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A SCREENING METHOD FOR THE OPTIMAL SELECTION OF PLATE HEAT EXCHANGER CONFIGURATIONS

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Abstract - An optimization method for determining the best configuration(s) of gasketed plate heat exchangers is presented. The objective is to select the configuration(s) with the minimum heat transfer area that still satisfies constraints on the number of channels, the pressure drop of both fluids, the channel flow velocities and the exchanger thermal effectiveness. The configuration of the exchanger is defined by six parameters, which are as follows: the number of channels, the numbers of passes on each side, the fluid locations, the feed positions and the type of flow in the channels. The resulting configuration optimization problem is formulated as the minimization of the exchanger heat transfer area and a screening procedure is proposed for its solution. In this procedure, subsets of constraints are successively applied to eliminate infeasible and nonoptimal solutions. Examples show that the optimization method is able to successfully determine a set of optimal configurations with a minimum number of exchanger evaluations. Approximately 5 % of the pressure drop and channel velocity calculations and 1 % of the thermal simulations are required for the solution.
Keywords: plate heat exchanger, heat exchanger configuration, optimization, screening method.

INTRODUCTION

The plate heat exchanger (PHE) consists of a pack of gasketed corrugated metal plates, pressed together in a frame. The fluids flow through a series of parallel flow channels and exchange heat through the thin corrugated metal plates. The gasket design and the closed ports of the plates determine the fluid flow arrangement, which can be parallel, in series or one of several possible combinations of the two. The flow distribution, number of plates, type of gaskets and feed locations characterize the exchanger configuration.

To the author's knowledge there is no rigorous design method for PHEs in the literature. Shah and Focke (1988) have developed a detailed step-by-step design procedure for rating and sizing a PHE, which is however restricted to parallel flow arrangements. Optimization of the PHE flow arrangement to yield a minimum annual operating cost was studied by Jarzebski and Wardas-Koziel (1985). However, the use of approximate expressions to evaluate the PHE jeopardizes the optimization results.

Kandlikar and Shah (1989) analyzed several usual configurations and presented guidelines for selecting the appropriate flow arrangement from among those considered. It was verified that in most cases symmetric configurations with countercurrent flow yield the highest effectiveness. However, some applications require nonsymmetrical configurations

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due to differences in fluid heat capacities, and a more careful analysis is required for configuration selection from the heat-exchange and pressure-drop viewpoints.

In this work, an optimization method to select a detailed configuration that minimizes the heat transfer area of a PHE is presented. Rigorous simulation models are used for the exchanger evaluation, and a screening procedure is proposed to solve the problem. An example of optimization is presented to illustrate the efficiency of the proposed method.

CONFIGURATION CHARACTERIZATION

To characterize the PHE configuration, six distinct parameters are used: N_C, P^I, P^{II}, ϕ, Y_h and Y_f, which are described as follows:

N_C : Number of Channels

The PHE is represented by a row of channels (the space between two plates), numbered from 1 to N_C. The odd-numbered channels belong to side I, and the even-numbered ones belong to side II. N_C^I and N_C^{II} denote the numbers of channels on each side. If N_C is even, both sides have the same number of channels; otherwise side I has one more channel. Allowable values: 2, 3, 4, 5…

P^I and P^{II} : Number of Passes on Sides I and II

A pass is a set of channels where the main stream is split and distributed (see Fig. 1 for an example). For regular configurations, each side of the PHE has the same number of channels per pass (N^I and N^{II}). Passes with different numbers of channels are not usual (Kakaç and Liu, 1998). Parameters N_C, P^I and P^{II} are interrelated. Allowable values for P^I and P^{II}: respectively from the factorization of N_C^I and N_C^{II}.

ϕ : Feed Connection Relative Location

The feed connection of side I is set arbitrarily in channel 1 at coordinate η=0. The relative position of the feed of side II is given by parameter ϕ, as shown in Fig. (1) (Pignotti and Tamborenea, 1988). Allowable values: 1, 2, 3 and 4.

Y_h : Hot Fluid Location

This binary parameter assigns the fluids to the exchanger sides. If Y_h = 1, the hot fluid is on side I, and the cold fluid on side II. Otherwise, Y_h = 0.

Y_f : Type of Flow in Channels.

