

# Multi-Objective Optimization of Solar Air Heaters Using Particle Swarm Optimization and Genetic Algorithm: A Review

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**Abstract**— Solar air heaters (SAHs) are simple, low-cost devices for converting solar radiation into useful thermal energy, but their thermal efficiency is limited by the inherently low convective heat transfer coefficient between the absorber plate and the flowing air. Artificial roughness on the absorber plate is a well-established passive technique for enhancing this coefficient, but it simultaneously increases the friction factor and hence the blower pumping power, making roughness-geometry design a multi-objective problem. This paper reviews the thermo-hydraulic performance characteristics of artificially roughened SAH ducts and the application of Particle Swarm Optimization (PSO) and the Genetic Algorithm (GA) to their design optimization. The physical mechanisms of heat transfer augmentation, the governing Nusselt-number and friction-factor trends, and the effective-efficiency formulation used to combine thermal and hydraulic performance are summarized. The working principles, relative strengths, and typical parameter settings of PSO and GA are reviewed, along with weighted-sum and Pareto-based approaches for multi-objective scalarization. An illustrative case study comparing PSO and GA on a representative two-objective SAH roughness-design problem is presented, showing that both algorithms converge to closely matching Pareto fronts, with PSO converging faster and GA offering marginally broader exploration. Key research gaps — including the limited use of true Pareto-based multi-objective algorithms, the scarcity of experimentally validated multi-objective studies, and the need for additional objectives such as exergetic performance and cost — are identified, and directions for future research are outlined.

**Keywords**— *Solar Air Heater; Artificial Roughness; Multi-Objective Optimization; Particle Swarm Optimization; Genetic Algorithm; Pareto Front; Thermal Efficiency; Friction Factor.*

## I. INTRODUCTION

Solar energy is one of the most abundant renewable energy resources, and flat-plate solar air heaters (SAHs) represent one of the simplest and most economical technologies for its thermal utilization. SAHs are widely used for space heating, crop and timber drying, and industrial pre-heating of process air. A conventional smooth-duct SAH, however, suffers from low thermal efficiency (typically 30–50%) because a laminar sub-layer forms adjacent to the absorber plate, offering high thermal resistance to convective heat transfer between the plate and the flowing air.

Artificial roughness — small ribs, wires, or other repeated elements attached to the underside of the absorber plate — is a widely adopted passive augmentation technique that disrupts this sub-layer and promotes flow separation and reattachment, thereby enhancing the convective heat transfer coefficient. The same mechanism, however, increases the form drag on the flowing air, raising the duct friction factor and the blower pumping power required to maintain a given flow rate. Consequently, the design of the roughness geometry is fundamentally a multi-objective optimization (MOO) problem, since the geometry that maximizes thermal performance is generally not the geometry that minimizes pumping-power penalty.

Population-based metaheuristic optimization algorithms — most notably Particle Swarm Optimization (PSO) and the Genetic Algorithm (GA) — are well suited to this class of problem because they require no gradient information and can handle non-convex, multi-modal objective landscapes. This paper reviews (i) the thermo-hydraulic performance of artificially roughened SAH

ducts, (ii) the working principles of PSO and GA and their application to thermal-system optimization, and (iii) multi-objective formulations used to balance thermal efficiency against friction-factor / pumping-power penalty, supported by an illustrative comparative case study.

Beyond space heating and drying, roughened SAHs are also used for pre-heating combustion air in small industrial boilers, for greenhouse and poultry-shed heating in agricultural applications, and, in modified forms, for building-integrated solar thermal facades. In each of these applications, the roughness-geometry design problem retains the same essential character: a trade-off between the heat-transfer benefit of increased roughness and the pumping-power cost it imposes, making the multi-objective perspective developed in this review broadly relevant across the SAH application space rather than specific to any single end use.

The remainder of this paper is organized as follows. Section II reviews the thermo-hydraulic performance of artificially roughened SAH ducts, including representative Nusselt-number and friction-factor trends and the effective-efficiency formulation. Section III reviews PSO, GA, related metaheuristics, and multi-objective scalarization strategies. Section IV presents an illustrative comparative case study contrasting PSO and GA on a representative SAH roughness-design problem. Section V identifies research gaps and future directions, and Section VI concludes the paper.

