Development of an Effective Cyclone Simulator under Excel

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An effective cyclone simulator has been developed under Microsoft Excel spreadsheet software. The simulator is based on a mathematical model from the literature, and uses the advantages of the Excel software. The simulator has proved to be a powerful tool in the design and operation of cyclone separation systems.

Commercial simulators are effective for large system and plant design but they are sometimes inappropriate for one process's detailed design, since they incorporate simple models which are insufficient for detailed process design. Of course, commercial simulators usually offer the possibility for introducing a model, reflecting the customer's knowledge and experience on the specific process, but this is an expensive solution. On the other hand, modern general-purpose software for analysing and presenting information is cheap and with the ability for the development of one-process simulators.

Microsoft Excel with Visual Basic for Applications seems to be an effective tool for process engineering. Spreadsheets offer sufficient process model 'hospitality'. They are connected easily and on-line with charts and graphic objects, resulting in powerful and easy-to-use graphical interfaces. Excel also supports mathematical and statistical tools. Databases are effective and easily accessed. In addition, Visual Basic for Applications (which is included in the new version of Excel) offers a powerful object-oriented programming language.

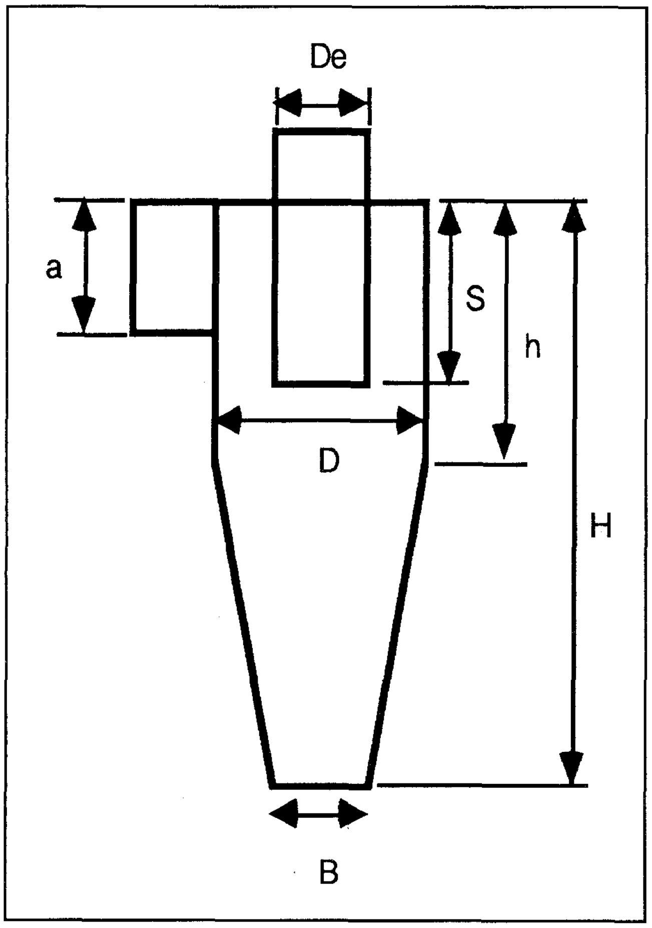

Figure 1. Cyclone geometry.

The purpose of this paper is to develop an effective cyclone simulator under Excel. A detailed cyclone mathematical model is presented as well as the philosophy, structure and information on the use of the Excel-based simulator.

Problem definition

Cyclones used in industry as dust collectors for particles greater than 5 μm in diameter. We shall suppose that a system of cyclones in parallel is used for removing some solid particles from a gas stream.

The cyclone system characteristics are as follows:

☐ N: Number of cyclones in the system, in parallel.

☐ D: Cyclone diameter, m.

☐ $\underline{G}$: Vector of dimension = 7, containing the cyclone geometric characteristics (Figure 1), *i.e.*:
  - a: Gas entry height, m.
  - b: Gas entry width, m.
  - D_e: Gas outlet diameter, m.
  - S: Gas outlet height, m.
  - h: Cyclone cylinder height, m.
  - H: Cyclone overall height, m.
  - B: Dust outlet diameter, m.

The input gas characteristics are as follows:

☐ Q: Gas flow rate, m^3/h.

☐ C_{in}: Particle loading, g/m^3.

☐ $R_{in}(d_p)$: Particle size distribution.

The output gas characteristics are as follows:

☐ C_{out}: Particle loading, g/m^3.

☐ $R_{out}(d_p)$: Particle size distribution.

The two following typical problems can thus be defined:

☐ *The design problem:* Given the gas input characteristics and one of the gas output characteristics (for example, C_{out} or one point from $R_{out}(d_p)$), we need to calculate the optimal cyclone system characteristics.

☐ *The operational problem:* Given the cyclone system characteristics and the gas input characteristics, we need to calculate the gas output characteristics.

Process model

The following model is based on the efficiency approach of Iozia

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and Leith[1] and on the Dirgo pressure drop work,[2] as summarised by Ramachandran *et al.*[3]

The diameter d_{50} of the particle collected with 50% efficiency is calculated from

$$d_{50} = \left[\frac{9\mu(Q/N)}{\pi\rho_p z_c U_{tmax}^2}\right]^{0.5} \tag{1}$$

where Q is the gas flow through the cyclones, N is the number of cyclones in parallel, μ is the gas viscosity, ρ_p is the particle density, U_{tmax} is the maximum tangential gas velocity, and z_c is the core length.

