Optimizing the Overall Heat Transfer Coefficient of a Spiral Plate Heat Exchanger Using GAMS

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ABSTRACT: *Spiral plate heat exchangers should be efficient devices because they are widely employed in the petrochemical and food industries; furthermore, their operation has a direct impact on electricity consumption in such sectors. For those reasons, this article aims to improve the efficiency of heat exchangers by means of optimization techniques. Using as an objective function the maximization of the overall heat transfer coefficient of a spiral plate heat exchanger. The mathematical formulation includes several variables in the problem: width, length, spacing between the plates, and plate thickness. And as a set of constraints the heat duty and the pressure drop, along with technical considerations associated with this type of system. The General Algebraic Modelling System (GAMS) was purposed as a solution method and compared with the Particle Swarm Optimization (PSO) algorithm, a Genetic Algorithm (GA), the original design proposed by Minton, and the Tuned Wind-Driven Optimizer (TWDO). Results show that the purposed method obtains the highest value of objective function being 1.5% better than the best of the used comparison methods with a computing time of 1e-4s, finding a solution with high quality at a low computational cost.*

KEYWORDS: *Heat exchangers; Optimization; Thermal design; Mathematical modeling.*

INTRODUCTION

Heat exchangers are widely implemented in the industrial sector to transfer heat between two fluids by means of two phenomena known as convection and conduction [1], which is also the case in air conditioning and heating systems. Exchangers have different shapes, transfer areas, types of fluid, heat to be transferred, stream direction, and location of the installation. They can be shell and tube, spiral plate, or rectangular plate heat exchangers, and their evaporators or condensers play an important role in their refrigeration cycles [2]. In order to design that type of systems, several factors should be taken into account, such as transfer area, transferred heat, and pressure drops, among others, in order to produce an efficient design, not only from the thermal perspective but also in terms of construction [3]. The process of designing heat exchangers integrates multiple variables that depend on different values and ranges (according to the mathematical formulation employed) and, as a result, it produces a highly complex problem, mathematically and computationally. Therefore, several current design methods integrate computer simulations to validate the design subjecting it to a virtual scenario based on a physical model structured by the variables that define the model. Among the methods proposed in the specialized literature, the work in [4] stands out because it presents a sizing method whose objective function is the reduction of the maximum allowable pressure in order to obtain spiral plate heat exchangers as small as possible, while respecting a heat transfer coefficient previously established. In [5], a conventional method combined with simulations is used to obtain the optimal size of a heat exchanger.

Since the design of those elements is considered nonlinear, optimization techniques and methods have been introduced to solve that kind of problem, and they have proven to be an effective tool for that purpose [6]. That is the case of heuristic and metaheuristic techniques, linear and nonlinear methods, and commercial optimization packages, among others. In recent years, several studies have implemented these techniques to solve different mathematical formulations in specific study fields. For instance, the authors of [7] minimized the heat transfer and the pumping power of a tube and shell heat exchanger by means of the multi-objective Non-dominated Sorting Genetic Algorithm (NSGA-II), thus reducing manufacturing costs. They found that, by implementing the NSGA-II, they obtained a quick and accurate solution that meets the constraints of pressure drop and heat duty. In turn, in [8], a Particle Swarm Optimization (PSO) algorithm is used to reduce the production and operating costs of a shell and tube heat exchanger, while respecting a set of constraints defined by pressure drops and heat duty; as a result, the cost decreased by over 5% with a low computational cost. In [9], a spiral plate heat exchanger is investigated to minimize its operating and construction costs using a Wind Turbine Optimization (WTO) algorithm. In that case a reduction of 19.3% of the total annual cost was achieved. The authors of [10] propose the implementation of a multi-objective optimization method to obtain the size of a small-scale model of a thermoacoustic refrigerator; they aimed at finding the optimal size of the stack and the spacing between the plates, which were the interdependent variables in their design problem. Their nonlinear mathematical model was programmed and solved using the General Algebraic Modelling System (GAMS), and the best solution to the problem was selected by implementing an optimal Pareto front. In addition, the same authors in [11] carried out a multi-objective study focused as well on the optimization of the dimensions of the stack to find a configuration that ensures high efficiency, low heat loss, and a given output power. They also implemented GAMS and Pareto's solution model to find the solution to the problem while respecting the set of constraints associated with the latter. In [12], the level of pollutants in a waste water treatment plant is minimized by means of adsorption in order to reduce the total hardness, alkalinity, and chemical demand for oxygen. The variables in that process were adsorbent dose and mixing time and speed. To solve the mathematical model that describes their problem, they used Response Surface Methodology (RSM) and GAMS. RSM found 15 different optimal configurations whose validation would increase the calculation time. Conversely, GAMS suggested a single optimal solution of higher quality than those obtained by RMS, thus demonstrating the former is the fastest and most efficient method.