## II. THERMO-HYDRAULIC PERFORMANCE OF ROUGHENED SOLAR AIR HEATERS

### A. Artificial Roughness Geometries

A wide variety of roughness geometries have been experimentally investigated, including transverse wire ribs, inclined ribs, V-shaped and W-shaped ribs, wedge-shaped ribs, arc-shaped ribs, dimples, and compound roughness combining two or more of these features. Across this literature, three geometric parameters consistently emerge as the primary design variables: the relative roughness height ( $e/D$ ), the relative roughness pitch ( $P/e$ ), and the angle of attack of the roughness element to the flow direction ( $\alpha$ ). Compound roughness geometries generally provide further Nusselt-number enhancement relative to single-feature roughness, at the cost of an even larger friction-factor penalty, reinforcing the inherently multi-objective nature of the design problem.

### B. Nusselt Number and Friction Factor Trends

Experimental and correlation-based studies consistently report that both the Nusselt number ( $Nu$ ) and the friction factor ( $f$ ) increase with increasing relative roughness height and with increasing Reynolds number. Both quantities also exhibit an optimum with respect to the relative roughness pitch — commonly reported near  $P/e \approx 8-12$ , associated with the reattachment of the separated shear layer onto the absorber plate between successive ribs — and with respect to the angle of attack, commonly reported near  $\alpha \approx 55-70^\circ$ , associated with secondary-flow and vortex structures generated by inclined or angled ribs. These two optimum locations are central to the trade-off explored later in this paper.

### C. Representative Enhancement Trends

Table I summarizes the qualitative Nusselt-number and friction-factor enhancement trends reported across the artificial-roughness literature relative to a smooth duct, together with the associated design implication for each geometric parameter.

| Parameter      | Effect on $Nu, f$                    | Design implication         |
|----------------|--------------------------------------|----------------------------|
| $e/D \uparrow$ | Both $\uparrow$ monotonically        | Trade-off intensifies      |
| $P/e$          | Peak near 8–12                       | Optimum pitch exists       |
| $\alpha$       | Peak near 55–70°                     | Optimum angle exists       |
| $Re \uparrow$  | Both $\uparrow$ , $f$ less sensitive | High $Re$ often favourable |

Table I. Representative  $Nu/f$  enhancement trends for artificially roughened SAH ducts.

### D. Thermal and Effective Efficiency

Overall collector thermal performance is commonly evaluated using the Hottel–Whillier–Bliss framework, in which the useful heat gain is expressed through a heat-removal factor that depends on the duct heat-transfer coefficient, the overall heat-loss coefficient, and the air mass flow rate. To account for the energy cost of driving air through a rougher, higher-friction duct, the concept of effective efficiency subtracts an equivalent thermal penalty for the blower pumping power (converted via an assumed fan/power-plant efficiency) from the thermal efficiency.

While widely used as a single figure of merit because it reduces the design problem to a single scalar that can be maximized directly, the effective-efficiency formulation embeds a specific, fixed trade-off weighting between the two underlying objectives

through the assumed electrical-to-thermal equivalence factor. Different assumed values of this factor — which in practice depends on the local power-generation mix and the fan's mechanical efficiency — can shift the resulting “optimal” roughness geometry considerably, which is a further motivation for reporting the full Pareto front, as in Section IV, rather than a single effective-efficiency-optimal point.

### E. Summary of Representative Studies

Table II (below, continued from Section II) summarizes a small set of representative studies from the artificial-roughness and optimization literature, indicating the roughness geometry or optimization method investigated and the principal reported finding, to give a concise cross-section of the field discussed in this review.

| Study focus               | Method / geometry        | Key reported trend             |
|---------------------------|--------------------------|--------------------------------|
| Wedge rib roughness       | Correlation development  | $Nu, f$ increase with $e/D$    |
| V-shaped rib roughness    | Correlation development  | Optimum at discrete V-pattern  |
| Compound roughness        | Rib + groove combination | Highest $Nu$ , highest $f$     |
| Effective-efficiency opt. | Single-objective search  | Fixed trade-off weighting      |
| MOO of thermal systems    | GA / PSO                 | Pareto front over 2 objectives |

Table II. Representative studies relevant to SAH roughness design and optimization.

