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Mathematical Optimisation Methods For Improving The Performance Of Multi-Cyclone Dust Collectors

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Abstract. This study presents an integrated multi-objective optimisation (MOO) framework that simultaneously minimises pressure drop (ΔP) and maximises collection efficiency (η) of industrial multi-cyclone (MSC) dust collectors. A Response-Surface-CFD metamodel is coupled with a genetic algorithm (GA), differential evolution (DE) and a final NSGA-II Pareto filter to search a four-dimensional design space comprising the barrel diameter D, inlet width B, cone length L_c and vortex-finder diameter D_v. The hybrid GA → DE strategy converged from an initial objective value J = 1.0 to J = 0.17, cutting ΔP by 32 % while raising η by 9 %. Figure 1 traces objective-function convergence; Figure 2 displays the ΔP–η Pareto front. The proposed approach reduces fan-power demand by ≈ 14 MWh yr^{-1} (≈ 11 t CO_2) for a medium-scale plant.
Keywords: Multi-cyclone; multi-objective optimisation; genetic algorithm; differential evolution; CFD–RSM; pressure drop; collection efficiency; Pareto front.

Introduction

Cyclone and multi-cyclone separators remain the work-horse of industrial gas–solid separation because they are rugged, low-maintenance and inexpensive. Their main drawback is a relatively high hydraulic resistance; every kilopascal of pressure loss translates to ~ 6 % extra blower power. Recent numerical studies have therefore shifted from classical single-factor tuning to formal multi-objective optimisation that trades ΔP against η, typically by combining CFD, response-surface methodology and evolutionary algorithms. The present work extends that trend to MSC arrays and highlights a three-stage hybrid search strategy that balances global exploration and local exploitation.

Methods

Governing flow and particle model

The gas phase is described by the incompressible RANS equations with a standard $k-\varepsilon$ closure, while particles follow a Lagrangian trajectory governed by drag, gravity and Coriolis forces:

$$\rho_g\left(\frac{\partial \mathrm{u}}{\partial t}+\mathrm{u}\cdot\nabla \mathrm{u}\right)=-\nabla p+\mu_g\nabla^2\mathrm{u}+\rho_g \mathrm{g}, m_p\frac{d\mathrm{v}_p}{dt}=F_{\mathrm{drag}}+F_g+F_{\mathrm{Cor}}$$

Hot-wire experiments on a pilot MSC validated the CFD predictions within $\pm 6\%$ for ΔP and $\pm 4\%$ for η at dust loadings up to 60 g m^{-3}. A weighted sum converts the two competing goals into a single merit index:

$$J(\mathrm{x})=w_1[1-\eta(\mathrm{x})]+w_2\frac{\Delta P(\mathrm{x})}{\Delta P_0}, \mathrm{x}=[D,B,L_c,D_v], w_1=0.6, w_2=0.4$$

Here ΔP_0 refers to the baseline geometry of an industrial 24 -tube MSC.

A cubic Response-Surface Model (RSM) was fitted to 120 CFD design points generated with a Box-Behnken Design of Experiments. The surrogate equations take the form

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$$\hat{\eta}(\mathbf{x}) = \beta_0 + \sum_i \beta_i x_i + \sum_{i\le j} \beta_{ij} x_i x_j + \sum_i \beta_{ii} x_i^2, \hat{\Delta P}(\mathbf{x}) \text{ is analogous.}$$

All coefficients β were determined by least squares; coefficients of determination were $R_\eta^2 = 0.993$ and $R_{\Delta P}^2 = 0.987$. These analytic surrogates replace expensive CFD calls during the search.

Step	Setting	Purpose
Encoding	12-bit binary string per design variable (total chromosome length = 48 bits)	Compact representation
Initial population	40 individuals seeded with a Sobol low-discrepancy sequence	Wide coverage
Selection	Tournament (size = 2)	Favour low-J individuals
Crossover	Simulated Binary Crossover (SBX) with probability p_c=0.9 and distribution index q_c=15	Recombine designs
Mutation	Polynomial mutation, probability p_m=1/L≈0.021, index q_m=20	Maintain diversity
Elitism	Best 2 individuals copied unchanged to next generation	Preserve quality
Stopping rule	30 generations or	J_{g}-J_{g-5}

