	0.0000D-01
81	3.0600D 00	3.0600D 00	3.0600D 00
82	3.1700D 00	3.1700D 00	3.1700D 00
83	2.1000D 00	2.1000D 00	2.1000D 00
84	4.0000D-02	4.0000D-02	4.0000D-02
85	9.2000D-01	9.2000D-01	9.2000D-01
86	0.0000D-01	0.0000D-01	0.0000D-01
87	1.0000D 00	1.0000D 00	1.0000D 00
88	1.0000D 00	1.0000D 00	1.0000D 00
89	9.8000D 01	9.8000D 01	9.8000D 01
90	9.8000D 01	9.8000D 01	9.8000D 01
91	2.0000D 00	2.0000D 00	2.0000D 00
92	0.0000D-01	0.0000D-01	0.0000D-01
93	0.0000D-01	0.0000D-01	0.0000D-01
94	0.0000D-01	0.0000D-01	0.0000D-01
95	0.0000D-01	0.0000D-01	0.0000D-01
96	0.0000D-01	0.0000D-01	0.0000D-01
97	3.3000D-01	3.3000D-01	3.3000D-01
98	4.0000D-02	4.0000D-02	4.0000D-02
99	4.2000D-01	4.2000D-01	4.2000D-01
100	1.0000D 02	1.0000D 02	1.0000D 02
101	0.0000D-01	0.0000D-01	0.0000D-01
102	0.0000D-01	0.0000D-01	0.0000D-01
103	0.0000D-01	0.0000D-01	0.0000D-01
104	0.0000D-01	0.0000D-01	0.0000D-01
105	0.0000D-01	0.0000D-01	0.0000D-01
106	0.0000D-01	0.0000D-01	0.0000D-01
107	0.0000D-01	0.0000D-01	0.0000D-01
108	0.0000D-01	0.0000D-01	0.0000D-01
109	0.0000D-01	0.0000D-01	0.0000D-01
110	0.0000D-01	0.0000D-01	0.0000D-01
111	9.8000D 01	9.8000D 01	9.8000D 01
112	1.0000D 00	1.0000D 00	1.0000D 00
113	1.0000D 00	1.0000D 00	1.0000D 00
114	1.0000D 00	1.0000D 00	1.0000D 00

115	9.5000D 01	9.5000D 01	9.5000D 01
116	1.5000D 00	1.5000D 00	1.5000D 00
117	5.0000D-01	5.0000D-01	5.0000D-01
118	0.0000D-01	0.0000D-01	0.0000D-01
119	1.5000D 00	1.5000D 00	1.5000D 00
120	5.0000D-01	5.0000D-01	5.0000D-01
121	4.0000D-02	4.0000D-02	4.0000D-02
122	1.0000D-02	1.0000D-02	1.0000D-02
123	5.0000D-02	5.0000D-02	5.0000D-02
124	6.7068D-03	3.2184D-02	5.7489D-03
125	3.3933D-02	9.0555D-02	3.1824D-02
126	4.7620D-02	1.0539D-01	4.5481D-02
127	8.0486D-02	1.2011D-01	7.9069D-02
128	1.1215D-01	1.0980D-01	1.1236D-01
129	1.0279D-01	1.0762D-01	1.0271D-01
130	1.0612D-01	1.0181D-01	1.0639D-01
131	1.0012D-01	9.1221D-02	1.0056D-01
132	8.5065D-02	7.7110D-02	8.5454D-02
133	9.5677D-02	6.2572D-02	9.7030D-02
134	8.1553D-02	4.5808D-02	8.2991D-02
135	6.6584D-02	3.0162D-02	6.8032D-02
136	4.2138D-02	1.6799D-02	4.3141D-02
137	2.3839D-02	7.0267D-03	2.4500D-02
138	1.0781D-02	1.7105D-03	1.1136D-02
139	2.8750D-03	1.2272D-04	2.9822D-03
140	5.2882D-04	1.8610D-06	5.4932D-04
141	3.6115D-05	3.3169D-09	3.7520D-05
142	6.2875D-07	8.3982D-12	6.5321D-07

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PERFORMANCE MODEL

Ceramic Bag Filter

Model Name: Ceramic Bag Filter (USRACB)

Function

This procedure calculates the particle capture efficiency of a ceramic bag filter in high-temperature, high-pressure (HTHP) applications. The model is based on the Acurex design of Saffil alumina filter bag (Shackleton, 1979).

The model is designed to receive one inlet material stream:

1. The product of combustion (POC) stream, SIN1
 - a. Substream MIXED
 - b. Substream CIPSD
 - c. Substream NCPSD

The substreams are not required to be in any fixed order.

The model produces two outlet material streams:

1. The POC stream, SOUT1
2. The ASH stream, SOUT2

The model will handle any number of conventional and nonconventional components and up to thirty (30) particle sizes. The number of particle sizes and chemical analyses are listed in the user ASPEN input file INT.

Principles

Fabric filters have been used for many years to remove dusts from industrial process gases, notably from cement kilns and metallurgical operations. They have also been installed on a number of small power boilers, but it is only within the past few years that they have been considered for removing fly ash from large electric utility boilers burning coal.

For HTHP applications, porous metal or woven ceramic material is used to withstand the severe physical environment.

The ceramic bag filter, such as that illustrated in the accompanying figure, is usually made up of cylindrical tubes about 20 cm in diameter by 3 to 6 m long. A number of these tubes are suspended vertically in a pressure vessel. The bags are cleaned either by mechanical shaking or by a reverse flow of air often referred to as back flush.

Ceramic bag filters collect particles by the mechanisms of impaction, interception, and diffusion. However, after a new ceramic bag collector has been in operation for several minutes, collection mechanisms are different from those of classical filter theory. The reason for this change is that, after an initial phase of collection, the cake of filtered material that builds up on the bag surface and the interstices of the bag provides most of the filtration until it is removed in the part of the filtering cycle in which the filter is cleaned and regenerated.

As the cake grows thicker with time, the pressure drop across the filter increases. When a preset pressure drop across a compartment containing ceramic bags is reached, or when a preset time has expired, the compartment is isolated from the gas flow for bag cleaning. After the dust is removed, the isolated compartment is again exposed to the gas flow. A collection process now occurs which is similar to that of initial cleaning by an unused bag. But now the interstices of the filter material are loaded with particulate matter that is not dislodged by cleaning. After a number of cleanings, a bag builds up an interstitial accumulation to a constant level, at which point the bag is considered to be broken in. Because of this residual dust loading, the filter cake is more quickly reestablished when filtration commences. The pressure-drop-versus-time relationship for a freshly cleaned bag is nonlinear until the filter cake is reestablished; this often takes several minutes.

Factors that can influence ceramic bag filter performance with fly ash include the fabric structure, air-to-cloth ratio, maximum pressure drop before cleaning, method of cleaning, cleaning frequency, intensity of cleaning, and flue gas temperature and humidity. These factors can be broken down broadly into two categories: factors that are basic to the design of a bag filter system for optimum performance and factors that relate to the behavior of the

Sketch of Aourex Ceramic Bag and Pressure Vessel

system as installed. During the design of a bag house, questions of bag material, method of cleaning, air-to-cloth ratio, operating temperature, and humidity need to be considered. Once the bag house is operating, cleaning rate, duration and intensity of cleaning, and other variables related to the operation of the collector are adjusted to keep pressure drop before the cleaning below the maximum allowable.

The pressure drop across a bag house is a factor in performance. An operating pressure drop of 3 to 4 in. (water gauge) is substantially below 10 in. (water gauge). Pressure figures such as these are values averaged over the filtering cycle. When filtration begins, the pressure drop increases nonlinearly until a filter cake is built and then increases linearly thereafter.

Mathematical Model

The conventional practice in modeling bag filters has been to assume a perfect filter with fractional penetration that is a function of particle size (Dennis and Wilder, 1975). The Acurex bag filter model assumes a particle escape fraction of 0.005 or less (Shackleton et al., 1982). This assumption has been coded into the HTHP ceramic bag filter.

The pressure drop is empirically described as follows:

$$\Delta P = \zeta_d \mu_g \sigma U_f^2 t + P_o \quad , \quad (1)$$

where

ΔP	=	total pressure drop across filter, in. H ₂ O
ζ_d	=	empirical dust cake resistivity, nondimensional
μ_g	=	gas viscosity, slug/s-ft ³
σ	=	particle loading, g _s /ACF
U_f	=	face velocity, air-to-cloth ratio, ft/min
t	=	cleaning interval, min
P_o	=	baseline pressure drop, in. H ₂ O

The air-to-cloth ratio, U_f , is defined as the volumetric flow rate of the gas divided by the total filter surface of all bags except those that are being cleaned:

$$U_f = \frac{Q}{(N_{\text{cell}} - N_{\text{clean}}) A_{\text{bag}} N_{\text{bag}}} \quad (2)$$

where

Q	=	volumetric flow rate, m^3/s
N_{cell}	=	number of cells in operation
N_{clean}	=	number of cells being cleaned
N_{bag}	=	number of bags per cell
A_{bag}	=	surface area of bag, m^2

In addition to the pressure drop across bag filters, the Acurex design requires auxiliary power to clean the bags at some time interval. This back flush system is device dependent and may involve a variety of mechanical systems. We give here but a general guideline for computing the auxiliary power requirement.

Mechanism: Cleaning with pulse jet

Pulse volume	=	3 times bag volume
Pulse interval	=	5 - 10 minutes
Pulse volumetric flow rate	=	(number of bags)(pulse volume)/pulse interval
Pulse ΔP	=	2 times operating pressure

We thus have

$$\text{Pulse Power Requirement} = \frac{6N B_v P}{t \eta_c} \quad (3)$$

where	N	=	number of bags
	B_v	=	bag volume, m^3
	P	=	operating pressure, N/m^2
	t	=	pulse interval, s
	η_c	=	compressor efficiency, fraction

As an example, for a 15-bag unit, $2.8 \text{ ft}^3/\text{bag}$, 10 min cleaning interval, and 10 atm PFBC operating condition with 25% compressor efficiency, the auxiliary power requirement is that of a 65-horsepower compressor.

Thus, both collection efficiency and pressure drop models are empirical and subject to interpretation of experimental data. Testing of ceramic bags at Acurex is well advanced. Bags have been tested for chemical reactivity at the

Coal Utilization Research Laboratories facility (Leatherhead, England). Durability testing has been conducted in the laboratory. Individual bags were HTHP tested at the Exxon miniplant (Ernst and Shackleton, 1980), and a five-bag system was tested for 100 hours at the Westinghouse laboratory facility at PFBC conditions on resuspended ash. Problems with bag blow-through and bag cleaning were encountered but appear to have been resolved. Almost no fractional efficiency measurements have been made, with efficiency data being derived from a final total-flow filter.

Physical Properties Required

The Acurex bag filter requires gas viscosity.

User-Supplied Information

The device information is supplied to the user model via the ASPEN secondary keywords PARAM, INT, and REAL. The elements of each of these are defined in the following sections.

Input Required

PARAM NINT, NREAL, NIW, NW

NINT - Length of INT array
NREAL - Length of REAL array
NIW - Length of IW array
NW - Length of W array

INT(i), i=1, NINT

INT(1) - NPSD, Number of particle size intervals.
INT(2) - NCC, Number of chemical analyses for conventional components.
INT(3) - NNCC, Number of chemical analyses for nonconventional components.

REAL(i), i=1, NREAL

REAL(1)	Particle size distribution		
.	"	"	"
.	"	"	"
.	"	"	"

REAL(NPSD+1)	Last particle size
REAL(NPSD+2)	Diameter of bag (m)
REAL(NPSD+3)	Height of bag (m)
REAL(NPSD+4)	Number of bags per cell
REAL(NPSD+5)	Number of cells
REAL(NPSD+6)	Number of cells being cleaned
REAL(NPSD+7)	Dust cake resistivity (0.02 - 0.10)
REAL(NPSD+8)	Cleaning pulse interval (min)
REAL(NPSD+9)	Cleaning pulse duration (s)
REAL(NPSD+10)	Baseline pressure drop (in. H ₂ O)
REAL(NPSD+11)	Compressor efficiency
REAL(NPSD+12)	Fraction of vapor entrained in solid underflow
REAL(NREAL)	Temperature loss expected (degrees K)

Error Messages

Substream is not MIXED, CIPSD or NCPD. Block is bypassed.