This binary parameter defines the type of flow inside the channels, which can be straight or crossed depending on the gasket type (Fig. 1). The crossed flow avoids the formation of stagnation areas, but the straight flow type is easier to assemble. It is not possible to use both types together. If Y_f = 1, then the flow is crossed in all channels. If Y_f = 0, the flow is straight in all channels.

The six parameters can represent any regular configuration and an example of configurations for a nine-plate PHE is shown in Fig. (2). For any given number of channels, N_C, the five remaining parameters have a finite set of allowable values, which limits the number of possible configurations, as shown in Fig. (3). The disperse pattern is due to the variation in the number of integer factors of N_C^I and N_C^{II}. For the range of number of channels between 2 and 500 there are 284,976 different configurations.

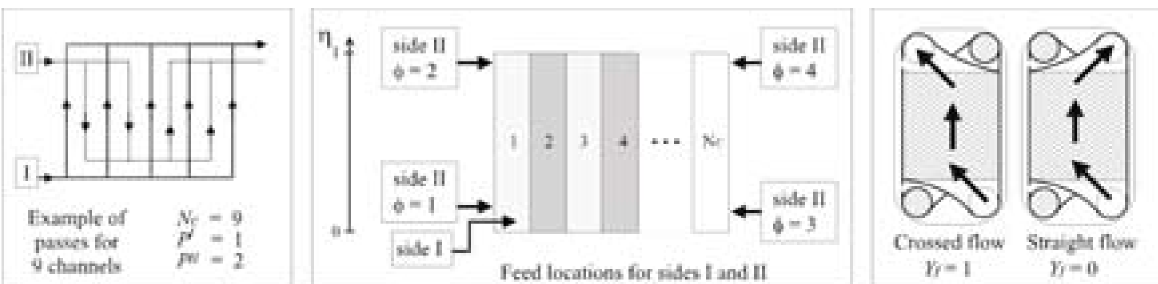

Figure 1: Spatial definition of parameters P^I, P^{II}, ϕ and Y_f.

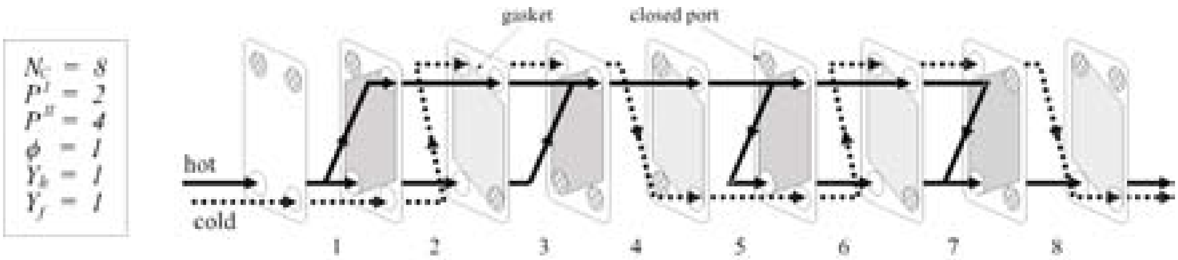

Figure 2: Example of configuration for a PHE with nine plates (eight channels).