The maximum tangential gas velocity U_{tmax} is calculated from

$$U_{tmax} = 6.1U\left(\frac{ab}{D^2}\right)^{0.61}\left(\frac{D_e}{D}\right)^{-0.74}\left(\frac{H}{D}\right)^{-0.33} \tag{2}$$

where the gas tangential velocity U is defined by

$$U = \frac{Q/N}{ab} \tag{3}$$

The core length z_c and the core diameter d_c are calculated as follows:

$$\begin{aligned} z_c &= (H-S) - \left[\frac{H-S}{(D/B)-1}\right][(d_c/B)-1] && \text{for } d_c > B \\ &= (H-S) && \text{for } d_c < B \end{aligned} \tag{4}$$

$$d_c = 0.47D\left(\frac{ab}{D^2}\right)^{-0.25}\left(\frac{D_e}{D}\right)^{1.4} \tag{5}$$

The collection efficiency η_i of particles with diameter d_{pi} is calculated from

$$\eta_i = \frac{1}{1 + (d_{50}/d_{pi})^\beta} \tag{6}$$

where:

$$\ln\beta = 0.62 - 0.87\ln\left(\frac{d_{50}}{100}\right) + 5.21\ln\left(\frac{ab}{D^2}\right) + 1.05\left[\ln\left(\frac{ab}{D^2}\right)\right]^2 \tag{7}$$

where d_{50} is in cm. The average efficiency η is calculated from

$$\eta = \frac{\sum(\eta_i \Delta W_i)}{\sum(\Delta W_i)} \tag{8}$$

where ΔW_i is the mass fraction of the particles with average diameter d_{pi}.

Thus the output particle loading C_{out} is

$$C_{out} = (1 - \eta)C_{in} \tag{9}$$

The pressure loss Δp is estimated from

$$\Delta p = 0.5\Delta H \rho_g U^2 \tag{10}$$

where

$$\Delta H = 20\left(\frac{ab}{D_e^2}\right)\left[\frac{S/D}{(H/D)(h/D)(B/D)}\right]^{1/3} \tag{11}$$

Thus the required fan power E_c is

$$E_c = \frac{Q\Delta p}{E_f} \tag{12}$$

where E_f is the fan efficiency.

The required mass of cyclone construction material M_c is given as a function of the cyclone geometry:

$$M_c = 1.2\rho_c\left[\pi\frac{D+B}{2}\left(\frac{(D-B)^2}{4} + (H-h)^2\right)^{0.5} + \pi Dh + \pi D_e S + \frac{\pi}{4}(D^2 - D_e^2) + \frac{\pi}{4}B^2\right]\Delta x \tag{13}$$

where Δx is the wall thickness, and ρ_c is the density of the construction material.

The annual energy cost C_{op} and the installation cost C_{eq} can be estimated using the equations:

$$C_{op} = N t_y E_c C_E \tag{14}$$

$$C_{eq} = C_M N^\gamma M_c^\delta \tag{15}$$

where t_y is the annual time of operation, C_E is the energy unit cost, and C_M, γ and δ are constants.

Topics relative to cyclone cost analysis have been presented by Benitez.[4] Experienced designers can use their corrected functions for cost analysis. For example, the following equation has proved to be suitable for Greek conditions:

$$C_{eq} = 45N^{1.10}M_c^{0.85} \tag{15a}$$

where the installation cost is calculated in US dollars, and the mass of the construction material is in kilograms. The above cost includes carbon steel cyclones, support stand, fan, motor and hopper for collecting the captured dust.

The annual total cost can be estimated from

$$C_{TL} = C_{op} + eC_{eq} \tag{16}$$

where e is the depreciation.

The optimal system is obtained by minimisation of the annual total cost (objective function):

$$\min(C_{TL}) \tag{17}$$

The following geometric constraints should be added to the mathematical model:

$$a < S \tag{18}$$

$$S + z_c < H \tag{19}$$

$$S < h \tag{20}$$

$$h < H \tag{21}$$

Also, the pressure loss Δp and the air flow rate per cyclone Q/N should not exceed some specifications:

$$\Delta p < \Delta p_{max} \tag{22}$$

$$Q/N < Q_{max} \tag{23}$$

In addition, the gas velocity U should not be much greater than the entrainment velocity U_s:

$$U < \lambda U_s \tag{24}$$

where $1.20 < \lambda < 1.35$, and the entrainment velocity U_s is calculated from

$$U_s = 2400\frac{\mu\rho_p}{\rho_g^2}D^{0.2}\frac{(b/D)^{1.2}}{[1-(b/D)]} \tag{25}$$

In conclusion, the mathematical model consists of one objective function (Expr. 17), 16 equality constraints (Eqns. $1-16$) and seven inequality constraints (Exprs. $18-24$). The problem can be solved sequentially (without iterations) for the operation problem described in the previous paragraph. In this case the following variables are given:

☐ Cyclone characteristics: N, D, G.

☐ Input gas characteristics: $Q, C_{in}, R_{in}(d_p)$.