Not enough particle sizes were specified in the REAL array. At least two are required. Block is bypassed.

Gas temperature is zero. Block is bypassed.

Gas pressure is zero. Block is bypassed.

The particle size delimiters are not in ascending order or a mean particle size is less than or equal to zero. Block is bypassed.

Diameter of bag is negative or zero. Block is bypassed.

Height of bag is negative or zero. Block is bypassed.

Number of bags is less than one. Block is bypassed.

Number of cells is less than one. Block is bypassed.

Number of cells being cleaned is greater than the total number of cells. Block is bypassed.

Cleaning time interval is less than zero. Block is bypassed.

Compressor efficiency is negative or zero. Block is bypassed.

Results

User input data for the ceramic bag filter: REAL array

Diameter of bag (m) : 1.5240D-01
 Height of bag (m) : 3.0480D 00
 Number of bags per cell : 3.0000D 01
 Number of cells : 1.0000D 01
 Number of cells being cleaned : 1.0000D 00
 Dust cake resistivity (0.02-0.10) : 5.0000D-02
 Cleaning pulse interval (min) : 1.0000D 01
 Cleaning pulse duration (s) : 1.0000D-01
 Baseline pressure drop (in. H₂O) : 3.0000D 00
 Compressor efficiency : 2.5000D-01
 Fraction of vapor entrained in solid underflow : 1.0000D-06
 Temperature loss expected (degrees K) : 0.0000D-01
 Gas operating temperature (degrees K) : 1.0610D 03
 Gas operating pressure (Pa) : 5.1782D 05

Diam. Range (μ m)	Mean Diameter (μ m)	Mass Fract. In (%)	Mass Fract. Out (%)	Cleanup (%)
0.0 - 0.6	0.30	0.67	0.56	99.9
0.6 - 0.8	0.70	3.39	2.83	99.9
0.8 - 1.0	0.90	4.76	3.97	99.9
1.0 - 1.3	1.15	8.05	6.72	99.9
1.3 - 1.6	1.45	11.21	9.36	99.9
1.6 - 2.0	1.80	10.28	8.58	99.9
2.0 - 2.5	2.25	10.61	8.86	99.9
2.5 - 3.2	2.85	10.01	8.35	99.9
3.2 - 4.0	3.60	8.51	7.10	99.9
4.0 - 5.0	4.50	9.57	7.98	99.9
5.0 - 6.4	5.70	8.16	6.81	99.9
6.4 - 8.0	7.20	6.75	5.63	99.9
8.0 - 10.1	9.05	4.21	3.52	99.9
10.1 - 12.7	11.40	2.38	1.99	99.9
12.7 - 16.0	14.35	1.08	0.90	99.9
16.0 - 20.2	18.10	0.29	0.24	99.9
20.2 - 25.4	22.80	0.05	0.04	99.9
25.4 - 32.0	28.70	0.00	0.00	99.9
32.0 - 40.0	36.00	0.00	0.00	99.9

Net efficiency of device (by mass)..... 99.9

Total change in enthalpy (J/kmole) -2.6718D 07
 Viscosity of the gas (centipoise) 4.3542D-02
 Gas volumetric flow rate (m³/s) 2.2334D 01
 Backflush power required (watts) 1.6915D 04
 Fan power required (watts) 2.5890D 05
 Total auxiliary power required (watts).. 2.7582D 05

Peak pressure drop across bag (Pa) 4.6369D 03
 Peak pressure drop across bag (in. H₂O).. 1.8615D 01
 Particle loading (kg/m³) 1.3183D-02
 Bag surface area (m²) 1.4593D 00
 Face velocity (m/s) 5.6683D-02

Pointers to the start of the substreams

Start of the MIXED substream : IDXMIX = 1
 Start of the CIPSD substream : IDXCIP = 21
 Start of the NCPSP substream : IDXNCP = 60
 End of input stream SIN1 : IDXEND = 142

Pointers to the substreams in their order of occurrence in the streams

substrm	entry	flow-F	particles
NSUBS	IDXSUB	IDXFLO	IDXPSD
1	1	12	0
2	21	32	41
3	60	63	124

Number of conventional components... : NCC = 11
 Number of nonconventional components : NNCC = 3
 Number of solid particle sizes..... : INT(1) = 19
 Number of CIPSD analysis items..... : INT(2) = 0
 Number of NCPSP analysis items..... : INT(3) = 52

Ceramic bag filter stream data

Index	SIN1	SOUT1	SOUT2
No	POC Stream In	POC Stream Out	ASH Stream
1	1.1116D-01	1.1116D-01	1.1116D-07
2	5.3277D-02	5.3277D-02	5.3277D-08
3	2.4256D-04	2.4256D-04	2.4256D-10
4	0.0000D-01	0.0000D-01	0.0000D-01
5	9.9932D-01	9.9932D-01	9.9932D-07
6	1.5747D-01	1.5747D-01	1.5747D-07
7	0.0000D-01	0.0000D-01	0.0000D-01
8	0.0000D-01	0.0000D-01	0.0000D-01
9	0.0000D-01	0.0000D-01	0.0000D-01
10	0.0000D-01	0.0000D-01	0.0000D-01
11	0.0000D-01	0.0000D-01	0.0000D-01
12	1.3197D 00	1.3197D 00	1.3197D-06
13	1.0610D 03	1.0610D 03	1.0610D 03
14	5.1782D 05	5.1318D 05	5.1318D 05

15	-6.1140D 05	0.0000D-01	0.0000D-01
16	0.0000D-01	0.0000D-01	0.0000D-01
17	0.0000D-01	0.0000D-01	0.0000D-01
18	1.0970D 03	0.0000D-01	0.0000D-01
19	1.7390D 00	1.7390D 00	1.7390D 00
20	2.9430D 01	2.9430D 01	2.9430D 01
21	0.0000D-01	0.0000D-01	0.0000D-01
22	0.0000D-01	0.0000D-01	0.0000D-01
23	0.0000D-01	0.0000D-01	0.0000D-01
24	0.0000D-01	0.0000D-01	0.0000D-01
25	0.0000D-01	0.0000D-01	0.0000D-01
26	0.0000D-01	0.0000D-01	0.0000D-01
27	0.0000D-01	0.0000D-01	0.0000D-01
28	0.0000D-01	0.0000D-01	0.0000D-01
29	1.3820D-03	8.2920D-07	1.3812D-03
30	1.9231D-03	1.1539D-06	1.9220D-03
31	7.5938D-04	4.5563D-07	7.5893D-04
32	4.0645D-03	2.4387D-06	4.0621D-03
33	1.0610D 03	1.0610D 03	1.0610D 03
34	5.1728D 05	5.1264D 05	5.1264D 05
35	-1.1520D 07	0.0000D-01	0.0000D-01
36	0.0000D-01	0.0000D-01	0.0000D-01
37	0.0000D-01	0.0000D-01	0.0000D-01
38	-2.1980D 03	0.0000D-01	0.0000D-01
39	3.2530D 03	3.2530D 03	3.2530D 03
40	6.3570D 01	6.3570D 01	6.3570D 01
41	6.7068D-03	6.7068D-03	6.7068D-03
42	3.3933D-02	3.3933D-02	3.3933D-02
43	4.7620D-02	4.7620D-02	4.7620D-02
44	8.0486D-02	8.0486D-02	8.0486D-02
45	1.1215D-01	1.1215D-01	1.1215D-01
46	1.0279D-01	1.0279D-01	1.0279D-01
47	1.0612D-01	1.0612D-01	1.0612D-01
48	1.0012D-01	1.0012D-01	1.0012D-01
49	8.5065D-02	8.5065D-02	8.5065D-02
50	9.5677D-02	9.5677D-02	9.5677D-02
51	8.1553D-02	8.1553D-02	8.1553D-02
52	6.7584D-02	6.7584D-02	6.7584D-02
53	4.2138D-02	4.2138D-02	4.2138D-02
54	2.3839D-02	2.3839D-02	2.3839D-02
55	1.0781D-02	1.0781D-02	1.0781D-02
56	2.8750D-03	2.8750D-03	2.8750D-03
57	5.2882D-04	5.2882D-04	5.2882D-04
58	3.6115D-05	3.6115D-05	3.6115D-05
59	6.2875D-07	6.2875D-07	6.2875D-07
60	0.0000D-01	0.0000D-01	0.0000D-01
61	3.3621D-02	2.0152D-05	3.3567D-02
62	2.4387D-03	1.4618D-06	2.4348D-03
63	3.6055D-02	2.1611D-05	3.5997D-02

64	1.0610D 03	1.0610D 03	1.0610D 03
65	5.1782D 05	5.1318D 05	5.1318D 05
66	1.3930D 05	0.0000D-01	0.0000D-01
67	0.0000D-01	0.0000D-01	0.0000D-01
68	0.0000D-01	0.0000D-01	0.0000D-01
69	1.0000D 70	0.0000D-01	0.0000D-01
70	1.9770D 03	1.9770D 03	1.9770D 03
71	1.0000D 00	1.0000D 00	1.0000D 00
72	5.3000D 00	5.3000D 00	5.3000D 00
73	5.4000D 01	5.4000D 01	5.4000D 01
74	3.8080D 01	3.8080D 01	3.8080D 01
75	7.9200D 00	7.9200D 00	7.9200D 00
76	7.9200D 00	7.9200D 00	7.9200D 00
77	7.8350D 01	7.8350D 01	7.8350D 01
78	6.0200D 00	6.0200D 00	6.0200D 00
79	1.4800D 00	1.4800D 00	1.4800D 00
80	0.0000D-01	0.0000D-01	0.0000D-01
81	3.0600D 00	3.0600D 00	3.0600D 00
82	3.1700D 00	3.1700D 00	3.1700D 00
83	2.1000D 00	2.1000D 00	2.1000D 00
84	4.0000D-02	4.0000D-02	4.0000D-02
85	9.2000D-01	9.2000D-01	9.2000D-01
86	0.0000D-01	0.0000D-01	0.0000D-01
87	1.0000D 00	1.0000D 00	1.0000D 00
88	1.0000D 00	1.0000D 00	1.0000D 00
89	9.8000D 01	9.8000D 01	9.8000D 01
90	9.8000D 01	9.8000D 01	9.8000D 01
91	2.0000D 00	2.0000D 00	2.0000D 00
92	0.0000D-01	0.0000D-01	0.0000D-01
93	0.0000D-01	0.0000D-01	0.0000D-01
94	0.0000D-01	0.0000D-01	0.0000D-01
95	0.0000D-01	0.0000D-01	0.0000D-01
96	0.0000D-01	0.0000D-01	0.0000D-01
97	3.3000D-01	3.3000D-01	3.3000D-01
98	4.0000D-02	4.0000D-02	4.0000D-02
99	4.2000D-01	4.2000D-01	4.2000D-01
100	1.0000D 02	1.0000D 02	1.0000D 02
101	0.0000D-01	0.0000D-01	0.0000D-01
102	0.0000D-01	0.0000D-01	0.0000D-01
103	0.0000D-01	0.0000D-01	0.0000D-01
104	0.0000D-01	0.0000D-01	0.0000D-01
105	0.0000D-01	0.0000D-01	0.0000D-01
106	0.0000D-01	0.0000D-01	0.0000D-01
107	0.0000D-01	0.0000D-01	0.0000D-01
108	0.0000D-01	0.0000D-01	0.0000D-01
109	0.0000D-01	0.0000D-01	0.0000D-01
110	0.0000D-01	0.0000D-01	0.0000D-01
111	9.8000D 01	9.8000D 01	9.8000D 01
112	1.0000D 00	1.0000D 00	1.0000D 00