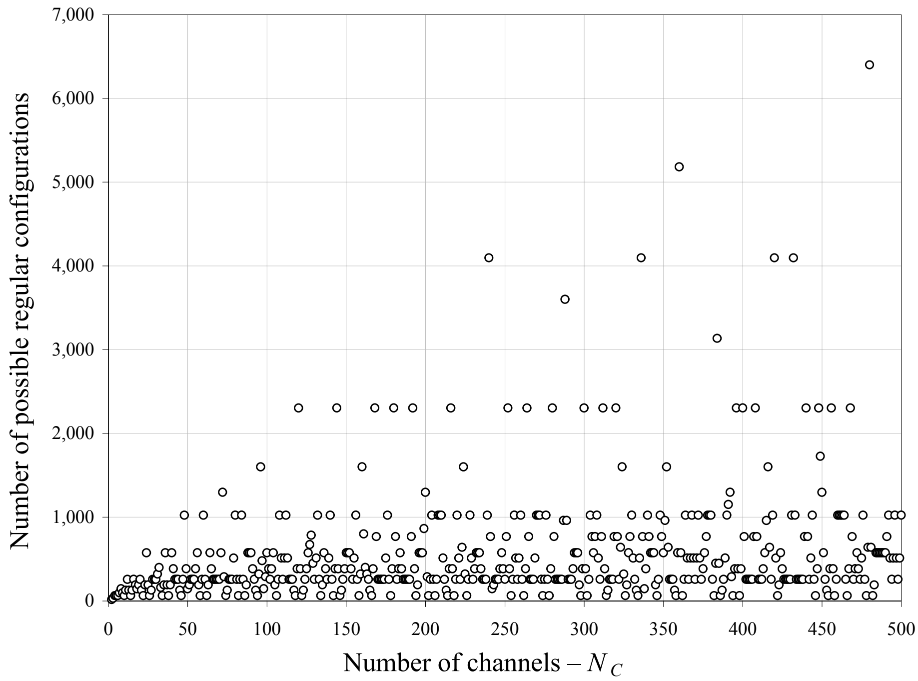

Figure 3: Number of possible regular configurations as a function of the number of channels.

Table 1: Identification of equivalent configurations for a given value of N_C and Y_f.

N_C	(P^I/P^{II})	Groups of equivalent values of ϕ	Reduction in the number of simulations
odd	(1/1) ; (1/odd) ; (odd/1)	{1, 3}; {2, 4}	50%
	(1/even) ; (even/1)	{1, 2, 3, 4}	75%
	(odd/odd) ; (even/even)	{1}; {2}; {3}; {4}	0%
	(odd/even) ; (even/odd)	{1, 2}; {3, 4}	50%
even	(1/1) ; (1/odd) ; (odd/1)	{1h, 3h, 1c, 3c}; {2h, 4h, 2c, 4c}	75%
	(1/even)h	{1h, 4h, 2c, 4c}; {2h, 3h, 1c, 3c}	75%
	(even/1)h	{1h, 3h, 2c, 3c}; {2h, 4h, 1c, 4c}	75%
	(odd/odd) ; (even/even)	{1h, 1c}; {2h, 2c}; {3h, 3c}; {4h, 4c}	50%
	(odd/even) ; (even/odd)	{1h, 2c}; {2h, 1c}; {3h, 3c}; {4h, 4c}	50%

Note: When N_C is even, "h" denotes $Y_h = 1$ and "c" denotes $Y_h = 0$.
When N_C is odd, equivalent configurations have the same value for Y_h.

Equivalent Configurations

For a given value of number of channels and a fixed type of flow, the existence of equivalent configurations (that have the same thermal effectiveness and pressure drops) is possible. Identification of equivalent configurations is important to avoid unnecessary exchanger evaluations. The equivalence of two or more configurations occurs due to the property of flow reversibility (Pignotti & Tamborenea, 1988), to the presence of single pass or to geometrical similarity (the configuration can be freely rotated or mirrored).

A methodology to detect equivalent configurations is shown in Tab. (1). For each set of N_C, P^I, P^{II} and Y_f there are groups of values for parameter ϕ that result in equivalent configurations. In the case of even-numbered N_C, there may be equivalency between $Y_h = 0$ and $Y_h = 1$ because sides I and II have the same number of channels and therefore can have the same numbers of passes. Consider for instance the exchanger shown in Fig. (2), which is arranged for $\phi = 1$ and $Y_h = 1$; according to Tab. (1), changing the sides of the fluids ($Y_h = 1 \rightarrow Y_h = 0$) will yield a different although equivalent configuration.

CONFIGURATION OPTIMIZATION

The configuration optimization problem is formulated as the minimization of the number of channels, N_C, which is equivalent to minimizing the exchanger heat transfer area or its fixed cost (Eq. 1). There are constraints on the number of channels (N_C), fluid pressure drops (ΔP_{hot}, ΔP_{cold}), channel flow velocities (v_{hot}, v_{cold}) and exchanger effectiveness (E), as shown in Constraints (2a) to (2f). The optimization model is also subject to the PHE model, necessary for calculation of the aforementioned variables (Constraint 3).