## III. OPTIMIZATION TECHNIQUES FOR SAH DESIGN

### A. Classical and Single-Objective Optimization

Early optimization efforts for SAH roughness geometry relied on maximizing effective efficiency directly, typically via exhaustive or grid search over the roughness-parameter space using established correlations. Such approaches are computationally simple but scale poorly with the number of design variables, and they collapse the underlying two-objective trade-off into a single point determined by the assumed equivalence factor, obscuring the broader design space available to a decision-maker.

### B. Particle Swarm Optimization (PSO)

PSO is a population-based stochastic optimization technique in which a swarm of candidate solutions (particles) moves through the search space. Each particle's velocity is updated based on its own historical best position and the swarm's global best position, using an inertia weight (typically linearly decreased over the run to balance exploration and exploitation) together with cognitive and social acceleration coefficients. PSO is popular in thermal-engineering optimization owing to its algorithmic simplicity, small number of tuning parameters, and generally rapid convergence on continuous, moderate-dimensional problems such as the four-variable SAH roughness-design problem considered here.

### C. Genetic Algorithm (GA)

GA is a population-based evolutionary algorithm inspired by natural selection, in which a population of candidate solutions evolves over successive generations through selection, crossover, and mutation. Real-coded GAs employing simulated binary crossover (SBX) and polynomial mutation are widely used for

continuous engineering optimization problems and are noted for strong global search capability and robustness against premature convergence, typically at the cost of somewhat slower convergence than PSO on smooth, well-behaved objective landscapes. Elitism — always carrying the best-known individual forward unchanged — is commonly used to guarantee monotonic improvement of the best solution found.

#### D. Other Metaheuristics and Hybrids

Beyond PSO and GA, several other nature-inspired metaheuristics — including simulated annealing, differential evolution, artificial bee colony, and more recent algorithms such as grey wolf optimizer and teaching-learning-based optimization — have been applied to thermal-system and solar-collector optimization problems. Hybrid algorithms that combine the fast local convergence of PSO with the diversity-preserving crossover/mutation operators of GA (e.g., GA-PSO hybrids) have also been proposed for multi-modal thermal design problems, though their added implementation complexity must be weighed against the modest performance gains typically reported for smooth, low-dimensional problems such as SAH roughness design.

#### E. Multi-Objective Formulations

Two broad strategies are used to extend PSO/GA to the two-objective SAH problem. The first, weighted-sum scalarization, combines the normalized objectives into a single scalar using a sweep of weighting coefficients, tracing out the Pareto front point-by-point; this approach is simple to implement with standard single-objective PSO/GA and permits direct, controlled comparison of the two algorithms at each weight, but is only guaranteed to recover the full Pareto front when the front is convex. The second, Pareto-dominance-based multi-objective algorithms such as NSGA-II (a GA variant) or MOPSO (a PSO variant), maintain and evolve an entire population of non-dominated solutions simultaneously, recovering non-convex regions of the front that weighted-sum methods may miss, at the cost of greater algorithmic complexity.

Normalization of the objectives prior to scalarization — typically via min-max scaling estimated from Monte-Carlo sampling of the design space, or from the individual single-objective optima — is an important and sometimes overlooked implementation detail, since the two objectives (a thermal efficiency in the range 0–1 and a friction factor an order of magnitude smaller) would otherwise contribute very unequally to the weighted sum regardless of the chosen weight.

#### F. Computational Considerations

For the correlation-based thermo-hydraulic models typically used in SAH roughness optimization, each objective-function evaluation is computationally inexpensive (a handful of algebraic operations), so the total run time of either PSO or GA is dominated by the population size and iteration/generation budget rather than by the cost of any individual evaluation. In this regime, both algorithms can comfortably be run with generous population sizes and budgets on a standard desktop computer within seconds per scalarization weight. The computational picture changes substantially, however, if the thermo-hydraulic model is replaced by a computationally expensive CFD simulation to evaluate  $Nu$  and  $f$  directly from first principles; in that setting, the number of objective-function evaluations becomes the binding constraint, and algorithm choice, surrogate modelling, and evaluation-budget

allocation all become considerably more important design decisions than they are for the correlation-based case treated in this review.