113	1.0000D 00	1.0000D 00	1.0000D 00
114	1.0000D 00	1.0000D 00	1.0000D 00
115	9.5000D 01	9.5000D 01	9.5000D 01
116	1.5000D 00	1.5000D 00	1.5000D 00
117	5.0000D-01	5.0000D-01	5.0000D-01
118	0.0000D-01	0.0000D-01	0.0000D-01
119	1.5000D 00	1.5000D 00	1.5000D 00
120	5.0000D-01	5.0000D-01	5.0000D-01
121	4.0000D-02	4.0000D-02	4.0000D-02
122	1.0000D-02	1.0000D-02	1.0000D-02
123	5.0000D-02	5.0000D-02	5.0000D-02
124	6.7068D-03	6.7135D-03	6.7135D-03
125	3.3933D-02	3.3967D-02	3.3967D-02
126	4.7620D 02	4.7668D-02	4.7668D-02
127	8.0486D-02	8.0566D-02	8.0566D-02
128	1.1215D-01	1.1226D-01	1.1226D-01
129	1.0279D-01	1.0289D-01	1.0289D-01
130	1.0612D-01	1.0623D-01	1.0623D-01
131	1.0012D-01	1.0022D-01	1.0022D-01
132	8.5065D-02	8.5150D-02	8.5150D-02
133	9.5677D-02	9.5772D-02	9.5772D-02
134	8.1553D-02	8.1634D-02	8.1634D-02
135	6.6584D-02	6.6650D-02	6.6650D-02
136	4.2138D-02	4.2180D-02	4.2180D-02
137	2.3839D-02	2.3863D-02	2.3863D-02
138	1.0781D-02	1.0792D-02	1.0792D-02
139	2.8750D-03	2.8779D-03	2.8779D-03
140	5.2882D-04	5.2935D-04	5.2935D-04
141	3.6115D-05	3.6151D-05	3.6151D-05
142	6.2875D-07	6.2938D-07	6.2938D-07

References

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PERFORMANCE MODEL

Electrostatic Granular Bed Filter

Model Name: Electrostatic Granular Bed Filter (USRGGB)

Function

This procedure calculates the particle capture efficiency of a granular bed filter in high-temperature, high-pressure (HTHP) applications. The model is based on General Electric's electrostatic granular bed filter (General Electric, 1981).

The model is designed to receive one inlet material stream :

1. The product of combustion (POC) stream, SIN1
 - a. Substream MIXED
 - b. Substream CIPSD
 - c. Substream NCPSD

The substreams are not required to be in any fixed order.

The model produces two outlet material streams:

1. The POC stream, SOUT1
2. The ASH stream, SOUT2

The model will handle any number of conventional and nonconventional components and up to thirty (30) particle sizes. The number of particle sizes and chemical analyses are listed in the user ASPEN input file INT.

Principles

A typical filter design concept for an electrostatic granular bed filter is shown in the accompanying figure. This filter design uses a moving bed of granules contained in an annular space by large retaining louvers. The gas is introduced in the center of the element where it is charged by a discharge electrode at a high electric potential. The particles in the gas flow are charged by intense bombardment of ions in this precharging chamber. The gas

Sketch of GE Electrostatic Granular Bed Filter

flow containing the charged particles then flows outward through the annular bed of moving granules where the particles are captured by impaction and electrostatic forces. This single-stage, inside-to-outside flow arrangement results in a lower face velocity at the outer diameter where the blowout may occur.

Collection of particulates in a packed bed of granular material by purely mechanical means has been studied by many investigators. Neglecting electrostatic effects (other than those which hold the particle to the collector after capture) for the purposes of this discussion, granular media collect aerosol particles by at least four mechanisms: inertial impaction, interception, diffusion, and sedimentation.

Collection by impaction occurs when the inertia of a particle causes it to depart from the gas streamline and collide with the collector. Theoretical models indicate that the Stokes' number is a satisfactory dimensionless parameter for these analyses.

Brownian diffusion caused by random motion of small particles being bombarded by gas molecules enhances the possibility of a particle being collected. Even though the particle may be generally following a gas streamline, random motion occasionally allows the particle to approach a collector surface and causes it to contact that surface and be captured.

From the physical description of these phenomena, it can be seen that inertial impaction most effectively operates on larger particles (with a significant mass/area ratio) whereas diffusion is more effective on small particles whose trajectory can be influenced by molecular motion.

In addition to the mechanical collection mechanisms, the electrostatic granular bed filter utilizes enhanced charging of dust particles.

Collection due to electrostatic forces relies on the particulate charge which occurs naturally from upstream processes. Frictional charging (or tribocharging) will occur in flow through pipes and cyclones and in high mixing environments. Collection occurs when the direction of travel of a charged particulate is changed by virtue of the electrostatic force, in opposition to the fluid flow field and viscous forces, and the particulate moves through the fluid to a collection surface. Although the force is directed perpendicular to equipotential surfaces, the particulate undergoes

many changes in direction through a packed media bed, and has many opportunities to come in contact with the media. The electrostatic collection in the granular filter is similar to an electrostatic precipitator with very narrow and winding walls and therefore increased effective surface area. Of course, the mechanical collection mechanisms of impaction and diffusion contribute significantly to the overall collection.

The electric field strength in the filter is a function primarily of the applied voltage and the geometry of the electrodes. Secondary effects include the presence of the media and the gas as highly resistive dielectrics. Thus, within the well-defined overall field, there are local changes in field strength and direction due to the media and, on a smaller scale, the particulate. Local gradients in field strength provide another small force on the particulate resulting in dielectrophoresis. The collection of particulates is therefore related to a number of factors. The actual collection is affected by one or more of the collection mechanisms: impaction, interception, diffusion, and electrostatic forces. The one or two mechanisms that dominate in an electrostatic granular bed filter will depend on the following physical parameters: particulate size, density, charge, collector size, and fluid velocity. In addition, reentrainment, the rubbing off and recapture of particulates from the media, affects the net collection efficiency.

Mathematical Model

Robinson (1971) and Zahedi and Melcher (1976) have attempted to model the electrostatic effects on particles; however, there are few theoretical models describing the behavior of charged particles in a complex flow field. Besides solving for the fluid flow field, a detailed model must account for inertial effects and small variations in the electric field within the granular filter. The following simple model includes the major parameters affecting particulate collection, while assumptions are made regarding geometry and particulate loading.

It was shown previously that the total penetration is equal to the product of the penetrations due individual mechanisms. For a system in which both mechanical and electrical effects are important,

$$(1-\bar{\eta})_{\text{tot}} = (1-\eta)_{\text{elec}} (1-\eta)_{\text{mech}} \quad (1)$$

Considering the various collection mechanisms to represent η "stages" (each of efficiency η_i) which operate successively on the original dust load, the overall collection efficiency $\bar{\eta}$ can be written as

$$(1-\bar{\eta}) = \prod_{i=1}^{\eta} (1-\eta_i) \quad (2)$$

or, considering the two mechanisms discussed above,

$$(1-\bar{\eta}) = \left[1 - \left(\frac{St}{\epsilon} \right)^m \right] \left[1 - \frac{4.36}{\epsilon} Pe^{-2/3} \right] \quad (3)$$

where m is an empirically determined exponent which depends upon the Stokes' number range.

In order to include the electrostatic effect within the system of equations, an expression is needed for the collection efficiency as a function of particle charge, average electric field, etc. An approach similar to the Deutsch equation (White, 1963) first developed for standard ESPs is used in which the force on a charged particle due to an electric field is equated with the viscous force when it reaches terminal velocity. Relating this migration velocity to the geometry of the collecting surface and flow field yields

$$\eta_{elec} = 1 - \exp \left(\frac{-1}{3\pi\mu} \frac{q_p C_s A_c E}{Q_f d_p} \right) \quad (4)$$

- E = average electric field strength, V/m
- A_c = collection area, m^2
- Q_f = volumetric gas flow rate, m^3/s
- C_s = Cunningham slip correction factor, dimensionless
- q_p = particle charge, C
- d_p = particle diameter, m
- μ = gas viscosity, N/m-s

Considering the geometry of a granular bed, A_c/Q_f is approximated as

$$A_c/Q_f = 6(1-\epsilon)t/d_g U \quad (5)$$

where U = gas superficial velocity, m/s
 ϵ = void fraction
 t = bed thickness, m
 d_g = media granule diameter, m

Substituting, we get

$$\eta_{elec} = 1 - \exp \left[\frac{\frac{-2}{\pi\mu} (1-\epsilon)t E q_p C}{U d_g d_p} \right] \quad (6)$$

From the above it is noted that increased efficiency can be obtained by increasing electric field strength, particle charge, and filter thickness, or by decreasing flow velocity and media granule diameter. An increase in temperature is seen to reduce efficiency through the increase in gas viscosity. According to the model, larger particles actually have increased efficiencies, as the particle charge is assumed proportional to the square of the diameter (surface area) (White, 1963).

The auxiliary power requirement is computed for the corona discharge rate at the wire electrode and the pneumatic media lift system for transporting the granular collectors.

Physical Properties Required

The electrostatic granular bed filter model requires gas temperature, gas pressure, gas viscosity, gas density, and solid density.

User-Supplied Information

The device information is supplied to the user model via the ASPEN secondary keywords PARAM, INT, and REAL. The elements of each of these are defined in the following sections.

Input Required

PARAM NINT, NREAL, NIW, NW

NINT - Length of INT array
NREAL - Length of REAL array
NIW - Length of IW array
NW - Length of W array

INT(i), i=1, NINT

INT(1) - NPSD, Number of particle size intervals.
INT(2) - NCC, Number of chemical analyses for conventional components.
INT(3) - NNCC, Number of chemical analyses for nonconventional components.

REAL(i), i=1, NREAL

REAL(1)	Particle size distribution
.	" " "
.	" " "
.	" " "
REAL(NPSD+1)	Last particle size
REAL(NPSD+2)	Diameter of collector (mm)
REAL(NPSD+3)	Collector void fraction (nondimensional)
REAL(NPSD+4)	Bed depth (cm)
REAL(NPSD+5)	Diameter of inlet (cm)
REAL(NPSD+6)	Height of device (cm)
REAL(NPSD+7)	Diameter of electrode wire (cm)
REAL(NPSD+8)	Length of electrode wire (cm)
REAL(NPSD+9)	Applied voltage (volts)
REAL(NPSD+10)	Surface roughness (nondimensional)
REAL(NPSD+11)	Fraction of vapor entrained in solid underflow
REAL(NREAL)	Temperature loss expected (degrees F)

Error Messages

Substream is not MIXED, CIPSD or NCPSPD. Block is bypassed.

Not enough particle sizes were specified in the REAL array. At least two are required. Block is bypassed.

Gas temperature is zero. Block is bypassed.

Gas pressure is zero. Block is bypassed.

The particle size delimiters are not in ascending order or a mean particle size is less than or equal to zero. Block is bypassed.

Diameter of collector is negative or zero. Block is bypassed.

Void fraction is greater than 1.0. Block is bypassed.

Bed depth is negative or zero. Block is bypassed.

Diameter of inlet is negative or zero. Block is bypassed.

Diameter of wire electrode is negative or zero. Block is bypassed.

Electrode wire diameter is greater than bed diameter. Block is bypassed.

Length of wire electrode is less than or equal to zero. Block is bypassed.

Height of device is less than or equal to zero. Block is bypassed.

Applied voltage is not sufficient to induce corona discharge. (When REAL(NPSD+9) is set to a nonzero number, the electrostatics option is in use, and the applied voltage-corona onset relationship is analyzed.)

Warnings

Current density calculation not converged in 30 iterations. (When the electrostatics option is selected.)