Simulator outline

The simulator has been developed on an Excel workbook, and has the architecture presented in Figure 2. Four different units are distinguished, with each one developed in a different sheet:

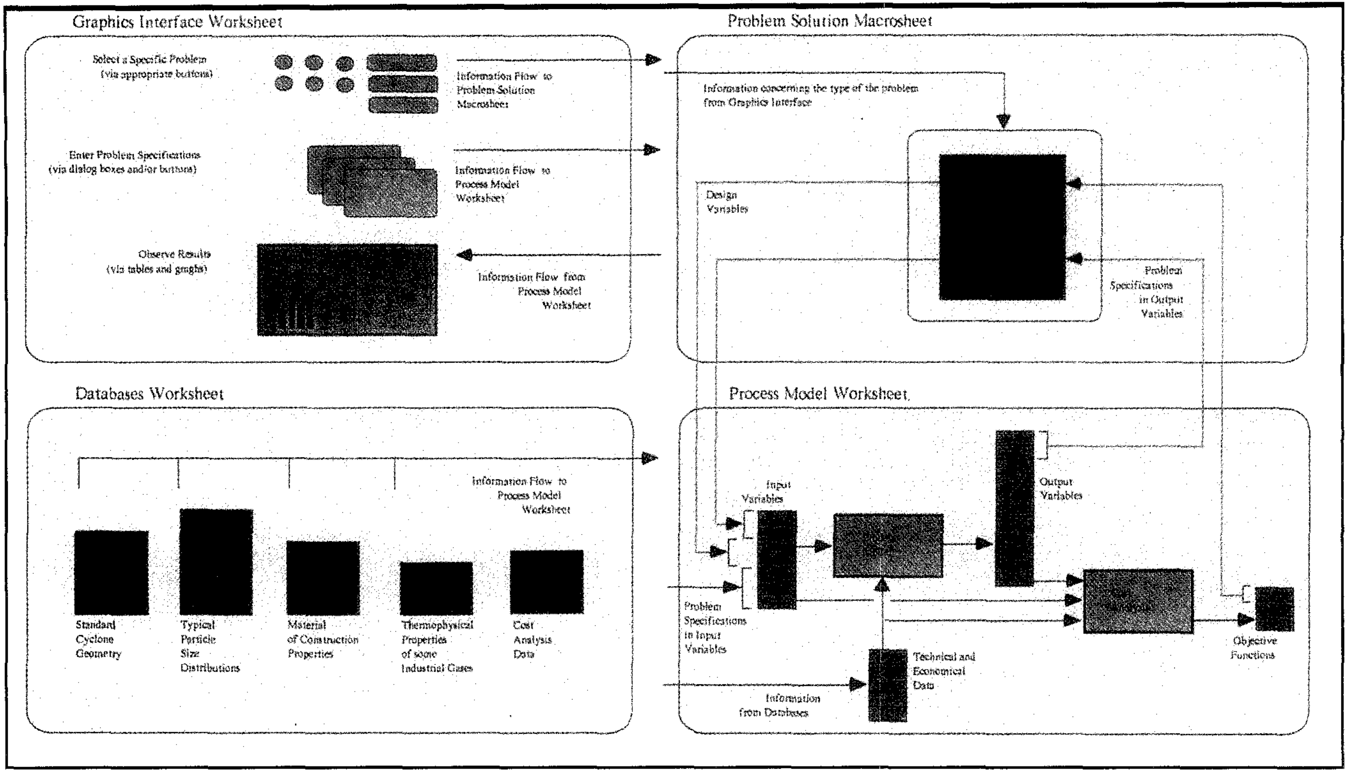


Figure 2. Simulator architecture.

Process model worksheet

This is the heart of the system calculations. It contains the process model exactly in the form of the operational problem described above. Since no iterations are needed, the model solution uses only worksheet functions. When any changes in input variables (free variables) occur, the solution is obtained automatically on this worksheet.

Problem solution macrosheet

Since the use of the simulator requires the solution of different problems, some different problems have been formulated. Their solution is based on the operational problem of the Process Model worksheet above, and uses the Solver or the Goal Seek utilities of Excel via a Visual Basic program, to obtain the solution.

Databases worksheet

This sheet contains all the data needed for calculations in the form of Data Lists. These data can be extended or modified via appropriate dialogue boxes. The following databases have been developed:

- ☐ *Standard cyclone geometry:* This contains the geometry (*i.e.* the $\underline{G}$ vector) of the following standard configurations: Stairmand High Efficiency, Stairmand High Throughput, Swift General Purpose, Swift High Efficiency, Swift High Throughput, Lapple General Purpose, Stern Consensus etc. Any other configuration can be easily inserted via dialogue boxes.
- ☐ *Typical particle size distributions:* This contains some typical particle size distributions for industrial gases (superfine, fine, coarse). Experimental particle size analysis data can be added, as well as fitted empirical functions.
- ☐ *Thermophysical properties of some industrial gases and some materials for cyclone construction:* Here variations of density and viscosity with temperature for some industrial gases are incorporated. The densities of some materials of construction are also included.
- ☐ *Cost analysis data:* This includes material cost, electricity cost, and also typical values of some economical magnitudes (such as depreciation).

Graphics interface worksheet

This is the only method for man-machine communication. The main menu is shown in Figure 3. The graphics interface essentially consists of three parts:

- ☐ *Problem specifications:* The specifications and the required data for the problem to be solved are entered by the user or estimated from the databases. Data are inserted via dialogue boxes or buttons for changing some important magnitudes.
- ☐ *Problem type selection:* The type of problem to be solved is selected via buttons. Some common problems are:
  - The operational problem already described.
  - The design problem already described.
  - Some modified design problems, such as for example, estimating the optimal cyclone shape for a given design problem.
- ☐ *Results presentation:* The results are obtained automatically, and are presented in the form of tables or graphs. The most important graphs in the interface are:
  - The obtained cyclone efficiency versus the particle size.
  - The particle size distribution in the input and output streams.