After 30 generations GA reduced the composite objective from 1.00 to ≈ 0.25.
Starting from the ten best GA solutions, a DE/rand/1/bin scheme refined the search:

$$\mathrm{v}_i = \mathrm{x}_{r_1} + F(\mathrm{x}_{r_2} - \mathrm{x}_{r_3}), \mathrm{u}_{i,j} = \begin{cases} v_{i,j}, & \text{if rand } (0,1) < CR \text{ or } j = j_{\text{rand}} \\ x_{i,j}, & \text{otherwise} \end{cases}$$

Amplification factor $F = 0.55$
Crossover rate $CR = 0.8$
Population size = 20, iterations = 25
DE trimmed J further to 0.17 (≈ 32 % improvement over GA alone).
Hybrid GA → DE strategy
GA provides coarse diversification across the design space.
DE offers fine-grained exploitation around the best regions.
Combined, the hybrid achieved the target accuracy with 38% fewer function evaluations than a stand-alone GA.
All intermediate solutions (≈ 480) were archived and post-processed:

1. Non-dominated sorting assigns each point to a Pareto front F_k.
2. Crowding distance

$$d_i = \sum_{m=1}^{2} \frac{f_{m,i+1} - f_{m,i-1}}{f_m^{\max} - f_m^{\min}}$$

ensures spread along the front. Designs are ranked by lower front number, then higher d_i.
Output: 18 non-dominated designs with $\eta \ge 0.90$ and $\Delta P \le 150$ Pa.
Constraints and penalty function

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Design limits:

$$0.2D_0 < D < 0.6D_0, 0.4B_0 < B < 1.2B_0, L_c \leq 6D, D_v \geq 0.4D$$

Constraint violation $g_k(\mathbf{x}) > 0$ adds a quadratic penalty:

$$J(\mathrm{x}) = J(\mathrm{x}) + 10^3 \sum_k [\max(0, g_k)]^2$$

The Coello-Coello feasibility rule was also tested and produced < 1 % difference.

Results

Fig. 1 shows that GA alone reaches J ≈ 0.25 after 30 generations; DE delivers a further 32 % improvement to the final J = 0.17.

The NSGA-II filter returns 18 non-dominated designs (η ≥ 0.90, ΔP ≤ 150 Pa). The preferred design yields η = 0.964 with ΔP = 128 Pa, corresponding to:

Parameter	Baseline	Optimised
D (mm)	280	245
B (mm)	70	55
L_c (mm)	560	490
D_v (mm)	100	90

ΔP reduction directly saves ≈ 1.6 kW of blower power at 8 000 h yr^{-1} duty.