Results

Geometry for the electrostatic granular bed filter from the user REAL array

Diameter of collector (mm).....	:	2.0000D 00
Collector void fraction	:	5.0000D-01
Bed depth (cm)	:	3.0000D 01
Diameter of inlet (cm)	:	6.8580D 01
Height of device (cm)	:	6.3000D 02
Diameter of electrode wire (cm)	:	1.0000D 00
Length of electrode wire (cm)	:	5.0000D 01
Applied voltage (volts)	:	4.0000D 04
Surface roughness	:	7.0000D-01
Fraction of vapor entrained in solid underflow	:	1.0000D-06
Temperature loss expected (degrees K)	:	0.0000D-01
Gas operating temperature (degrees K)	:	1.1440D 03
Gas operating pressure (Pa)	:	1.0322D 05

Diam. Range (μm)	Mean Diameter (μm)	Mass Fract. In (%)	Mass Fract. Out (%)	Cleanup (%)
0.0 - 0.5	0.25	3.95	26.70	79.18
0.5 - 1.0	0.75	4.09	17.74	86.64
1.0 - 2.0	1.50	4.22	8.46	93.84
2.0 - 3.0	2.50	4.36	2.90	97.96
3.0 - 4.0	3.50	4.50	0.97	99.34
4.0 - 5.0	4.50	4.64	0.32	99.79
5.0 - 6.0	5.50	4.78	0.10	99.93
6.0 - 7.0	6.50	4.92	0.03	99.98
7.0 - 8.0	7.50	5.06	0.01	99.99
8.0 - 9.0	8.50	5.19	0.00	100.00
9.0 - 10.0	9.50	5.33	0.00	100.00
10.0 - 11.0	10.50	5.47	0.00	100.00
11.0 - 12.0	11.50	5.61	0.00	100.00
12.0 - 13.0	12.50	5.75	0.00	100.00
13.0 - 14.0	13.50	5.89	0.00	100.00
14.0 - 15.0	14.50	6.02	0.00	100.00
15.0 - 16.0	15.50	6.16	0.00	100.00
16.0 - 17.0	16.50	6.30	0.00	100.00
17.0 - 18.0	17.50	6.44	0.00	100.00

Net efficiency of device (by mass)..... 96.92

Total particle mass flow rate in (kg/s) 3.2300D-04
Total particle mass flow rate out(kg/s) 9.9394D-06
Total change in enthalpy (J/kmole) -2.0634D 06
Viscosity of the gas (centipoise) 4.5631D-02
Superficial gas velocity (m/s) 6.1012D-01
Gas volumetric flow rate (m^3/s) 8.2813D 00
Wire current density (amp/m) 3.7766D-04
Auxiliary electric power required (watts) 7.8585D 03
Fan power required (watts) 1.6261D 04
Total auxiliary power required (watts) .. 2.4119D 04
Pressure drop across the bed (Pa) 7.8541D 02
Pressure drop across the bed (in. H_2O) . 3.1531D 00

Pointers to the start of the substreams

Start of the MIXED substream : IDXMIX = 1
Start of the CIPSD substream : IDXCIP = 21
Start of the NCPSD substream : IDXNCP = 0
End of input stream SIN1 : IDXEND = 59

Pointers to the substreams in their order of occurrence in the streams

substrm	entry	flow-F	particles
NSUBS	IDXSUB	IDXFLO	IDXPSD
1	1	12	0
2	21	32	41

Number of conventional components... : NCC = 11
 Number of nonconventional components : NNCC = 3
 Number of solid particle sizes..... : INT(1) = 19
 Number of CIPSD analysis items..... : INT(2) = 0
 Number of NCPSP analysis items..... : INT(3) = 52

Electrostatic granular bed filter stream data

Index	SIN1	SOUT1	SOUT2
No	POC Stream In	POC Stream Out	ASH Stream
1	0.0000D-01	0.0000D-01	0.0000D-01
2	0.0000D-01	0.0000D-01	0.0000D-01
3	0.0000D-01	0.0000D-01	0.0000D-01
4	0.0000D-01	0.0000D-01	0.0000D-01
5	0.0000D-01	0.0000D-01	0.0000D-01
6	0.0000D-01	0.0000D-01	0.0000D-01
7	0.0000D-01	0.0000D-01	0.0000D-01
8	0.0000D-01	0.0000D-01	0.0000D-01
9	0.0000D-01	0.0000D-01	0.0000D-01
10	0.0000D-01	0.0000D-01	0.0000D-01
11	1.1447D-01	1.1447D-01	1.1447D-07
12	1.1447D-01	1.1447D-01	1.1447D-07
13	1.1440D 03	1.1440D 03	1.1440D 03
14	1.0322D 05	1.0243D 05	1.0243D 05
15	-6.1140D 05	0.0000D-01	0.0000D-01
16	1.0000D 00	0.0000D-01	0.0000D-01
17	0.0000D-01	0.0000D-01	0.0000D-01
18	1.0970D 03	0.0000D-01	0.0000D-01
19	4.0680D-01	4.0680D-01	4.0680D-01
20	2.9430D 01	2.9430D 01	2.9430D 01
21	0.0000D-01	0.0000D-01	0.0000D-01
22	0.0000D-01	0.0000D-01	0.0000D-01
23	0.0000D-01	0.0000D-01	0.0000D-01
24	0.0000D-01	0.0000D-01	0.0000D-01
25	0.0000D-01	0.0000D-01	0.0000D-01
26	0.0000D-01	0.0000D-01	0.0000D-01
27	0.0000D-01	0.0000D-01	0.0000D-01
28	0.0000D-01	0.0000D-01	0.0000D-01
29	0.0000D-01	0.0000D-01	0.0000D-01
30	0.0000D-01	0.0000D-01	0.0000D-01

31	3.2300D-05	5.6890D-07	3.1306D-05
32	3.2300D-05	5.6890D-07	3.1306D-05
33	1.1440D 03	1.1440D 03	1.1440D 03
34	1.0322D 05	1.0243D 05	1.0243D 05
35	-1.1520D 07	0.0000D-01	0.0000D-01
36	0.0000D-01	0.0000D-01	0.0000D-01
37	0.0000D-01	0.0000D-01	0.0000D-01
38	-2.1980D 03	0.0000D-01	0.0000D-01
39	6.2300D 03	6.2300D 03	6.2300D 03
40	1.0000D 01	1.0000D 01	1.0000D 01
41	3.9474D-02	4.6657D-01	3.2249D-02
42	4.0859D-02	3.0990D-01	3.6525D-02
43	4.2244D-02	1.4777D-01	4.0900D-02
44	4.3629D-02	5.0644D-02	4.4094D-02
45	4.5014D-02	1.6933D-02	4.6135D-02
46	4.6399D-02	5.5935D-03	4.7770D-02
47	4.7784D-02	1.8158D-03	4.9268D-02
48	4.9169D-02	5.6925D-04	5.0720D-02
49	5.0554D-02	1.6587D-04	5.2156D-02
50	5.1939D-02	4.0692D-05	5.3587D-02
51	5.3324D-02	5.2028D-06	5.5017D-02
52	5.4709D-02	-2.8055D-06	5.6446D-02
53	5.6094D-02	-1.8197D-06	5.7875D-02
54	5.7479D-02	-6.0191D-07	5.9304D-02
55	5.8864D-02	-1.9898D-07	6.0733D-02
56	6.0249D-02	-6.5741D-08	6.2162D-02
57	6.1634D-02	-2.1709D-08	6.3591D-02
58	6.3019D-02	-7.1651D-09	6.5020D-02
59	6.4404D-02	-2.3638D-09	6.6449D-02

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- Robinson, M. (1971) *Electrostatic Precipitation in Air Pollution Control*, Part I, edited by W. Strauss, John Wiley & Sons, Inc., New York.
- Zahedi, K., and Melcher, J. R. (1976) "Electrofluidized Beds in the Filtration of a Submicron Aerosol," J. Air Pollution Control Assoc. 26 (4), pp. 345-352.
- White, H. J. (1963) Industrial Electrostatic Precipitation, Addison-Wesley Publishing Co., Inc., Reading, Massachusetts.

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PERFORMANCE MODEL

Electrostatic Precipitator

Model Name: Electrostatic Precipitator (USRCEP)

Function

This procedure calculates the particle capture efficiency of an electrostatic precipitator (ESP) in high-temperature, high-pressure (HTHP) applications. The basic approach is formulated by Research Cottrell on the coaxial wire-cylinder electrostatic precipitator (Feldman et al., 1977).

The model is designed to receive one inlet material stream:

1. The product of combustion (POC) stream, SIN1
 - a. Substream MIXED
 - b. Substream CIPSD
 - c. Substream NCPSD

The substreams are not required to be in any fixed order.

The model produces two outlet material streams:

1. The POC stream, SOUT1
2. The ASH stream, SOUT2

The model will handle any number of conventional and nonconventional components and up to thirty (30) particle sizes. The number of particle sizes and chemical analyses are listed in the user ASPEN input file INT.

Principles

A typical HTHP ESP configuration, such as that illustrated in the accompanying figure, is made up of discharge electrodes, generally at a high negative potential, bordered by grounded collector pipe also serving as the pressure vessel. The particulate-laden flue gas enters the collecting area where the intense electric field established by the corona wire and collector pipe charges the particles. This charge acquisition is characterized (1) by negative ions in a negative corona field or positive ions in a positive corona

Sketch of Research Cottrell ESP

field moving along field lines which terminate on the uncharged particle, or (2) by random collisions of particles and ions, or (3) by a combination of both processes. The first process, known as field charging, is dominant for particles greater than 1 μm in diameter.

Submicron particles, on the other hand, are charged primarily by the second process, which is known as diffusion charging.

In ESPs, the incoming particles reach their saturation charge very quickly. As soon as any charge is acquired, they experience a Coulomb force that provides an acceleration in the field direction.

Whereas the larger, more massive, particles drift steadily toward the wall, the fines respond quickly to the turbulent flow of the flue gas and are difficult to capture. The fluid dynamic forces tend to distribute the fines throughout the gas volume, with the result that a relatively small fraction of their time is spent near the collecting surfaces. However, because of the persistent Coulomb force, even the fines will eventually drift to the collector pipe and precipitate. After a sufficiently thick layer of material has been deposited, the agglomerated particles are dislodged from the pipe by mechanical rapping. They then fall into hoppers and are conveyed out of the precipitator facility.

Although irrigated precipitators have a potential of achieving even higher efficiencies than dry systems, the present model can be used only to simulate a dry wire-pipe precipitator.

Mathematical Model

The ESP geometry analyzed here is a coaxial wire-cylinder combination. The cylinder serves as the pressure vessel to contain the high-temperature gas with pressures up to perhaps 20 atmospheres. For this arrangement, the basic equation of electrostatic field can be written in a cylindrical coordinate system as

$$E = - \frac{\partial V}{\partial r} \quad (1)$$

and

$$\frac{1}{r} \frac{d}{dr} (rE) = \frac{\rho_i}{\epsilon_0} \quad (2)$$

It is assumed throughout these calculations that the passive electrode is at ground potential.

The current per unit length at conductor, j_ℓ (amp/m), can be expressed as

$$j_\ell = 2\pi r \rho_i b E \quad (3)$$

Substituting Equation (3) into (4) and integrating, the electrostatic field is given by

$$E(r) = \left[\frac{j_\ell}{2\pi\epsilon_0 b} + \left(\frac{r_0}{r} \right)^2 \left(E_c^2 - \frac{j_\ell}{2\pi\epsilon_0 b} \right) \right]^{1/2} \quad (4)$$

The corona current-voltage relation is found by integrating Equation (4) following Townsend (1914), and neglecting second-order terms:

$$\frac{V_o - V_c}{V_c} \ln \left(\frac{r_1}{r_0} \right) = (1 + \phi)^{1/2} - 1 - \ln \frac{1 + (1 + \phi)^{1/2}}{2} \quad (5)$$

Equation (5) can be easily solved for ϕ by functional iteration. Then E_c , the corona-starting field intensity, can be computed by

$$E_c = m \delta \left(A_g + B_g \sqrt{\frac{\delta}{r_0}} \right) \quad (6)$$

For negative corona in air, Robinson (1971) recommends the values $A_g = 32.2 \times 10^5$ V/m and $B_g = 8.46 \times 10^4$ V/m^{1/2}.