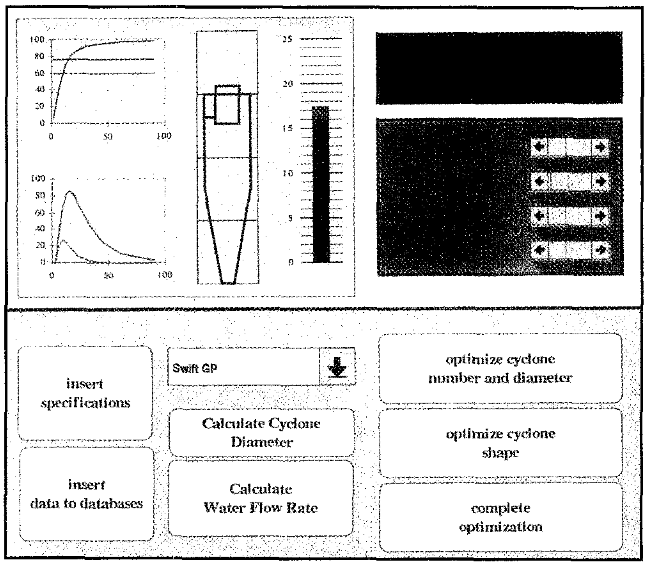


Figure 3. Simulator interface.

Table 1. Geometric parameters for various cyclones.

	a/D	b/D	D_e/D	S/D	h/D	H/D	B/D
Standard shape:							
Stairmand HE	0.50	0.20	0.50	0.50	1.50	4.00	0.38
Swift HE	0.44	0.21	0.40	0.50	1.40	3.90	0.40
Lapple GP	0.50	0.25	0.50	0.63	2.00	4.00	0.25
Swift GP	0.50	0.25	0.50	0.60	1.75	3.75	0.40
Stern C	0.45	0.20	0.50	0.63	0.75	2.00	0.40
Stairmand HT	0.75	0.38	0.75	0.88	1.50	4.00	0.38
Swift HT	0.80	0.35	0.75	0.85	1.70	3.70	0.40
Range of variation:							
min	0.44	0.20	0.40	0.50	0.75	2.00	0.25
max	0.80	0.38	0.75	0.88	2.00	4.00	0.40
Optimum shape:							
for 5 μm	0.50	0.38	0.47	0.50	2.00	4.00	0.40
for 10 μm	0.80	0.38	0.75	0.80	2.00	3.95	0.40
for 15 μm	0.80	0.38	0.75	0.80	1.78	2.32	0.40

Table 2. Required diameter and cost of the various cyclones in Table 1 to match the design specifications of the examined problem.

	D	C_{eq}	C_{op}	C_{TL}
d_p = 5 μm:				
Optimum	1.33	13.1	12.0	14.6
Stairmand HE	1.47	14.9	15.0	18.0
Swift GP	1.37	13.2	16.0	18.7
Swift HE	1.67	18.0	15.5	19.1
Swift HT	0.90	6.9	19.3	20.6
Lapple GP	1.35	13.3	18.8	21.4
Stairmand HT	0.90	7.1	20.2	21.6
SternC	1.29	7.4	47.6	49.1
d_p = 10 μm:				
Optimum	1.43	15.8	2.6	5.7
Swift HT	1.42	14.9	3.2	6.1
Stairmand HT	1.42	15.3	3.3	6.4
Swift GP	2.06	26.5	3.1	8.4
Stairmand HE	2.19	29.5	3.0	8.9
Lapple GP	2.03	26.5	3.7	9.0
Swift HE	2.48	35.4	3.2	10.2
SternC	1.92	14.6	9.7	12.6

- The cyclone sketched to scale.
- The operating and installation costs.

Since these graphs are updated automatically, the user has at his/her disposal all the information needed for sizing, sensitivity analysis, or comparison of alternative solutions. For example, when the simulator is asked for a shape optimisation, the cyclone sketch is changed 'on-line' as the Solver passes through various solutions towards the optimal one. The sensitivity analysis is also a useful animation since, when the values of a free variable are changed continuously via a button, all the graphs are automatically updated.

Case study

The proposed simulator was used to solve several typical design problems. We will consider here the design of a cyclone for removing 60% of the dust from a gas stream with a gas flow rate of 30,000 m^3/h and a dust loading of 0.10 g/m^3. The gas and dust thermophysical properties are known, and also that the particle size distribution is log-normal with an average particle diameter of 5 μm and a standard deviation of 2 μm.

Seven different standard cyclones were examined. Table 1 contains the values for the geometric parameters for these standard cyclones. These values determine a range of variation for the geometric parameters, and this range is used as the bounds in the shape optimisation problem. The optimal shape parameters obtained by the simulator are presented in Table 1. The optimal shape is also calculated for the cases where the average dust particle size is 10 and 15 μm.

Table 2 presents the required diameter and cost for the cyclones of Table 1 to match the problem specifications. Two different cases for average particle sizes of 5 and 10 μm are presented. The cost refers to installation cost and to annual operating cost, both in thousands of US dollars. The corresponding values of the objective function are also presented. This is the annual operating cost plus the annual depreciation of the installation cost.

The above results are also shown in Figures 4 and 5, which show (*a*) a cyclone sketch to scale, (*b*) the annual depreciation of the installed cost as well as the annual energy cost, (*c*) the particle collection efficiency plotted versus the particle diameter, as well as the average efficiency, which is 60% if the design specifications are matched, and (*d*) the inlet and outlet differential loading plotted versus the particle diameter.