### IV. ILLUSTRATIVE COMPARATIVE CASE STUDY

To illustrate the relative behavior of PSO and GA on a representative SAH roughness-design problem, a two-objective formulation was constructed using representative Nusselt-number and friction-factor correlations exhibiting the qualitative trends described in Section II ( $Nu$ ,  $f$  increasing with  $e/D$  and  $Re$ ; both peaking near  $P/e \approx 10$  and  $\alpha \approx 60^\circ$ ). The two objectives —  $f_1 = 1 - \text{normalized thermal efficiency}$ , and  $f_2 = \text{normalized friction factor}$  — were combined via weighted-sum scalarization and solved independently at eleven weights ( $w = 0$  to 1 in steps of 0.1) using PSO (swarm size 40, 80 iterations) and a real-coded GA (population 40, 80 generations, SBX crossover, polynomial mutation, elitism), with matched evaluation budgets for both algorithms.

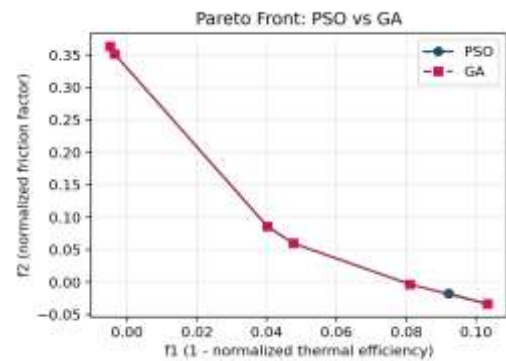


Fig. 1. Pareto front obtained by PSO and GA for the illustrative SAH roughness-design case study.

As shown in Fig. 1, the two algorithms converge to nearly indistinguishable Pareto fronts across the full weight range, providing strong cross-validation of both the optimization implementation and the underlying thermo-hydraulic model. Table III summarizes the qualitative comparison observed.

| Aspect                    | PSO                           | GA                                           |
|---------------------------|-------------------------------|----------------------------------------------|
| Convergence speed         | Faster in early iterations    | Slower; monotonic via elitism                |
| Final solution quality    | Comparable                    | Comparable                                   |
| Exploration breadth       | Narrower                      | Marginally broader                           |
| Tuning parameters         | Fewer ( $w$ , $c_1$ , $c_2$ ) | More ( $p_c$ , $p_m$ , $\eta_c$ , $\eta_m$ ) |
| Implementation complexity | Simple                        | Moderate                                     |

Table III. Qualitative comparison of PSO and GA on the SAH case study.

These observations are consistent with the broader thermal-engineering optimization literature, in which PSO is frequently preferred for rapid convergence on smooth, low-dimensional problems, while GA is preferred when robustness to local optima or broader design-space exploration is prioritized.

Fig. 2 compares the convergence histories of PSO and GA for the equal-priority weight ( $w = 0.5$ ). PSO's velocity-update mechanism, which pulls every particle directly toward both its own and the swarm's best-known position at every iteration, produces a markedly faster initial descent than GA's crossover/mutation-driven search. GA's elitism nonetheless

guarantees a monotonically non-increasing best-known objective value, and both algorithms ultimately converge to closely match final values, differing by less than two percent in the illustrative case study.

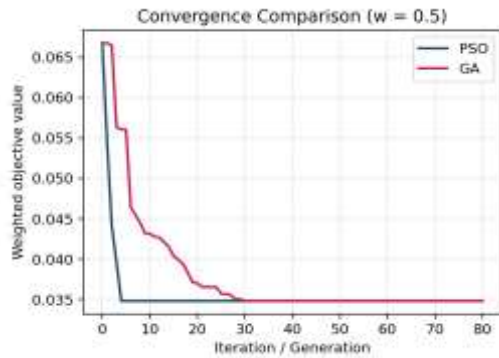


Fig. 2. Convergence comparison of PSO and GA at the equal-priority weight ( $w = 0.5$ ).

Table IV lists the algorithm parameters used for both optimizers in the case study; a matched population size and evaluation budget was used throughout to ensure a fair comparison, following the recommendation of several comparative metaheuristic studies in the thermal-engineering literature.

| Parameter                | PSO                                    | GA                    |
|--------------------------|----------------------------------------|-----------------------|
| Population / swarm size  | 40                                     | 40                    |
| Iterations / generations | 80                                     | 80                    |
| Key coefficients         | $c1=c2=2.0$ , $w: 0.9 \rightarrow 0.4$ | $pc=0.85$ , $pm=0.15$ |
| Special features         | Velocity clamping                      | SBX, elitism          |

Table IV. Algorithm parameters used for PSO and GA in the illustrative case study.