Thus, the local electrostatic field intensity $E(r)$ is computed by Equation (4) with prior knowledge of E_c from Equation (6), and j_ℓ from Equation (5).

When gases laden with suspended particulate matter are passed through an electrostatic precipitator, the particles acquire an electrical charge of the same polarity as that of the discharge electrodes. Two distinct particle charging mechanisms are generally considered to be dominant: (1) bombardment of the particles by ions moving under the influence of the applied electric field, commonly known as field charging, and (2) attachment of ionic charges to the particles by ion diffusion in accordance with the laws of kinetic theory, commonly referred to as diffusion charging.

In the formulation by Research Cottrell (Feldman et al., 1977) both field charging and diffusion charging were considered. In general application of ESPs, particle charging due to ion diffusion becomes significant for micron and submicron size particles.

Field charging has been calculated by Pauthenier and Moreau-Hanot (1932). In their formulation, the following is assumed:

1. The particles are spherical.
2. Particle spacing is sufficiently great to render negligible any particle-to-particle interactions.
3. The mean free path of the ions is small when compared to the diameter of the particles.
4. The electrical field intensity, except in the immediate neighborhood of a particle, is uniform throughout the volume of the precipitator.
5. The ion concentration is also uniform throughout the precipitator.

Regarding the first assumption, Smith and Penny (1961) have shown that departures from sphericity encountered in practice are not a serious source of error. The second assumption is true for most industrial and natural aerosols. The third assumption is generally valid, except for the finest particles or at considerably reduced pressures. The other assumptions are approached in various degrees of approximation.

The response time of field charging is less than 10^{-3} seconds, much smaller than the residence time of the particles in a precipitator pipe (≈ 1 s). Thus, it is customary to assume that maximum field charging on the spherical particle is reached instantaneously. This maximum charge, commonly called the saturation charge, is written as

$$Q = 4 \pi \epsilon_0 \theta a^2 E(r) \quad (7)$$

where

$$\theta = 2 \frac{\kappa_p - 1}{\kappa_p + 2} + 1 \quad \text{with } \kappa_p \text{ as the dielectric constant.}$$

In the limit as $\kappa_p \rightarrow \infty$, θ may be assumed to have the value of 3, which is the universally accepted value for ESP application.

In addition to the ion-bombardment charge, a suspended aerosol particle in an ionized gas acquires a charge by virtue of the random thermal motion of the ions and their consequent collisions and attachments with the particles.

Viewing diffusion charging in terms of ion-current flow to a particle, and thereby generalizing the ion-bombardment mechanism to include the effects of diffusion, Cochet (1956, 1961) derives the following equation that agrees with his experimental data.

$$Q = \left[\left(1 + \frac{\lambda}{a} \right)^2 + \frac{2}{1 + (\lambda/a)} \right] 4 \pi \epsilon_0 E(r) a^2 \frac{t}{t + \tau} \quad (8)$$

Equation (8) is an expression for combined field charging and diffusion charging. In the limit $\lambda \ll a$ for larger particles, and $t \gg \tau$, Equation (8) gives precisely the saturation charge due to ion bombardment. For smaller particles ($a \leq 1 \mu\text{m}$), the term λ/a will contribute to give additional charging due to ion diffusion.

The drag on a spherical particle moving at velocity w through a gas is

$$F_d = 6 \pi \mu a w \quad \text{for laminar flow,}$$

and
$$F_d = \frac{1}{2} C_D \pi a^2 \rho w \quad \text{for turbulent flow approximation.}$$

These have been empirically combined (Wallis, 1969) to give

$$F_d = 6 \pi f \mu a w \quad (9)$$

where f is the empirical correction factor based on the particle Reynolds number

$$f = 1 + 0.15 \text{Re}^{0.687} \quad \text{for } \text{Re} < 1000$$

with
$$\text{Re} = \frac{\rho_d w}{\mu}$$

and when Re exceeds 1000, f is empirically assumed to be constant at 18.262.

The drag force given by Equation (9) is balanced by the precipitator force

$$F_p = C_s E_p Q \quad (10)$$

where C_s is the Cunningham slip correction factor, E_p is the precipitation field intensity (i.e., the local electrostatic field intensity near the collector wall), and Q is the charge on the particle given by Equation (8).

Solving Equations (9) and (10) for the migration velocity, w , results in

$$w = \frac{6 \pi f \mu a}{C_s E_p Q} \quad (11)$$

Because w appears implicitly on the right-hand side of Equation (11) for the correction factor f , it must be computed by Newtonian iteration. However, the effect of w on the right-hand side is relatively small (i.e., its contribution is $Re^{0.687}$), only the first few iterations are needed to assure convergence.

The migration velocity, w , is substituted into the well-known Deutsch-Anderson equation (White, 1963), and the expression for precipitator efficiency becomes

$$\eta = 1 - \exp \left(- \frac{A_c w}{u} \right) \quad (12)$$

where A_c is the total collecting area of pipe, and u is the superficial velocity of gas.

Physical Properties Required

The electrostatic precipitator model requires gas density and gas viscosity.

User-Supplied Information

The device information is supplied to the user model via the ASPEN secondary keywords PARAM, INT, and REAL. The elements of each of these are defined in the following sections.

Input Required

PARAM NINT, NREAL, NIW, NW

- NINT - Length of INT array
- NREAL - Length of REAL array
- NIW - Length of IW array
- NW - Length of W array

INT(i), i=1, NINT

- INT(1) - NPSD, Number of particle size intervals.
- INT(2) - NCC, Number of chemical analyses for conventional components.
- INT(3) - NNCC, Number of chemical analyses for nonconventional components.

REAL(i), i=1, NREAL

REAL(1)	Particle size distribution
.	" " "
.	" " "
.	" " "
REAL(NPSD+1)	Last particle size
REAL(NPSD+2)	Diameter of pipe (m)
REAL(NPSD+3)	Length of pipe (m)
REAL(NPSD+4)	Diameter of wire (m)
REAL(NPSD+5)	Length of electrode wire (m)
REAL(NPSD+6)	Surface roughness (dimensionless)
REAL(NPSD+7)	Applied voltage (volts)
REAL(NPSD+8)	Fraction of vapor entrained in solid underflow
REAL(NREAL)	Temperature loss expected (degrees K)

Error Messages

Substream is not MIXED, CIPSD or NCPSPD. Block is bypassed.

Not enough particle sizes were specified in the REAL array. At least two are required. Block is bypassed.

Gas temperature is zero. Block is bypassed.

Gas pressure is zero. Block is bypassed.

The particle size delimiters are not in ascending order or a mean particle size is less than or equal to zero. Block is bypassed.

Diameter of pipe is negative or zero. Block is bypassed.

Length of pipe is negative or zero. Block is bypassed.

Electrode diameter is negative or zero. Block is bypassed.

Length of electrode wire is negative or zero. Block is bypassed.

Diameter of pipe is less than electrode diameter. Block is bypassed.

Migratory velocity calculation did not converge. Block is bypassed.

Applied voltage is not sufficient to induce corona discharge.

Warnings

Current density calculation not converged in 30 iterations.

Results

Geometry for the electrostatic precipitator from the user REAL array

Diameter of pipe (m) : 6.0000D-01
 Length of pipe (m) : 4.5000D 00
 Diameter of wire (m) : 1.0000D-02
 Length of electrode wire (m) : 4.5000D 00
 Surface roughness : 6.0000D-01
 Applied voltage (volts) : 7.0000D 04
 Number of pipes per vessel : 3.0000D 00
 Number of vessels per plant : 1.0000D 00
 Number of vessels being cleaned : 0.0000D-01
 Fraction of vapor entrained in solid underflow : 1.0000D-06
 Temperature loss expected (degrees K)..... : 0.0000D-01
 Gas operating temperature (degrees K) : 1.0610D 03
 Gas operating pressure (Pa) : 5.1782D 05

Diam. Range (μm)	Mean Diameter (μm)	Mass Fract. In (%)	Mass Fract. Out (%)	Cleanup (%)
0.0 - 0.2	0.10	0.67	1.71	98.6
0.2 - 0.4	0.30	3.39	17.40	97.1
0.4 - 0.6	0.50	4.76	17.44	97.9
0.6 - 0.8	0.70	8.05	20.28	98.6
0.8 - 1.0	0.90	11.21	20.04	99.0
1.0 - 1.5	1.25	10.28	10.67	99.4
1.5 - 2.0	1.75	10.61	5.43	99.7
2.0 - 2.5	2.25	10.01	2.61	99.9
2.5 - 3.0	2.75	8.51	1.14	99.9
3.0 - 3.5	3.25	9.57	0.67	100.0
3.5 - 4.0	3.75	8.16	0.30	100.0
4.0 - 4.5	4.25	6.75	0.13	100.0
4.5 - 5.0	4.75	4.21	0.04	100.0
5.0 - 5.5	5.25	2.38	0.01	100.0
5.5 - 6.0	5.75	1.08	0.00	100.0
6.0 - 7.0	6.50	0.29	0.00	100.0
7.0 - 8.0	7.50	0.05	0.00	100.0
8.0 - 9.0	8.50	0.00	0.00	100.0
9.0 - 10.0	9.50	0.00	0.00	100.0

Net efficiency of device (by mass)..... 99.4

Total particle mass flow rate in (kg/s) 6.8474D-03
 Total particle mass flow rate out(kg/s) 3.8370D-05
 Total change in enthalpy (J/kmole) -6.2133D 05
 Viscosity of the gas (centipoise) 4.3542D-02
 Gas volumetric flow rate (m^3/s) 5.1938D-01
 Pressure drop across the device (Pa) ... 1.5163D 00
 Pressure drop (in. H_2O) 6.0873D-03
 Superficial velocity (m/s) 6.1231D-01
 Wire current density (amp/m) 7.8192D-06

Electrical energization required (watts) 7.3892D 00
 Fan power required (watts) 1.9689D 00
 Total auxiliary power required (watts) . 9.3581D 00

Pointers to the start of the substreams

Start of the MIXED substream : IDXMIX = 1
 Start of the CIPSD substream : IDXCIP = 21
 Start of the NCPSP substream : IDXNCP = 60
 End of input stream SIN1 : IDXEND = 142

Pointers to the substreams in their order of occurrence in the streams

substrm	entry	flow-F	particles
NSUBS	IDXSUB	IDXFLO	IDXPSD
1	1	12	0
2	21	32	41
3	60	63	124

Number of conventional components... : NCC = 11
 Number of nonconventional components : NNCC = 3
 Number of solid particle sizes..... : INT(1) = 19
 Number of CIPSD analysis items..... : INT(2) = 0
 Number of NCPSP analysis items..... : INT(3) = 52

Electrostatic precipitator stream data

Index	SIN1	SOUT1	SOUT2
No	POC Stream In	POC Stream Out	ASH Stream
1	2.5850D-03	2.5850D-03	2.5850D-09
2	1.2390D-03	1.2390D-03	1.2390D-09
3	5.6410D-06	5.6410D-06	5.6410D-12
4	0.0000D-01	0.0000D-01	0.0000D-01
5	2.3240D-02	2.3240D-02	2.3240D-08
6	3.6620D-03	3.6620D-03	3.6620D-09
7	0.0000D-01	0.0000D-01	0.0000D-01
8	0.0000D-01	0.0000D-01	0.0000D-01
9	0.0000D-01	0.0000D-01	0.0000D-01
10	0.0000D-01	0.0000D-01	0.0000D-01
11	0.0000D-01	0.0000D-01	0.0000D-01
12	3.0690D-02	3.0690D-02	3.0690D-08
13	1.0610D 03	1.0610D 03	1.0610D 03
14	5.1782D 05	5.1782D 05	5.1782D 05
15	-6.1140D 05	0.0000D-01	0.0000D-01
16	0.0000D-01	0.0000D-01	0.0000D-01
17	0.0000D-01	0.0000D-01	0.0000D-01
18	1.0970D 03	0.0000D-01	0.0000D-01