In the petrochemical and food industries, it is common to deal with viscous fluids that produce fouling on the heat exchangers, thus reducing the overall heat transfer coefficient; for that reason, spiral plate heat exchangers are typically used in that case [13]. Since they are so widespread, such devices should be studied to optimize their performance by means of adequate sizing. Considering the importance of heat exchangers in the industry and the significant impact of optimization techniques and methods on the solutions to problems of that kind, this document presents a mathematical formulation that describes the design of a spiral plate heat exchanger. The objective function of this formulation is the maximization of the overall heat transfer coefficient subject to a set of constraints that define that type of devices: pressure drop, heat duty, and the limits that restrain their different elements [14]. This work proposes the optimization tool GAMS as solution method due to the excellent results it has produced in the optimization problems described above. Such method is compared to the original design by Minton, a PSO algorithm, and a Genetic Algorithm (GA) to analyse its results and demonstrate its impact.

THEORETICAL SECTION

Problem formulation

As heat exchangers are essential equipment in different industries, they should be correctly sized to guarantee high efficiency and thus reduce the operating costs associated with them. To direct that need, this study implements a mathematical model composed of a mono-objective optimization function and a set of restrictions that represent the problem (the design of the spiral plate heat exchanger in Fig. 1) to maximize the overall heat transfer coefficient (defined as the capacity of the equipment to exchange thermal energy). As a result, the size of the device can be reduced while the heat duty is respected, and the maximum pressure drop is not exceeded [15].

Mathematical model

The mathematical model that describes the problem under analysis was developed based on [2] and [15] to design a spiral plate heat exchanger with a counter flow configuration. In all the cases, the process starts by calculating the heat duty of the system (*Q*), which is defined in Eq. (1).

$$Q = \left[\dot{m}C_p(T_o - T_i)\right]_h = \left[\dot{m}C_p(T_i - T_o)\right]_c \qquad (1)$$

Where $\dot{m}$ is the mass flow of the fluid; C_p, the specific heat of each fluid; and T_i and T_o, the inlet and outlet temperatures of the fluids. Sub-indices *h* and *c* se will be used to denote the hot and cold fluid, respectively. *Q* can also be defined by Eq. (2) to be able to find the different values that comprise it.

$$Q = UATLMD \qquad (2)$$

where *U* is the overall heat transfer coefficient, which is defined in Eq. (3).

$$U = \left(\frac{1}{h_h} + \frac{t}{k_p} + \frac{1}{h_c} + R_f\right)^{-1} \qquad (3)$$

Where h_h, and h_c are the convective heat transfer coefficients of the hot and cold fluid, respectively; k_p, the

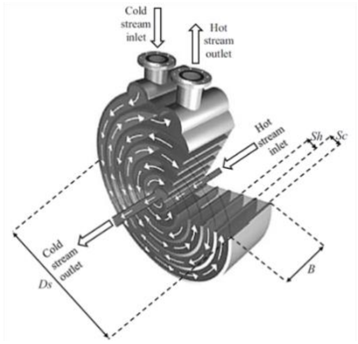

Fig. 1: Illustration of the spiral plate heat exchanger. [16].

thermal conductivity of the exchange wall; *t*, its thickness; and R_f, the fouling factor, which is added because the type of fluids used in this kind of exchangers deposit a layer of sediment on the walls; thus, reducing their conductivity.

Additionally, *TLMD* is the logarithmic mean temperature difference determined by Eq. (4) for a counter flow configuration.

$$TLMD = \frac{(T_{hi} - T_{co}) - (T_{ho} - T_{ci})}{\ln\left(\frac{T_{hi} - T_{co}}{T_{ho} - T_{ci}}\right)} \qquad (4)$$

Variable *A* denotes the transfer area defined by Eq. (5), where *L* represents the total length of the spiral and *B* is the height of the exchanger.

$$A = 2LB \qquad (5)$$

The Nusselt number and hydraulic diameter should be found to calculate convective coefficients. The average diameter of the spiral is described (*Rm*) in Eq. (6) and given by the maximum and minimum diameter of the spiral.

$$R_m = \frac{R_{min} + R_{max}}{2} \qquad (6)$$

The average hydraulic diameter (*Dh*) is defined by Eq. (7), where S is the spacing of the channels through which the fluid will circulate. This hydraulic diameter is approximately two times the spacing of the channel.

$$D_h = \frac{4(\text{stream area})}{(\text{wetted perimeter})} = \frac{2BS}{B + S} \qquad (7)$$

Reynolds (*Re*), Prandtl (*Pr*), and Nusselt (*Nu*) numbers are dimensionless parameters employed in the design of the exchanger to characterize the stream, fluid, and heat transfer capacity; in this study, they are defined in Eqs. (8) to (10).