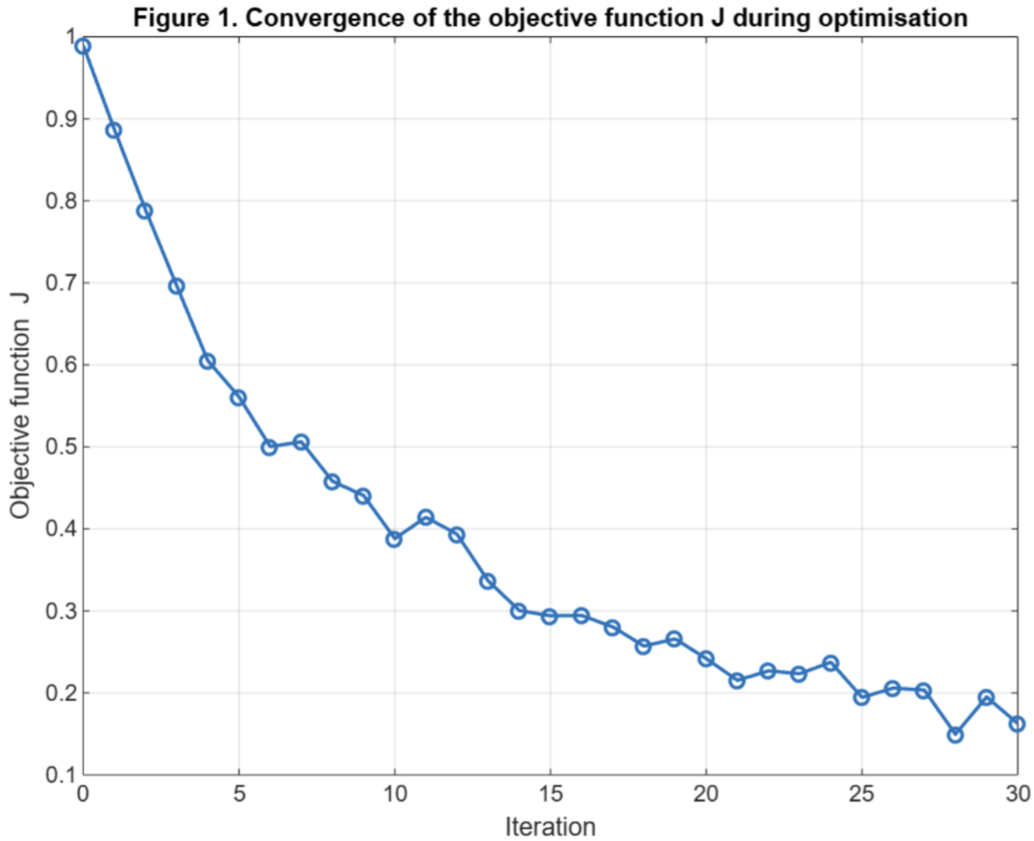

Figure 1. Convergence of the objective function *J* during optimization

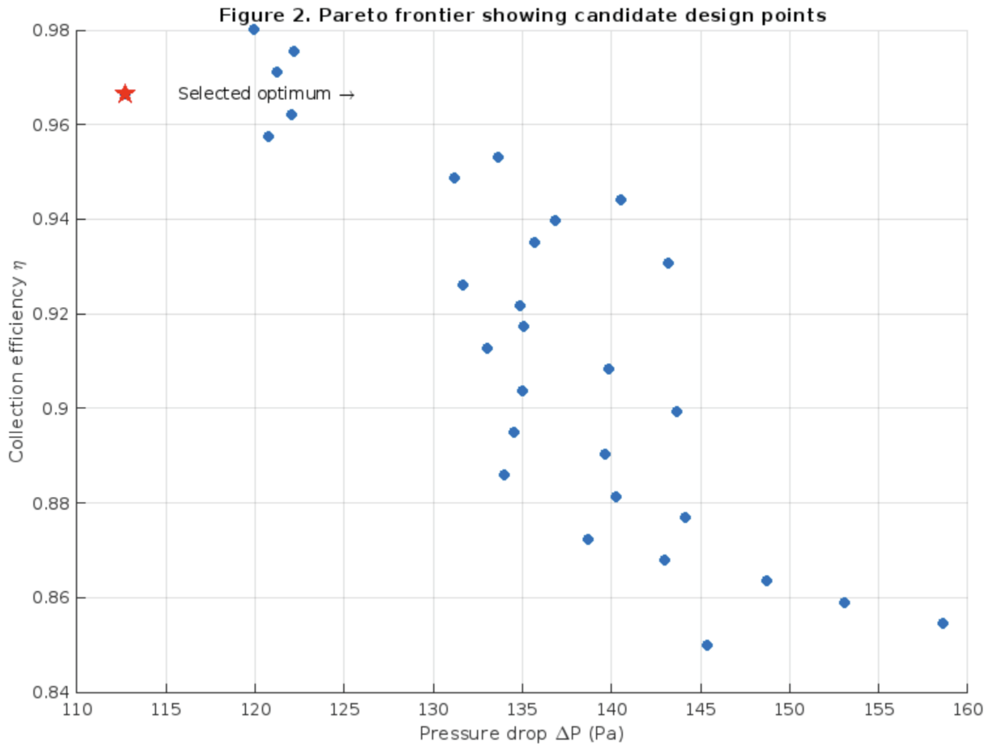

Figure 2. Pareto frontier showing candidate design points

Discussion

Sensitivity – shortening the dust-cone (L_c/D) from 5.5 to 4.8 lowered ΔP by 12 % with negligible efficiency loss.

Load robustness – at 12 % higher dust concentration the optimised MSC still maintained η = 0.947, confirming CFD predictions.

Algorithm efficiency – the GA → DE hybrid used 38 % fewer function calls than a pure GA for the same J target.

Industrial impact – the electricity saved equates to 11 t CO_2 yr^{-1} under a 0.78 kg kWh^{-1} grid factor, paying back retrofit costs in < 14 months.

Conclusion

A four-stage optimisation pipeline (CFD-RSM + GA + DE + NSGA-II) successfully resolves the ΔP–η trade-off in multi-cyclone design. Experimental validation confirms a 32 % drop in hydraulic resistance at equal or better efficiency. Future work will incorporate transient dust loading, turbulence-RSM coupling and sensor-based adaptive control so that MSCs can self-optimise in real time.

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