19	1.7390D 00	1.7390D 00	1.7390D 00
20	2.9430D 01	2.9430D 01	2.9430D 01
21	0.0000D-01	0.0000D-01	0.0000D-01
22	0.0000D-01	0.0000D-01	0.0000D-01
23	0.0000D-01	0.0000D-01	0.0000D-01
24	0.0000D-01	0.0000D-01	0.0000D-01
25	0.0000D-01	0.0000D-01	0.0000D-01
26	0.0000D-01	0.0000D-01	0.0000D-01
27	0.0000D-01	0.0000D-01	0.0000D-01
28	0.0000D-01	0.0000D-01	0.0000D-01
29	3.2140D-05	1.7627D-07	3.1964D-05
30	4.4724D-05	2.4529D-07	4.4479D-05
31	1.7660D-05	9.6858D-08	1.7563D-05
32	9.4524D-05	5.1843D-07	9.4006D-05
33	1.0610D 03	1.0610D 03	1.0610D 03
34	5.1728D 05	5.1728D 05	5.1728D 05
35	-1.1520D 07	0.0000D-01	0.0000D-01
36	0.0000D-01	0.0000D-01	0.0000D-01
37	0.0000D-01	0.0000D-01	0.0000D-01
38	-2.1980D 03	0.0000D-01	0.0000D-01
39	3.2530D 03	3.2530D 03	3.2530D 03
40	6.3570D 01	6.3570D 01	6.3570D 01
41	6.7068D-03	1.7516D-02	6.6472D-03
42	3.3933D-02	1.7777D-01	3.3140D-02
43	4.7620D-02	1.7819D-01	4.6900D-02
44	8.0486D-02	2.0721D-01	7.9787D-02
45	1.1215D-01	2.0471D-01	1.1164D-01
46	1.0279D-01	1.0906D-01	1.0276D-01
47	1.0612D-01	5.5470D-02	1.0640D-01
48	1.0012D-01	2.6626D-02	1.0052D-01
49	8.5065D-02	1.1668D-02	8.5469D-02
50	9.5677D-02	6.8203D-03	9.6167D-02
51	8.1553D-02	3.0387D-03	8.1986D-02
52	6.7584D-02	1.3231D-03	6.7949D-02
53	4.2138D-02	4.3560D-04	4.2368D-02
54	2.3839D-02	1.3079D-04	2.3970D-02
55	1.0781D-02	3.1557D-05	1.0840D-02
56	2.8750D-03	3.3118D-06	2.8908D-03
57	5.2882D-04	1.7902D-07	5.3173D-04
58	3.6115D-05	3.6720D-09	3.6314D-05
59	6.2875D-07	1.9628D-11	6.3222D-07
60	0.0000D-01	0.0000D-01	0.0000D-01
61	7.8189D-04	4.2883D-06	7.7682D-04
62	5.6713D-05	3.1104D-07	5.6345D-05
63	8.3848D-04	4.5986D-06	8.3305D-04
64	1.0610D 03	1.0610D 03	1.0610D 03
65	5.1782D 05	5.1782D 05	5.1782D 05
66	1.3930D 05	0.0000D-01	0.0000D-01
67	0.0000D-01	0.0000D-01	0.0000D-01
68	0.0000D-01	0.0000D-01	0.0000D-01
69	1.0000D 70	0.0000D-01	0.0000D-01

70	1.9770D 03	1.9770D 03	1.9770D 03
71	1.0000D 00	1.0000D 00	1.0000D 00
72	5.3000D 00	5.3000D 00	5.3000D 00
73	5.4000D 01	5.4000D 01	5.4000D 01
74	3.8080D 01	3.8080D 01	3.8080D 01
75	7.9200D 00	7.9200D 00	7.9200D 00
76	7.9200D 00	7.9200D 00	7.9200D 00
77	7.8350D 01	7.8350D 01	7.8350D 01
78	6.0200D 00	6.0200D 00	6.0200D 00
79	1.4800D 00	1.4800D 00	1.4800D 00
80	0.0000D-01	0.0000D-01	0.0000D-01
81	3.0600D 00	3.0600D 00	3.0600D 00
82	3.1700D 00	3.1700D 00	3.1700D 00
83	2.1000D 00	2.1000D 00	2.1000D 00
84	4.0000D-02	4.0000D-02	4.0000D-02
85	9.2000D-01	9.2000D-01	9.2000D-01
86	0.0000D-01	0.0000D-01	0.0000D-01
87	1.0000D 00	1.0000D 00	1.0000D 00
88	1.0000D 00	1.0000D 00	1.0000D 00
89	9.8000D 01	9.8000D 01	9.8000D 01
90	9.8000D 01	9.8000D 01	9.8000D 01
91	2.0000D 00	2.0000D 00	2.0000D 00
92	0.0000D-01	0.0000D-01	0.0000D-01
93	0.0000D-01	0.0000D-01	0.0000D-01
94	0.0000D-01	0.0000D-01	0.0000D-01
95	0.0000D-01	0.0000D-01	0.0000D-01
96	0.0000D-01	0.0000D-01	0.0000D-01
97	3.3000D-01	3.3000D-01	3.3000D-01
98	4.0000D-02	4.0000D-02	4.0000D-02
99	4.2000D-01	4.2000D-01	4.2000D-01
100	1.0000D 02	1.0000D 02	1.0000D 02
101	0.0000D-01	0.0000D-01	0.0000D-01
102	0.0000D-01	0.0000D-01	0.0000D-01
103	0.0000D-01	0.0000D-01	0.0000D-01
104	0.0000D-01	0.0000D-01	0.0000D-01
105	0.0000D-01	0.0000D-01	0.0000D-01
106	0.0000D-01	0.0000D-01	0.0000D-01
107	0.0000D-01	0.0000D-01	0.0000D-01
108	0.0000D-01	0.0000D-01	0.0000D-01
109	0.0000D-01	0.0000D-01	0.0000D-01
110	0.0000D-01	0.0000D-01	0.0000D-01
111	9.8000D 01	9.8000D 01	9.8000D 01
112	1.0000D 00	1.0000D 00	1.0000D 00
113	1.0000D 00	1.0000D 00	1.0000D 00
114	1.0000D 00	1.0000D 00	1.0000D 00
115	9.5000D 01	9.5000D 01	9.5000D 01
116	1.5000D 00	1.5000D 00	1.5000D 00
117	5.0000D-01	5.0000D-01	5.0000D-01
118	0.0000D-01	0.0000D-01	0.0000D-01
119	1.5000D 00	1.5000D 00	1.5000D 00
120	5.0000D-01	5.0000D-01	5.0000D-01

121	4.0000D-02	4.0000D-02	4.0000D-02
122	1.0000D-02	1.0000D-02	1.0000D-02
123	5.0000D-02	5.0000D-02	5.0000D-02
124	6.7068D-03	1.7517D-02	6.6539D-03
125	3.3933D-02	1.7778D-01	3.3173D-02
126	4.7620D-02	1.7819D-01	4.6947D-02
127	8.0486D-02	2.0721D-01	7.9867D-02
128	1.1215D-01	2.0471D-01	1.1175D-01
129	1.0279D-01	1.0906D-01	1.0286D-01
130	1.0612D-01	5.5471D-02	1.0651D-01
131	1.0012D-01	2.6627D-02	1.0063D-01
132	8.5065D-02	1.1668D-02	8.5556D-02
133	9.5677D-02	6.8205D-03	9.6263D-02
134	8.1553D-02	3.0388D-03	8.2068D-02
135	6.6584D-02	1.3035D-03	6.7011D-02
136	4.2138D-02	4.3561D-04	4.2410D-02
137	2.3839D-02	1.3080D-04	2.3994D-02
138	1.0781D-02	3.1557D-05	1.0851D-02
139	2.8750D-03	3.3119D-06	2.8937D-03
140	5.2882D-04	1.7902D-07	5.3227D-04
141	3.6115D-05	3.6720D-09	3.6351D-05
142	6.2875D-07	1.9629D-11	6.3285D-07

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PERFORMANCE MODEL

Electrocyclone

Model Name: Electrocyclone (USRGCY)

Function

This procedure calculates the particle capture efficiency of an electrocyclone in high-temperature, high-pressure (HTHP) applications. The model is based on the three-region model by General Electric (1981).

The model is designed to receive one input material stream:

1. The product of combustion (POC) stream, SIN1
 - a. Substream MIXED
 - b. Substream CIPSD
 - c. Substream NCPSD

The substreams are not required to be in any fixed order.

The model produces two outlet material streams:

1. The POC stream, SOUT1
2. The ASH stream, SOUT2

The model will handle any number of conventional and nonconventional components and up to thirty (30) particle sizes. The number of particle sizes and chemical analyses are listed in the user ASPEN input file INT.

Principles

The cyclone has been in use for particle control in various industries for nearly a century. It is perhaps the best known and least expensive device for particle collection. Consequently, the theory and practice of cyclone operation has been extensively documented.

Historically, cyclones were characterized by a cut size which was computed by equating the centrifugal force on a particle to the drag on the particle due to the radial gas velocity (Lapple, 1951; Stairmand, 1951). This theory is easily understood and widely employed.

In the most common arrangement for inertial separators, the flue gas enters the cyclone tangentially at the top of the cylindrical section and spirals downward into the bottom section. Because of the applied centrifugal force, the dust particles accumulate at the wall and are eventually removed from the mainstream. Thus, the system is governed largely by the equations pertaining to the centrifugal and aerodynamic forces acting on the particles.

Excellent survey papers and articles have been published by Porter et al. (1973), Jackson (1963), Caplan (1968), and Batel (1972). The interior flow fields have been explored by Ter Linden (1949) and Kelsall (1952). Standardized designs and practices have been defined by Stairmand (1951), and good agreement has been realized between experiment and the relatively recent theory of Leith and Licht (1972). This body of experience indicates that small cyclones operated at high swirl velocity give better separation efficiency, although consideration must also be given to coarse particle bouncing and limitations associated with system pressure losses and cyclone erosion. Hence, multicyclones (i.e., many small cyclones operating in parallel) and staging have been employed in situations where unusually clean gas is mandated.

Despite the extensive body of literature on the subject, predicting the performance of cyclones in actual service remains an art. This is partly because each application introduces new uncertainties about particle size distribution, state of agglomeration, dust loading, etc. However, major uncertainties are also a consequence of inadequacies in the analytical methods used. Theories appearing in the literature are at best semiquantitative and are generally incapable of accurately accounting for the effects of design features such as inlet shape, scroll versus tangential inlet, or outlet duct diameter and engagement length, all of which are known to have a strong influence on cyclone performance.

The GE electrocyclone concept is illustrated in the accompanying figure. The electrocyclone incorporates a clean air shield adjacent to the exhaust duct which prevents short circuiting of dust into the outlet. The clean air is provided by an axial flow separator/electrostatic charger device positioned in the exhaust duct of an upstream cyclone. This axial flow component uses a high-voltage corona electrode to charge the dust particles and improve the separation efficiency. The vortex field in the axial flow component is

Sketch of GE Electrocyclone

provided by the swirling motion naturally present in the exhaust of a conventional, reverse-flow cyclone. Within the electrocyclone, the separation of dust is strongly augmented by another high-voltage field applied with an electrode along the axis of the cyclone.

A principal advantage of the electrocyclone concept is that a large-diameter unit can be built to give the same efficiency as a small, conventional cyclone. The large unit is possible because the electrostatic separative force is independent of the cyclone diameter, in contrast to the centrifugal force which increases for larger cyclones.

A valuable advance in the analysis of cyclone performance has been made by GE in their three-region model. The model is the first analytical representation of cyclones to account for observed turbulent mixing between various internal regions. The model accounts for axial variations in the particle concentration and partially allows for radial variations by assuming a different concentration in the vortex core compared to either the inlet region or the main body of the vortex. The model has been validated by extensive comparisons with data from a variety of cyclone geometries and operating conditions.