$$\min F(N_C, P^I, P^{II}, \phi, Y_h, Y_f) = N_C \tag{1}$$

subject to

$$N_C^{min} \le N_C \le N_C^{max} \tag{2a}$$

$$\Delta P_{hot}^{min} \le \Delta P_{hot} \le \Delta P_{hot}^{max} \tag{2b}$$

$$\Delta P_{cold}^{min} \le \Delta P_{cold} \le \Delta P_{cold}^{max} \tag{2c}$$

$$v_{hot}^{min} \le v_{hot} \tag{2d}$$

$$v_{cold}^{min} \le v_{cold} \tag{2e}$$

$$E^{min} \le E \le E^{max} \tag{2f}$$

$$(\Delta P_{hot}, \Delta P_{cold}, v_{hot}, v_{cold}, E) = \text{PHE mathematical model} \tag{3}$$

Constraint (2a) on the number of channels is related to the available number of plates and exchanger capacity. The minimum values for fluid pressure drop avoid large variations between the average fluid pressures that can bend the plates. Lower bounds on channel flow velocities avoid the formation of preferential paths or stagnation areas inside the channels.

The thermal and hydraulic modeling of the PHE (Constraint 3) was developed by Gut and Pinto (2001). The rigorous thermal model accounts for the variation in the overall heat transfer coefficient in the exchanger and consists of a system of differential and algebraic nonlinear equations, which can be solved by numerical methods. Assuming the heat transfer coefficient invariable, the rigorous model can be reduced to the so-called simplified thermal model, which consists of a system of linear ordinary differential equations and has an analytical solution. Since there is little difference between the main simulation results achieved by rigorous and simplified thermal models, the latter will be used for the optimization, keeping the former for final verification of the results.

The resulting optimization model is thus composed of the nonlinear algebraic equations and the linear differential equations of the PHE simplified thermal modeling and hydraulic modeling and of variables of discrete nature, such as the configuration parameters. These conditions make the problem solution nontrivial. A mixed-integer nonlinear programming (MINLP) approach cannot be used since it is not possible to derive a PHE model that is explicitly a function of the six configuration parameters. To overcome this limitation, the PHE model in Constraint (3) is presented in the form of an assembling algorithm. Given the configuration parameters, fluid data and exchanger characteristics, the algorithm generates the mathematical model, which is then solved by analytical or numerical methods. The solution provides the temperature profiles in all channels and thus the effectiveness, E. The structure of the assembling algorithm is presented by Gut and Pinto (2001).

The Screening Method

The proposed optimization procedure is based on the screening method, also employed by Daichendt and Grossmann (1994) for heat exchanger network optimization. In this procedure, constraints are successively used to remove infeasible and nonoptimal solutions of a MINLP problem, thus reducing its size and complexity.

In the optimization of a PHE configuration, the Constraint on the number of channels (2a) defines the initial set, IS, of possible configurations, formed by combinations of the five remaining parameters. An exhaustive enumeration procedure could be used to obtain the optimal configurations within this set; however, this procedure requires a large computational effort due to the large number of thermal simulations needed.

Since it is possible to calculate (ΔP, v) prior to the thermal simulation using average values for the fluid temperatures, the constraints on pressure drops and channel velocities (Constraints 2b to 2e) can be used to eliminate all infeasible elements in set IS. Therefore, a reduced set of configurations, RS, is generated. It is important to note that to obtain set RS it is not necessary to calculate (ΔP, v) for all the configurations in IS because of the following:

A1) parameter ϕ has no influence over (ΔP, v),

A2) (ΔP, v) is independent for sides I and II. Thus, for a given N_C, the calculations are made only once for each allowable number of passes,

A3) for a given N_C, ΔP is proportional to the number of passes; therefore, if $\Delta P > \Delta P^{max}$ is verified, any configuration with a larger number of passes also results in an infeasible solution,

A4) for an even-numbered N_C, sides I and II have the same number of channels and therefore the same allowable numbers of passes. In this case, (ΔP, v) will have the same value for $Y_h = 1$ and $Y_h = 0$.

Once set RS is obtained, the effectiveness Constraint (2f) is used to select the optimal set of configurations, OS. However, it is not necessary to thermally simulate all elements in RS because of the following:

B1) there are equivalent configurations with the same effectiveness; thus only one needs to be simulated,

B2) if a search is conducted in increasing order of N_C, when the optimal set is found, all remaining configurations with higher values of N_C can be neglected.

Since the influence of parameter Y_f on the convective coefficients and friction factor is usually unknown, this parameter may be fixed prior to optimization, thus reducing the number of possible configurations by 50 %. Moreover, it is not possible to change the type of flow in an existing exchanger.