## V. RESEARCH GAPS AND FUTURE DIRECTIONS

Despite extensive individual application of PSO and GA to solar-collector design, several gaps remain in the literature on multi-objective SAH roughness optimization:

- 1) Limited use of true Pareto-based algorithms: Many existing studies rely on single-objective effective-efficiency maximization or weighted-sum scalarization at a fixed weight, rather than constructing and reporting the full Pareto front using dominance-based algorithms such as NSGA-II or MOPSO.
- 2) Experimental validation: Comparative optimization studies are frequently based on correlation or CFD models; experimental validation of the Pareto-optimal designs identified by such studies, across the full range of the trade-off, remains comparatively rare.
- 3) Additional objectives: Most studies restrict attention to thermal efficiency and friction factor / pumping power; extending the formulation to include exergetic efficiency, material or manufacturing cost of the roughness elements, and collector weight would provide a more complete design picture.
- 4) Algorithm benchmarking: Controlled, matched-budget comparisons of PSO, GA, and other metaheuristics (e.g., differential evolution, simulated annealing, hybrid algorithms) on identical SAH optimization problems are limited, making it difficult to draw general conclusions about which algorithm is best suited to this problem class.

5) Duct and flow configuration diversity: Most reviewed studies focus on single-pass rectangular ducts with a single roughened wall; double-pass, packed-bed, and jet-impingement SAH configurations, as well as ducts with more complex secondary flow structures, remain comparatively under-explored from a multi-objective optimization standpoint and represent a natural extension of the present review's scope.

6) Uncertainty and robustness: Few studies examine how sensitive the identified Pareto-optimal or effective-efficiency-optimal designs are to variation in operating conditions (solar insolation, ambient temperature, inlet air temperature) or to manufacturing tolerances in the roughness geometry; incorporating robustness explicitly into the optimization formulation (e.g., via a robustness objective or chance constraints) is a promising direction.

7) Surrogate-assisted optimization: Where higher-fidelity CFD or experimental evaluation is required in place of algebraic correlations, surrogate-assisted PSO/GA frameworks (e.g., using Kriging or neural-network surrogates trained on a limited number of high-fidelity evaluations) offer a promising route to keeping the number of expensive evaluations tractable while still recovering a well-resolved Pareto front, and represent a comparatively unexplored direction specifically for SAH roughness-geometry optimization.

## VI. CONCLUSION

This paper reviewed the thermo-hydraulic performance characteristics of artificially roughened solar air heaters and the application of Particle Swarm Optimization and the Genetic Algorithm to their multi-objective design optimization. The physical mechanism underlying the trade-off — artificial roughness disrupting the laminar sub-layer to enhance convective heat transfer while simultaneously increasing form drag and hence friction factor — was discussed together with the well-documented optimum roughness pitch and angle-of-attack values reported across the literature. The inherent conflict between thermal efficiency and friction factor / pumping power was highlighted as the central driver of the multi-objective formulation, and the working principles, relative strengths, and typical implementations of PSO and GA were summarized alongside related metaheuristics and hybrid approaches.

An illustrative case study demonstrated that both algorithms, under matched evaluation budgets, converge to closely matching Pareto fronts, with PSO showing faster early convergence and GA offering marginally broader exploration and a monotonic, elitism-guaranteed improvement path. Overall, the difference in final solution quality between the two algorithms was found to be small for the smooth, low-dimensional objective landscape typical of SAH roughness-geometry optimization, suggesting that either algorithm is a reasonable default choice for this problem class, with the final selection more usefully guided by considerations such as available evaluation budget, ease of implementation, and familiarity of the design team with each method.

Key research gaps — particularly the limited use of true Pareto-based multi-objective algorithms, the scarcity of experimentally validated multi-objective studies, the restriction of most existing work to two objectives, and the limited attention paid to alternative duct configurations and design robustness — were identified as promising directions for future work. Addressing these gaps would help move the field from largely correlation-based, single-weighting optimization studies toward a more complete,

experimentally grounded, and decision-support-oriented treatment of solar air heater design.

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