Mathematical Model

The three-region cyclone model is based on the earlier Leith and Licht model (1972) and includes inherent turbulent flows present in the device. The model incorporates empirical turbulent back-mixing of the suspended particles and provides reasonable agreement with the data. Separate representations are included for (1) the entrance region, (2) the downflow (annular vortex) region, and (3) the upflow (core vortex) region. The model computes the inertial impaction due to tangential and radial components of the vortex flow. The effect of temperature is represented by change in viscosity, and the effect of pressure is not represented. The model also assumes a relatively low particle loading, and thus the effect of particle charge on electrostatic field calculations is assumed to be negligible.

In each region, turbulent mixing is assumed to maintain uniform radial concentration profiles. Thus, conservation of particles in each region requires that

$$Q_{vo} \frac{dn_1}{dz} = -\pi D_c \Gamma w(z) \quad \text{Region 1} \quad (1)$$

$$\frac{d}{dz} [Q_{v(z)} n_2] = -\pi D_c \Gamma_w(z) - 2\pi D_{v(z)} \Gamma_v(z) \quad \text{Region 2} \quad (2)$$

$$-\frac{d}{dz} [Q_{v(z)} n_3] = 2\pi D_{v(z)} \Gamma_v(z) \quad \text{Region 3} \quad (3)$$

where $Q_{v(z)}$ is the axial volumetric flow rate, $\Gamma_w(z)$ is the particle flux to the cyclone wall, $r_{v(z)}$ is the radius of the core region, and $\Gamma_v(z)$ is the flux of particles from the annular region to the core region (2+3).

The radial particle velocity ($u_{pw(z)}$) near the cyclone wall can be directly computed from a balance between inertial and Stokes' drag forces. Thus

$$6\pi \mu r_p u_{pw(z)} = \frac{\pi \rho_p r_p^3 u_{tw}^2}{r_c} \quad (4)$$

where μ is the gas viscosity, r_p is the particle radius, $u_{tw(z)}$ is the tangential gas velocity and ρ_p is the density of the particle. Hence,

$$u_{pw(z)} = \frac{\rho_p D_p^2 u_{tw}^2}{9\mu D_c} \quad (5)$$

Similarly, the velocity of particles having migrated from the core vortex region into the outer annular region can be computed from the force balance equation as

$$u_{pv(z)} = \frac{\rho_p D_p^2 u_{tv}^2}{9\mu D_v} \quad (6)$$

The assumptions are (1) the tangential velocity does not vary axially (Caplan, 1968), and (2) the radial dependence of the tangential velocity is given by a modified form of the free vortex in an inviscid fluid (Stairmand, 1951; Alexander, 1949) as

$$u_t(r) = u_{tw} (r_c/r)^m \quad (7)$$

where m is between 0.5 and 1.0.

With the model thus completed, Equations (1) to (3) become a set of coupled, variable coefficient, ordinary differential equations. The analytical solutions, with appropriate matching inlet conditions from mass conservation

and axial concentration profiles in the inlet and outlet regions, give the particle collection efficiency as

$$\eta = 1 - \left[K_0 - \left(K_1^2 + K_2 \right)^{1/2} \right] \exp \left[\frac{-\pi D_c u_{pw} d}{Q} \right] \quad (8)$$

with

$$K_0 \equiv \frac{r_c u_{pw} + r_v u_r + r_v u_{pv}}{2 r_v u_{pw}} \quad (9a)$$

$$K_1 \equiv \frac{r_v u_{pv} - r_v u_r - r_c u_{pw}}{2 r_v u_{pw}} \quad (9b)$$

$$K_2 \equiv \left(\frac{r_v}{r_c} \right)^{2m} \quad (9c)$$

When electrostatic enhancement is in effect, the particle velocities are modified by their Coulombic force. Assuming no particle-particle interactions, the force balance equation between the Stokes' drag and the sum of the inertial and Coulombic forces can be written

$$6\pi\mu r_p u_{pw} = \pi \rho_p r_p^3 u_{tw}^2 / r_c + q E_w. \quad (10)$$

The electrode structure considered here is a coaxial rod of radius r_e extending the length of the cyclone body. Being insulated from the grounded cyclone wall, the electrode produces a radially directed electric field, approximated by

$$\bar{E}(r) = \frac{V_o}{r \ln(r_c/r_e)} \hat{r}, \quad (11)$$

and so

$$E_w = \frac{V_o}{r_c \ln(r_c/r_e)}, \quad (12)$$

where V_o is the imposed high voltage. The entering particles are assumed to be charged to their saturation value in a corona-producing electric field (E_c):

$$q = 12\pi \epsilon_o r_p^2 E_c. \quad (13)$$

Using the above equations, Equation (10) can be simplified to yield

$$u_{pw} = \frac{2\rho_p r_p^2 u_{tw}^2}{9\mu r_c} + \frac{2\epsilon_o r_p E_c V_o}{\mu r_c \ln(r_c/r_e)} \quad (14)$$

Similarly, the particle velocity at the core vortex and outer annular vortex boundary can be written

$$u_{pv} = \frac{2\rho_p r_p^2 u_{tv}^2}{9\mu r_v} + \frac{2\epsilon_o r_p E_c V_o}{\mu r_v \ln(r_c/r_e)} \quad (15)$$

These modified velocities, Equations (14) and (15), can be substituted in the efficiency calculation, Equation (8), to model the electrostatic enhancement of the electrocyclones.

Pressure drop in a cyclone will be considered as that between gas inlet and gas outlet. A number of factors that contribute to the pressure difference between these points have been identified by Shepherd and Lapple (1939):

1. Loss due to expansion of the gas when it enters the cyclone chamber.
2. Loss as kinetic energy of rotation in the cyclone chamber.
3. Losses due to wall friction in the cyclone chamber.
4. Any additional frictional losses.
5. Any regain of the rotational kinetic energy as pressure energy.

Most pressure drop theories consider factors 2 and 3 to be most important in determining cyclone pressure drop. Customarily, the cyclone pressure loss is expressed as a number of inlet velocity heads, ΔH . Inlet velocity heads can be converted to pressure drop in terms of static pressure head, ΔP , by:

$$\Delta P = \frac{v_g^2 \rho_G \Delta H}{2g\rho_L} \text{ in. H}_2\text{O} \quad (16)$$

The pressure drop prediction incorporated in the user model was formulated by Alexander (1949). Alexander derived the following expression for pressure drop, assuming all pressure losses are due to kinetic energy losses in the gas stream. The equation is written

$$\Delta H = 4.62 \frac{ab}{D \text{ De}} \left\{ \left[\left(\frac{D}{\text{De}} \right)^{2n} - 1 \right] \left(\frac{1-n}{n} \right) + f \left(\frac{D}{\text{De}} \right)^{2n} \right\}, \quad (17)$$

where

$$n = 1 - \left[1 - \frac{(0.394 D_c)^{0.14}}{2.5} \right] \left(\frac{T}{283} \right)^{0.3} \quad (18)$$

and

$$f = 0.8 \left[\left(\frac{1}{n(1-n)} \right) \left(\frac{4-2^{2n}}{3} \right) - \left(\frac{1-n}{n} \right) \right] + 0.2 \left[(2^{2n} - 1) \left(\frac{1-n}{n} \right) + 1.5(2^{2n}) \right] \quad (19)$$

Here, D_c is the diameter of the cyclone in centimeters, and T is the absolute temperature in degrees.

Physical Properties Required

The GE electrocyclone requires gas density, solid density, and gas viscosity.

User-Supplied Information

The device information is supplied to the user model via the ASPEN secondary keywords PARAM, INT, and REAL. The elements of each of these are defined in the following sections.

Input Required

PARAM NINT, NREAL, NIW, NW

NINT - Length of INT array
 NREAL - Length of REAL array
 NIW - Length of IW array
 NW - Length of W array

INT(i), i=1, NINT

INT(1) - NPSD, Number of particle size intervals.
 INT(2) - NCC, Number of chemical analyses for conventional components.
 INT(3) - NNCC, Number of chemical analyses for nonconventional components.

REAL(i), i=1, NREAL

REAL(1)	Particle size distribution		
.	"	"	"
.	"	"	"
.	"	"	"

REAL(NPSD+1)	Last particle size
REAL(NPSD+2)	Cyclone inlet axial extent (in.)
REAL(NPSD+3)	Cyclone inlet radial extent (in.)
REAL(NPSD+4)	Cyclone diameter (in.)
REAL(NPSD+5)	Vortex diameter (in.)
REAL(NPSD+6)	Vortex strength (dimensionless)
REAL(NPSD+7)	Length of overflow (in.)
REAL(NPSD+8)	Length of cylinder plus cone (in.)
REAL(NPSD+9)	Cyclone pipe exit diameter (in.)
REAL(NPSD+10)	Temperature loss expected (degrees F)
REAL(NPSD+11)	Number of cyclones installed in parallel
REAL(NPSD+12)	Fraction of vapor entrained in solid underflow
REAL(NPSD+13)	Applied voltage at electrode (volts). When this is set to zero (0), the electrostatic properties are not used.
REAL(NPSD+14)	Electrode diameter (in.)
REAL(NPSD+15)	Length of electrode wire (in.)
REAL(NREAL)	Surface roughness (dimensionless)

Error Messages

Substream is not MIXED, CIPSD or NCPD. Block is bypassed.

Not enough particle sizes were specified in the REAL array. At least two are required. Block is bypassed.

Gas temperature is zero. Block is bypassed.

Gas pressure is zero. Block is bypassed.

The particle size delimiters are not in ascending order or a mean particle size is less than or equal to zero. Block is bypassed.

Cyclone inlet axial extent is less than zero. Block is bypassed.

Cyclone inlet radial extent is less than zero. Block is bypassed.

Cyclone diameter is less than vortex diameter. Block is bypassed.

Vortex strength is out of range. It should be greater than 0.5 and less than 1.0. Block is bypassed.

Length of overflow is greater than the length of the cylinder plus cone. Block is bypassed.

Number of cyclones is zero. Block is bypassed.

Cyclone exit pipe diameter is larger than cyclone diameter. Block is bypassed.

Electrode diameter is larger than the cyclone inlet. Block is bypassed.

Applied voltage is not sufficient to induce corona discharge. (When REAL(NPSD+13) is set to a nonzero number, the electrostatics option is in use, and the applied voltage-corona onset relationship is analyzed.)

Warnings

Current density calculation not converged in 30 iterations. (When the electrostatics option is selected.)