Based on these principles, a screening algorithm is developed for the solution of the PHE configuration problem. The steps of the screening algorithm are as follows. For this algorithm, Y_f must have a given value ($Y_f = 0$ or 1). If there is available data on the influence of Y_f on the heat exchange and friction correlations, this algorithm can be used once for each case and the results compared.

1. The required data for plate (corrugation pattern, dimensions, area enlargement factor and thermal conductivity), hot and cold fluids (flow rate, inlet temperature, fouling factor and correlations for friction factor, convective heat transfer coefficients and physical properties) and constraints (lower and upper bounds for Constraints (2a) to (2f)) are read.
2. Initialization: $RS = \varnothing$, $N_C^{(k)} = N_C^{min}$, k = 1.
3. All allowable numbers of passes for sides I and II (P^I_i, P^{II}_j) are obtained for N_C^k.
4. Verification of constraints on pressure drop and channel flow velocities:

4.1. The (ΔP, v) pair is calculated for the cold fluid located on side I for each one of the numbers of passes P^I_i (in increasing order). If the constraints of (ΔP, v) are satisfied, the cold-fluid/sideI-pass pair is selected. If ΔP^{max} is exceeded, there is no need to evaluate larger numbers of passes. This procedure is applied to the cold fluid located on side II for all the numbers of passes, P^{II}_j, thereby selecting the cold-fluid/sideII-pass pairs.

4.2. The same procedure as that in step 4.1 is applied to the hot fluid, obtaining the hot-fluid/sideI-pass and hot-fluid/sideII-pass pairs.

5. The selected pairs of cold-fluid/sideI-pass and hot-fluid/sideII-pass are combined to generate all possible configurations with $Y_h = 0$. Each combination results in four configurations since ϕ has four values equivalent to (ΔP, v). The same procedure is applied to the selected hot-fluid/sideI-pass and cold-fluid/sideII-pass pairs, yielding configurations with $Y_h = 1$. All generated configurations are stored in RS.
6. If $N_C^{(k)} = N_C^{max}$, then proceed to step 7. Otherwise, $N_C^{(k+1)} = N_C^{(k)} + 1$, k = k + 1 and return to step 3.
7. Set RS is now complete. It contains all the configurations that satisfy the constraints on pressure drop and channel velocity for both sides. Now the optimal set, OS, must be obtained.
8. The configurations in RS with the minimum

value of N_C are selected.

9. The equivalent configurations are detected and grouped using the methodology shown in Tab. (1).

10. The simplified thermal model (the overall heat transfer coefficient is constant) is used to simulate one of the configurations in each group, obtaining the corresponding thermal effectiveness.

11. If one or more groups of equivalent configurations satisfy the effectiveness constraint, they are stored in set OS and there is no need to simulate other elements of RS. Otherwise, proceed to the next value of N_C in set RS and return to step 9.

12. The rigorous thermal model is used to simulate the nonequivalent elements in OS to verify the effectiveness results. In case of discrepancy ($|E^{simplified} - E^{rigorous}| / E^{rigorous} \leq \varepsilon$), the rigorous model should be used in the previous simulations after step 8. Otherwise, the optimal solution is achieved.

OPTIMIZATION RESULTS

The gPROMS software (Process Systems Enterprise Ltd, 2000) is applied for solution of the simplified and rigorous thermal simulation models using the finite differences method. A computer program was developed to automatically run steps 1 through 8 of the screening algorithm to obtain set RS. The program uses the model assembling algorithm (Gut and Pinto, 2001) to generate all the input files for simulation with gPROMS, pointing out all equivalent configurations in RS.

It was verified that the number of channels per pass has a strong effect on the pressure drop, and consequently, about 98 % of the elements in IS are eliminated in the first part of the screening (steps 1 through 8). Compared to an exhaustive enumeration procedure, the screening method demands approximately 5 % of the required evaluations of (ΔP, v). Further, to obtain set OS only a few elements are thermally simulated (approximately 1 % of the elements in IS or 20 % of the elements in RS).