The main conclusion is that the most promising standard cyclone is the Stairmand High Efficiency one, in the case where the average particle diameter is 5 μm. This solution requires an installation cost of US$14,900 and an annual operating cost of US$15,000. The corresponding value of the objective function is US$18,000. The cyclone with the optimum shape requires an installation cost of US$13,100 (*i.e.* 12% less than the best standard cyclone), and an annual operating cost of US$12,000 (*i.e.* 20% less than that of the best standard cyclone). The value of the objective function is US$14,600, that is 19% less than the best standard cyclone.

These values indicate the important role of the shape optimisation. It must be noted that the geometric parameters were varied only within the range specified in Table 1. Most of the optimal values of the geometric parameters are on the limits, which suggests further optimisation if these limits are relaxed.

For the case in which the average particle size is larger (for example, 10 μm), the separation is much easier. This is why high-throughput standard cyclones are preferred to those of high efficiency; and since high-throughput cyclones have lower operating costs, the separation task is much cheaper. The best standard cyclone is now the Swift High Throughput (see Table 2). The cyclone with the optimal shape results in a value of the objective

Figure 4. Accumulated results for the cyclone simulator.

The cases presented correspond to those in Table 2 for $d_p = 5\ \mu m$. For each case the following are presented:

- A sketch of the cyclone (to scale).
- Total installed cost and annual operating cost (in US$ 000), as well as average efficiency.
- Particle collection efficiency plotted versus particle diameter.
- Inlet and outlet differential loadings plotted versus particle diameter.

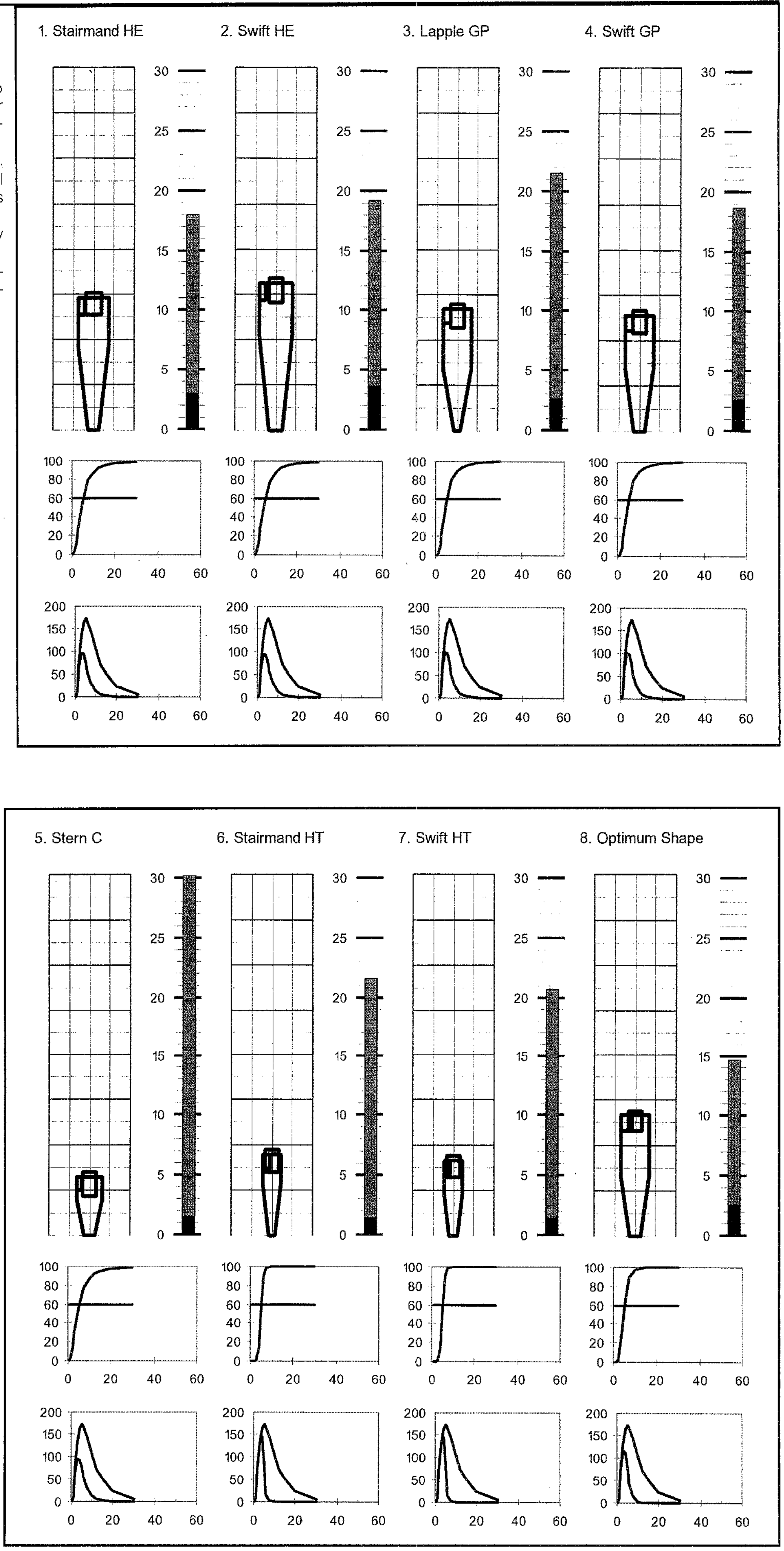
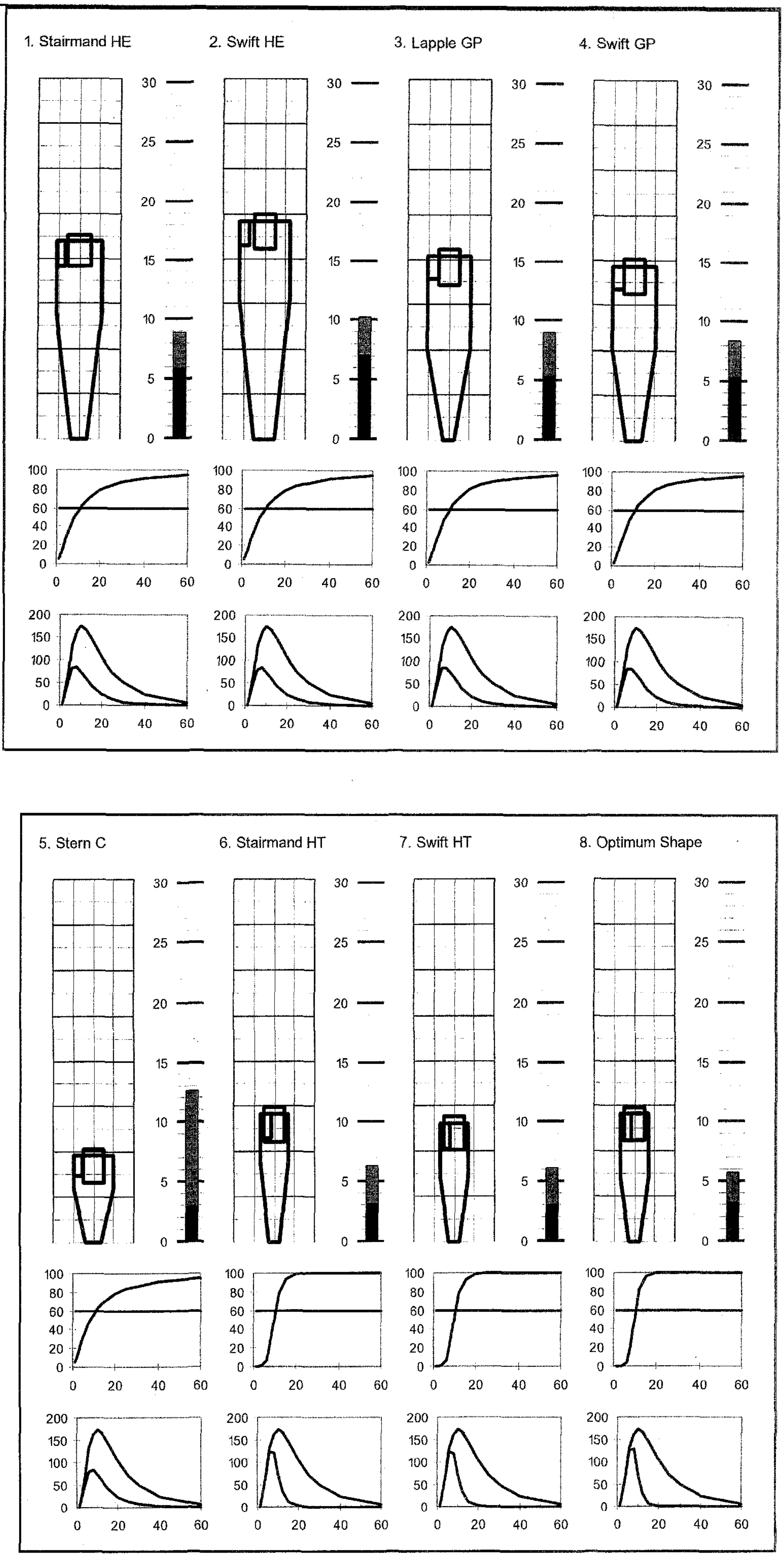