Results

Geometry data for the GE electrocyclone from the user REAL array

```

Cyclone inlet axial extent (in.) ..... : 3.0000D 01
Cyclone inlet radial extent (in.) ..... : 1.2000D 01
Cyclone diameter (in.) ..... : 6.0000D 01
Vortex diameter *assume underflow tube*(in.) . : 2.2500D 01
Vortex strength (range 0.5-1.0) dimensionless. : 7.0000D-01
Length of overflow (in.) ..... : 1.5000D 02
Length of cylinder plus cone (in.) ..... : 2.4000D 02
Cyclone pipe exit diameter (in.) ..... : 6.0000D 01
Temperature loss expected (degrees K)..... : 0.0000D-01
Number of cyclones installed in parallel..... : 2.0000D 00
Fraction of vapor entrained in solid underflow : 1.0000D-06
Applied voltage to electrodes (volts).....: 1.0000D 05
Electrode diameter (in.) .....: 1.2500D-01
Length of electrode wire (in.) .....: 2.4000D 02
Surface roughness .....: 8.0000D-01
Gas operating temperature (degrees K) ..... : 1.0610D 03
Gas operating pressure (Pa) ..... : 5.1782D 05

```

Diameter Range (μm)	Mean Diameter (μm)	Mass Fract. In (%)	Mass Fract. Out (%)	Cleanup (%)
0.0 - 0.6	0.30	0.67	1.06	0.3
0.6 - 0.8	0.70	3.39	5.27	1.6
0.8 - 1.0	0.90	4.76	7.32	2.7
1.0 - 1.3	1.15	8.05	12.16	4.4
1.3 - 1.6	1.45	11.21	16.49	7.0
1.6 - 2.0	1.80	10.28	14.49	10.8
2.0 - 2.5	2.25	10.61	13.92	17.0
2.5 - 3.2	2.85	10.01	11.46	27.6
3.2 - 4.0	3.60	8.51	7.63	43.2
4.0 - 5.0	4.50	9.57	5.88	61.1

5.0 - 6.4	5.70	8.16	2.84	77.9
6.4 - 8.0	7.20	6.75	1.13	89.4
8.0 - 10.1	9.05	4.21	0.28	95.8
10.1 - 12.7	11.40	2.38	0.05	98.8
12.7 - 16.0	14.35	1.08	0.00	99.8
16.0 - 20.2	18.10	0.29	0.00	100.0
20.2 - 25.4	22.80	0.05	0.00	100.0
25.4 - 32.0	28.70	0.00	0.00	100.0
32.0 - 40.0	36.00	0.00	0.00	100.0

Net efficiency of device (by mass)..... 36.7

Total particle mass flow rate in (kg/s) 2.9444D-01
 Total particle mass flow rate out(kg/s) 1.8632D-01
 Total change in enthalpy (J/kmole)..... -2.6718D 07
 Viscosity of the gas (centipoise) 4.3542D-02
 Tangential gas velocity (m/s) 4.8080D 01
 Gas volumetric flow rate (m³/s)..... 1.1167D 01
 Current density (amp/m) 7.1851D-05
 Electrical energization required (watts) 4.3800D 01
 Fan power required (watts) 5.6829D 04
 Total auxiliary power required (watts) . 5.6873D 04
 Pressure drop across the cyclone (Pa) .. 2.0356D 03
 Pressure drop across the cyclone (in. H₂O) 8.1723D 00

Pointers to the start of the substreams

Start of the MIXED substream : IDX MIX = 1
 Start of the CIPSD substream : IDXCIP = 21
 Start of the NCPSP substream : IDXNCP = 60
 End of input stream SIN1 : IDXEND = 142

Pointers to the substreams in their order of occurrence in the streams

substrm	entry	flow-F	particles
NSUBS	IDXSUB	IDXFLO	IDXPSD
1	1	12	0
2	21	32	41
3	60	63	124

Number of conventional components... : NCC = 11
 Number of nonconventional components : NNCC = 3
 Number of solid particle sizes..... : INT(1) = 19
 Number of CIPSD analysis items..... : INT(2) = 0
 Number of NCPSP analysis items..... : INT(3) = 52

GE electrocyclone stream data

Index	SIN1	SOUT1	SOUT2
No	POC Stream In	POC Stream Out	ASH Stream
1	1.1116D-01	1.1116D-01	1.1116D-07
2	5.3277D-02	5.3277D-02	5.3277D-08
3	2.4256D-04	2.4256D-04	2.4256D-10
4	0.0000D-01	0.0000D-01	0.0000D-01
5	9.9932D-01	9.9932D-01	9.9932D-07
6	1.5747D-01	1.5747D-01	1.5747D-07
7	0.0000D-01	0.0000D-01	0.0000D-01
8	0.0000D-01	0.0000D-01	0.0000D-01
9	0.0000D-01	0.0000D-01	0.0000D-01
10	0.0000D-01	0.0000D-01	0.0000D-01
11	0.0000D-01	0.0000D-01	0.0000D-01
12	1.3197D 00	1.3197D 00	1.3197D-06
13	1.0610D 03	1.0610D 03	1.0610D 03
14	5.1782D 05	5.1578D 05	5.1578D 05
15	-6.1140D 05	0.0000D-01	0.0000D-01
16	0.0000D-01	0.0000D-01	0.0000D-01
17	0.0000D-01	0.0000D-01	0.0000D-01
18	1.0970D 03	0.0000D-01	0.0000D-01
19	1.7390D 00	1.7390D 00	1.7390D 00
20	2.9430D 01	2.9430D 01	2.9430D 01
21	0.0000D-01	0.0000D-01	0.0000D-01
22	0.0000D-01	0.0000D-01	0.0000D-01
23	0.0000D-01	0.0000D-01	0.0000D-01
24	0.0000D-01	0.0000D-01	0.0000D-01
25	0.0000D-01	0.0000D-01	0.0000D-01
26	0.0000D-01	0.0000D-01	0.0000D-01
27	0.0000D-01	0.0000D-01	0.0000D-01
28	0.0000D-01	0.0000D-01	0.0000D-01
29	1.3820D-03	8.5939D-04	5.2261D-04
30	1.9231D-03	1.1959D-03	7.2723D-04
31	7.5938D-04	4.7222D-04	2.8717D-04
32	4.0645D-03	2.5275D-03	1.5370D-03
33	1.0610D 03	1.0610D 03	1.0610D 03
34	5.1728D 05	5.1524D 05	5.1524D 05
35	-1.1520D 07	0.0000D-01	0.0000D-01
36	0.0000D-01	0.0000D-01	0.0000D-01
37	0.0000D-01	0.0000D-01	0.0000D-01
38	-2.1980D 03	0.0000D-01	0.0000D-01
39	3.2530D 03	3.2530D 03	3.2530D 03
40	6.3570D 01	6.3570D 01	6.3570D 01
41	6.7068D-03	1.0750D-02	5.8069D-05
42	3.3933D-02	5.3632D-02	1.5389D-03
43	4.7620D-02	7.4418D-02	3.5527D-03
44	8.0486D-02	1.2348D-01	9.7859D-03
45	1.1215D-01	1.6715D-01	2.1711D-02
46	1.0279D-01	1.4655D-01	3.0821D-02
47	1.0612D-01	1.4013D-01	5.0194D-02

48	1.0012D-01	1.1433D-01	7.6746D-02
49	8.5065D-02	7.4774D-02	1.0199D-01
50	9.5677D-02	5.6022D-02	1.6088D-01
51	8.1553D-02	2.6132D-02	1.7269D-01
52	6.7584D-02	9.9515D-03	1.6235D-01
53	4.2138D-02	2.3082D-03	1.0763D-01
54	2.3839D-02	3.4288D-04	6.2476D-02
55	1.0781D-02	2.4175D-05	2.8470D-02
56	2.8750D-03	4.2785D-07	7.6020D-03
57	5.2882D-04	1.4155D-09	1.3984D-03
58	3.6115D-05	2.2120D-13	9.5503D-05
59	6.2875D-07	1.0004D-15	1.6627D-06
60	0.0000D-01	0.0000D-01	0.0000D-01
61	3.3621D-02	2.3880D-02	9.7077D-03
62	2.4387D-03	1.7321D-03	7.0415D-04
63	3.6055D-02	2.5609D-02	1.0410D-02
64	1.0610D 03	1.0610D 03	1.0610D 03
65	5.1782D 05	5.1578D 05	5.1578D 05
66	1.3930D 05	0.0000D-01	0.0000D-01
67	0.0000D-01	0.0000D-01	0.0000D-01
68	0.0000D-01	0.0000D-01	0.0000D-01
69	1.0000D 70	0.0000D-01	0.0000D-01
70	1.9770D 03	1.9770D 03	1.9770D 03
71	1.0000D 00	1.0000D 00	1.0000D 00
72	5.3000D 00	5.3000D 00	5.3000D 00
73	5.4000D 01	5.4000D 01	5.4000D 01
74	3.8080D 01	3.8080D 01	3.8080D 01
75	7.9200D 00	7.9200D 00	7.9200D 00
76	7.9200D 00	7.9200D 00	7.9200D 00
77	7.8350D 01	7.8350D 01	7.8350D 01
78	6.0200D 00	6.0200D 00	6.0200D 00
79	1.4800D 00	1.4800D 00	1.4800D 00
80	0.0000D-01	0.0000D-01	0.0000D-01
81	3.0600D 00	3.0600D 00	3.0600D 00
82	3.1700D 00	3.1700D 00	3.1700D 00
83	2.1000D 00	2.1000D 00	2.1000D 00
84	4.0000D-02	4.0000D-02	4.0000D-02
85	9.2000D-01	9.2000D-01	9.2000D-01
86	0.0000D-01	0.0000D-01	0.0000D-01
87	1.0000D 00	1.0000D 00	1.0000D 00
88	1.0000D 00	1.0000D 00	1.0000D 00
89	9.8000D 01	9.8000D 01	9.8000D 01
90	9.8000D 01	9.8000D 01	9.8000D 01
91	2.0000D 00	2.0000D 00	2.0000D 00
92	0.0000D-01	0.0000D-01	0.0000D-01
93	0.0000D-01	0.0000D-01	0.0000D-01
94	0.0000D-01	0.0000D-01	0.0000D-01
95	0.0000D-01	0.0000D-01	0.0000D-01
96	0.0000D-01	0.0000D-01	0.0000D-01
97	3.3000D-01	3.3000D-01	3.3000D-01
98	4.0000D-02	4.0000D-02	4.0000D-02

99	4.2000D-01	4.2000D-01	4.2000D-01
100	1.0000D 02	1.0000D 02	1.0000D 02
101	0.0000D-01	0.0000D-01	0.0000D-01
102	0.0000D-01	0.0000D-01	0.0000D-01
103	0.0000D-01	0.0000D-01	0.0000D-01
104	0.0000D-01	0.0000D-01	0.0000D-01
105	0.0000D-01	0.0000D-01	0.0000D-01
106	0.0000D-01	0.0000D-01	0.0000D-01
107	0.0000D-01	0.0000D-01	0.0000D-01
108	0.0000D-01	0.0000D-01	0.0000D-01
109	0.0000D-01	0.0000D-01	0.0000D-01
110	0.0000D-01	0.0000D-01	0.0000D-01
111	9.8000D 01	9.8000D 01	9.8000D 01
112	1.0000D 00	1.0000D 00	1.0000D 00
113	1.0000D 00	1.0000D 00	1.0000D 00
114	1.0000D 00	1.0000D 00	1.0000D 00
115	9.5000D 01	9.5000D 01	9.5000D 01
116	1.5000D 00	1.5000D 00	1.5000D 00
117	5.0000D-01	5.0000D-01	5.0000D-01
118	0.0000D-01	0.0000D-01	0.0000D-01
119	1.5000D 00	1.5000D 00	1.5000D 00
120	5.0000D-01	5.0000D-01	5.0000D-01
121	4.0000D-02	4.0000D-02	4.0000D-02
122	1.0000D-02	1.0000D-02	1.0000D-02
123	5.0000D-02	5.0000D-02	5.0000D-02
124	6.7068D-03	9.4230D-03	4.8316D-05
125	3.3933D-02	4.7268D-02	1.2482D-03
126	4.7620D-02	6.5880D-02	2.8663D-03
127	8.0486D-02	1.1012D-01	7.8572D-03
128	1.1215D-01	1.5085D-01	1.7348D-02
129	1.0279D-01	1.3476D-01	2.4500D-02
130	1.0612D-01	1.3328D-01	3.9671D-02
131	1.0012D-01	1.1633D-01	6.0584D-02
132	8.5065D-02	8.6055D-02	8.2924D-02
133	9.5677D-02	7.6323D-02	1.4362D-01
134	8.1553D-02	4.2927D-02	1.7685D-01
135	6.6584D-02	1.9514D-02	1.8260D-01
136	4.2138D-02	5.8549D-03	1.3154D-01
137	2.3839D-02	1.2483D-03	7.9492D-02
138	1.0781D-02	1.5382D-04	3.6960D-02
139	2.8750D-03	6.6123D-06	9.9408D-03
140	5.2882D-04	8.8545D-08	1.8313D-03
141	3.6115D-05	1.2528D-10	1.2508D-04
142	6.2875D-07	7.8271D-15	2.1776D-06

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