As an example to show the efficiency of the screening method, consider the selection of a configuration for a process-water (26.0 kg/s, 67 °C) / cooling-water (62.5 kg/s, 22 °C) PHE with 1.4 m chevron plates with crossed channel flow ($Y_f = 1$). The constraint bounds are shown in Constraints (4a) to (4f).

$$2 \leq N_C \leq 150 \tag{4a}$$

$$10 \leq \Delta P_{hot} \leq 20 \text{ psi} \tag{4b}$$

$$15 \leq \Delta P_{cold} \leq 25 \text{ psi} \tag{4c}$$

$$v_{hot} \geq 0.20 \text{ m/s} \tag{4d}$$

$$v_{cold} \geq 0.30 \text{ m/s} \tag{4e}$$

$$94 \leq E \leq 95 \text{ \%} \tag{4f}$$

In this problem, IS has 26,240 elements and only 1.8 % of the (ΔP, v) calculations and 0.06 % of the simulations were necessary for the solution of the problem by the screening method. The comparative performance of the screening and enumeration methods is shown in Fig. (4). The set RS obtained contains 84 configurations, ranging from $N_C = 43$ to $N_C = 144$, with pass arrangements of 1/2, 2/3 and 2/4 for hot fluid/cold fluid. The problem solution consists of two pairs of equivalent configurations, all with 120 channels, two passes for the hot fluid and three passes for the cold fluid, as shown in Tab. (2). The required CPU time in a DEC-Unix workstation for the simulations of the simplified model was under 1 min, and 5 min were necessary to validate the results using the rigorous model (the deviations in E were under 1 %).

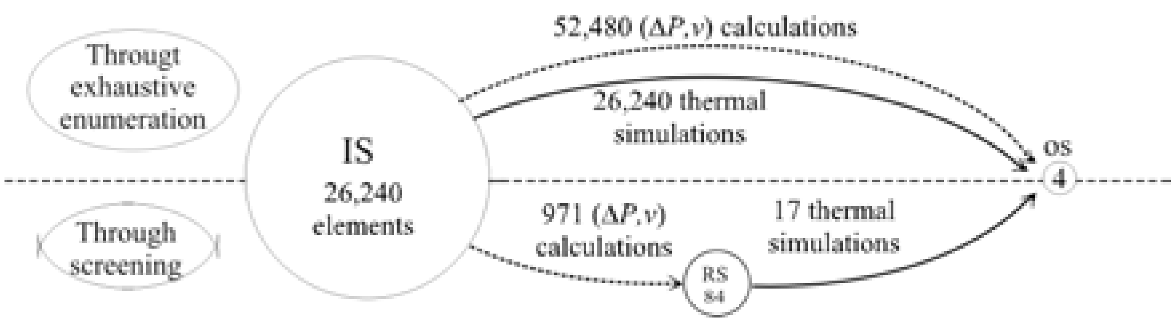

Figure 4: Performance of optimization approaches for the example.

Table 2: Optimal configurations obtained for the optimization example.

Configuration Parameters						Exchanger Performance				
N_C	P^I	P^{II}	ϕ	Y_h	Y_f *	E (%)	ΔP_{cold} (psi)	ΔP_{hot} (psi)	v_{cold} (m/s)	v_{hot} (m/s)
120	3	2	3	0	1	94.5	10.6	24.4	0.50	0.99
120	3	2	4	0	1	94.4	10.6	24.4	0.50	0.99
120	2	3	3	1	1	94.5	10.6	24.4	0.50	0.99
120	2	3	4	1	1	94.4	10.6	24.4	0.50	0.99

* fixed prior to optimization

CONCLUSIONS

The configuration of a gasketed plate heat exchanger (PHE) was represented by a set of six distinct parameters and a methodology to detect equivalent configurations was presented. The problem of optimizing the PHE configuration was formulated as the minimization of the heat transfer area, subject to constraints on the number of channels, the pressure drop and channel flow velocities for hot and cold fluids and the exchanger thermal effectiveness as well as the PHE simulation model. Since it is not possible to derive a mathematical model of the PHE that is explicitly a function of the configuration parameters, a mixed-integer nonlinear programming (MINLP) approach could not be used. A screening procedure was then proposed to solve the optimization problem. In this procedure, subsets of the constraints were successively used to eliminate infeasible and nonoptimal elements from the set defined by the bounds on the number of channels. An algorithm was developed to perform the screening with minimum computational effort. Examples show that this algorithm can successfully select a group of optimal configurations (rather than a single solution) for a given application using a very reduced number of thermal simulations.

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