Figure 5. Accumulated results for the cyclone simulator.

The cases presented correspond to those in Table 2 for $d_p = 10\ \mu m$.



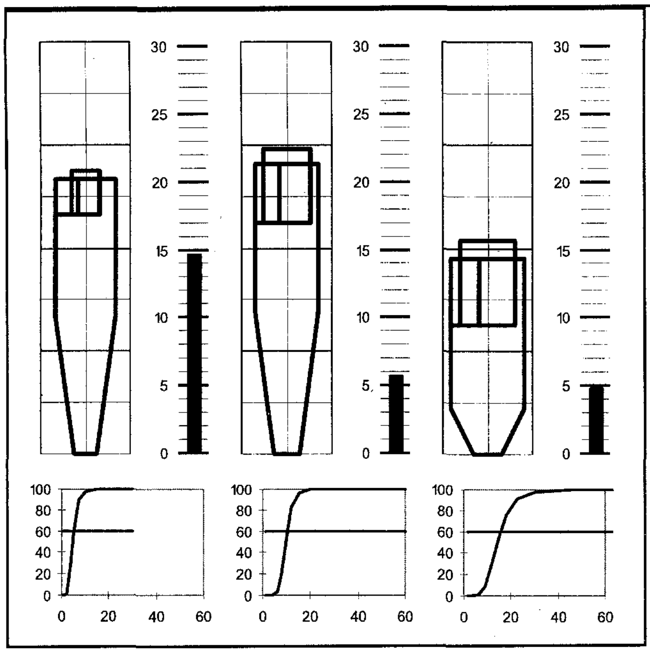


Figure 6. Cyclones of optimum shape for average particle diameters of 5, 10 and 15 μm, respectively.

function which is 6.5% less than that of the best standard cyclone. This suggests that the shape optimisation is more important in difficult separation problems.

The role of the cyclone shape in matching different separation problems is also visualised in Figure 6, in which the optimal cyclones are presented for the cases where the average particle size is 5, 10 and 15 μm.

We will now examine an operational problem, and suppose that a Swift General Purpose cyclone 1.37 m in diameter is selected. (Table 2 suggests that the Swift General Purpose cyclone performs relatively well for both cases of 5 and 10 μm.) The question is, how does it operate at conditions different to those of the design? The answer is given in Figure 7, in which the collection efficiency and the operating cost are shown plotted versus the average particle diameter and the gas flow rate. The design conditions are represented by the marked point.

We will now consider again the design problem in a more general approach. Theoretically, every cyclone of a given geometry can satisfy the required separation by adjustment of its diameter. As the cyclone diameter is reduced the collection efficiency improves, the installation cost is reduced and the operating cost increases; consequently the objective function depends on the trade-off between installation and operating cost. The relationship between the required cyclone diameter and the desired efficiency expresses in some way the technical performance of a cyclone of given shape. The relationship between the objective function and the the desired efficiency expresses the economic valuation of the given cyclone. Such design curves are presented in Figure 8 for the design problem examined here. Some standard configurations, as well as the optimum ones of Table 2, are presented. The curves in Figure 8 are drawn for different average particle diameters and different gas flow rates. The results refer to various collection efficiencies instead of the results of Table 2 and Figures 4 and 5, which refer only to a collection efficiency of 60%. Thus these curves are more general in nature.

It is verified here that the Stairmand High Efficiency cyclone is the best of the standard cyclones for a collection efficiency of 60%, but other cyclones dominate when a different collection efficiency is required (see Figure 8 for a gas flow rate of 30,000 m^3/h and an average particle diameter of 5 μm). For example, the Swift High Throughput cyclone is the best when a 20% collection efficiency is required; the cyclone with optimal shape for a collection efficiency of 60% is no longer optimal, and a new optimisation is required.

A complete set of such diagrams for various air flowrates, particle sizes, energy costs and installation costs can prove useful for the design engineer. Such diagrams can be easily generated by the simulator, but the presentation is beyond the scope of this paper.

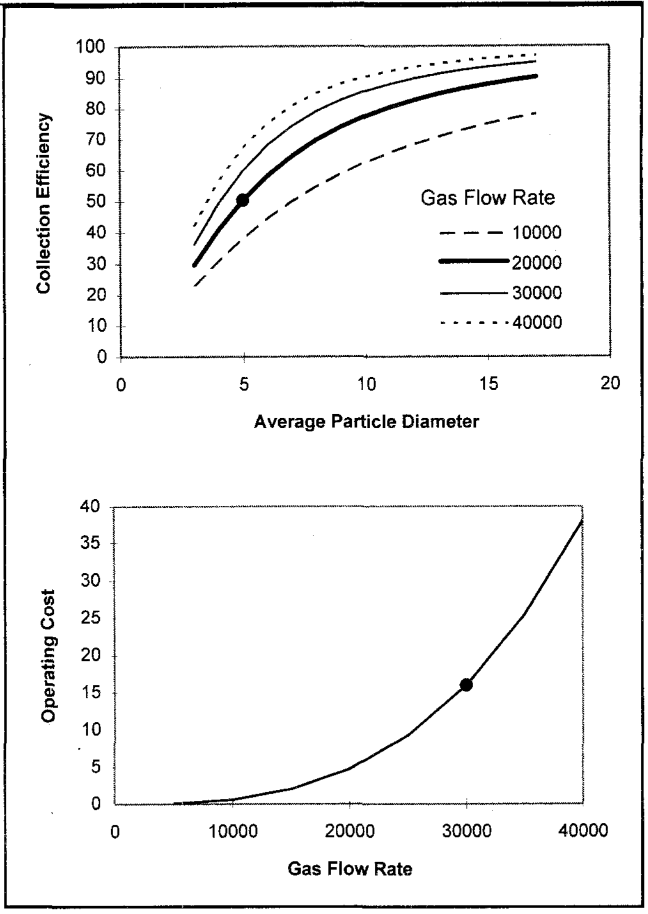


Figure 7. Cyclone operation under conditions different to those of the design.

Conclusion

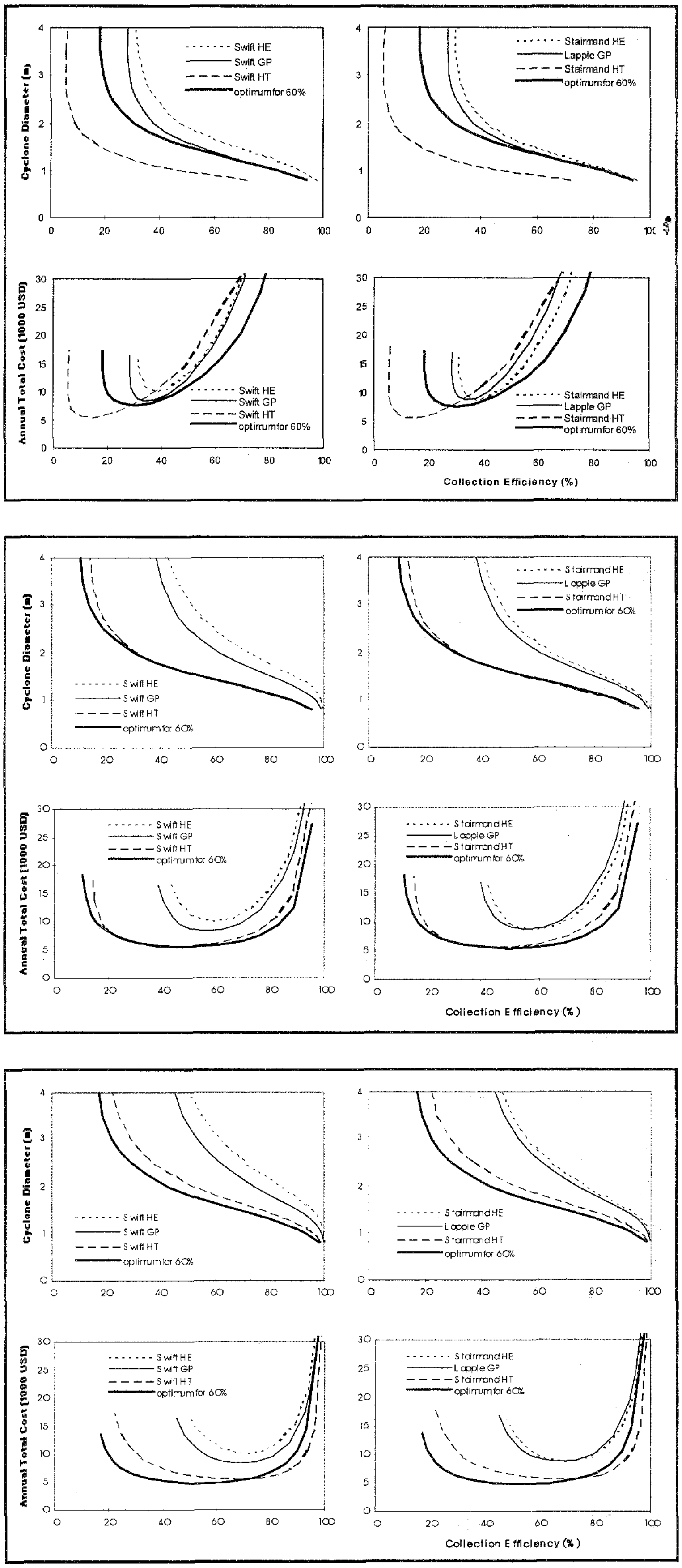
The problems discussed here have proved the simplicity with which alternative solutions for a specific problem can be derived using the simulator. It has also revealed the possibility of understanding the effect of various constructions or operating variables on the cyclone performance. Sensitivity analysis is clearly simple through the simulator. Any changes in input variables (process variables or technical and economical data) are automatically taken into account, and the new situation is immediately revealed. In addition, the simulator can be used for the construction of generalised design or operation curves, which could be useful in design and operational problems in engineering practice.

In conclusion, an effective cyclone simulator has been developed under Excel spreadsheet software. The simulator is based on a mathematical model from the literature, and uses the advantages of the Excel software. A powerful tool has been obtained for the design and operation of cyclone separation systems.

Nomenclature

a = Gas entry height, m
b = Gas entry width, m
B = Dust outlet diameter, m
C = Cyclone geometry parameter
C_E = Electricity cost, US$/kWh
C_{eq} = Total installation cost, US$
C_{in} = Particle loading of inlet gas, g/m^3
C_M = Construction material cost, US$/tonne
C_{op} = Annual operating cost, US$/yr
C_{out} = Particle loading of outlet gas, g/m^3
C_{TL} = Total annual cost, US$/yr
D = Cyclone diameter, m
d_c = Cyclone core diameter, m
D_e = Gas outlet diameter, m
d_p = Particle diameter, m or μm
d_{pi} = Average particle diameter of the ith fraction, m
d_{50} = Diameter of 50% collection, cut diameter, m
e = Depreciation

Figure 8. Design curves for the problem presented here. Gas flow rate: 30,000 m^3/h with average particle diameters of 5 μm (top), 10 μm (middle) and 15 μm (bottom).



Nomenclature (continued)

E_c = Fan power, kW
E_f = Fan efficiency, %
$\underline{G}$ = Vector containing cyclone geometric characteristics, m
h = Cyclone cylinder height, m
H = Cyclone overall height, m
M_c = Required mass of construction material, kg
N = Number of cyclones in the system
Q = Gas flow rate, m^3/h
Q_{max} = Maximum allowed gas flow rate, m^3/h
$R_{in}(d_p)$ = Particle size distribution of the inlet gas
$R_{out}(d_p)$ = Particle size distribution of outlet gas
S = Gas outlet height, m
T = Gas temperature, °C
t_y = Annual operating time, h/yr
U = Gas velocity, m/s
U_s = Entrainment velocity, m/s
U_{tmax} = Maximum tangential gas velocity, m/s
z_c = Cyclone core length, m

β = Parameter in Eqn. 6
γ, δ = Parameters in Eqn. 15
Δp = Total pressure loss
Δp_{max} = Maximum allowed total pressure loss
ΔW_i = Mass fraction of particles with average diameter d_{pi}
Δx = Wall thickness, m
η = Average collection efficiency
η_i = Collection efficiency for the fraction of particles with diameter d_{pi}
λ = Coefficient in Eqn. 24
μ = Gas viscosity, kg/ms
ρ_c = Density of construction material, kg/m^3
ρ_g = Gas density, kg/m^3
ρ_p = Particle density, kg/m^3

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