$$Re = \frac{\rho V L_C}{\mu} = \frac{\dot{m} D_h}{BS\mu} \quad (8)$$

Where ρ is the density of the fluid; μ, its dynamic viscosity; L_c, a length that characterizes the area of the cross-section the stream is going through (which, for this problem, is the hydraulic diameter); and *V*, the average velocity of the flow through the area *BS*.

$$Pr = \frac{\mu Cp}{k} \quad (9)$$

Where *k* is the thermal conductivity of the fluid.

$$Nu = \frac{hD_h}{k} = 0.0239\left(+5.54\frac{D_h}{R_m}\right)Re^{0.806}Pr^{0.268} \quad (10)$$

Equation (10) presents the experimental definition by correlation proposed by Minton [15] to estimate the Nusselt number in spiral plate heat exchangers. After the Nusselt number is calculated, the convective heat transfer coefficient is computed of the definition of *Nu*, as presented in Eq. (11).

$$h = \frac{kNu}{D_h} \quad (11)$$

The process described thus far should be repeated for both streams, hot and cold. Up to this point, values *B*, *S*, *L*, and *t* (which maximize *U*) can be defined to later evaluate their compliance with pressure drop constraints.

Pressure drop (*ΔP*) is defined in accordance with Darcy–Weisbach's expression, as in Eq. (12), where f is Darcy's dimensionless friction factor and *g* is gravitational acceleration. Eq. (12) presents the empirical correlation developed in [15].

$$\Delta P = f\frac{\rho(LV^2)}{2gL_c} = \frac{1.45\rho(LV^2)}{1705} \quad (12)$$

The outer diameter of the spiral is determined by Eq. (13), where C is the diameter of the core.

$$D_s = \sqrt{(1.28L(S_h + S_c + 2t) + C^2)} \quad (13)$$

The set of constraints of the problem is given by Eqs. (14) and (15), which limit the pressure drop based on the calculation of Eq. (12), being compared to the maximum pressure drop (6.894 kPa) and the required heat expressed in Eq. (1), which is compared to the calculation of Eq. (2).

$$\Delta P_{h,c} - \Delta P_{max} = 0 \quad (14)$$

$$Q - UA\Delta T_{LM} = 0 \quad (15)$$

Variable	Width	Length	Channel spacing	Thickness
Name	B	L	$S_{h,c}$	t

Fig. 2. Problem codification. Source: authors' own work.

Such constraints become necessary to limit the problem and avoid infeasible solutions because, as each restriction is penalized, the search space is limited, and the algorithm is forced to find an adequate solution.

Methodology

To solve the mathematical model of the problem, this work proposes the use of a PSO optimization algorithm, a GA, and the software General Algebraic Modeling System (GAMS), which will be defined below. In addition, the following section describes the problem codification, objective function, and constraints that represent the problem, as well as the properties of the fluids and constants of the heat exchanger.

Problem codification

A 1x4 vector (1 row and 4 columns) was implemented to codify this problem and represent different solutions provided by the optimization technique within the solution space (see Fig. 2). The four columns in this vector contain the values assigned to the width, length, channel spacing for the hot and cold fluids, and wall thickness, in that order. It should be highlighted that the values that can be assigned in this codification are limited by the set of constraints posed by the problem. They are listed in the following section.

Mathematical description

The objective function of the problem in Eq. (20) is defined by the sum of the value of the overall heat transfer coefficient and the penalties stemming from the set of constraints in Eq. (21), to obtain a feasible solution and allow the optimization techniques to cross the infeasible region to search for a high-quality solution.

$$F = U + Pen \quad (20)$$

$$Pen = p_1 + p_2 \quad (21)$$

Where p_1 is the penalty assigned to the pressure drop constraint (Eq. 14) and p_2, to the heat duty constraint (Eq. 15). Such values are determined with the selection of the maximum value between 0 (if the constraint is respected) and 1 (the constraint is not met). These penalties are expressed in Eqs. (22) and (23).

$$\mathbf{p_1} = \mathbf{max}\{\mathbf{0}, \Delta \boldsymbol{P}_{h,c} - \Delta \boldsymbol{P}_{max}\} \quad (22)$$

$$\mathbf{p_2} = \mathbf{max}\{\mathbf{0}, \boldsymbol{Q} - \boldsymbol{U}\boldsymbol{A}\Delta \boldsymbol{T}_{LM}\} \quad (23)$$

PSO algorithm

PSO, a bioinspired meta-heuristic algorithm based on the behavior of the flocks of birds and fish schools, was developed by *Eberhart* and *Kennedy* in 1995 [17]. It works by imitating the way these groups of animals explore the ocean or a given region to find a common source of food for the entire group. Each animal is modeled as a particle, and the exploring group is a swarm of particles dispersed over a solution space limited by a set of constraints associated with each problem [18]. The main feature of PSO is the way the individual particles move over the solution space: each step considers the information of each particle as well as that of the particle that offers the best solution in the swarm at each iteration or movement. The speed of the movement can be controlled, and a random component is included to prevent the algorithm from falling into local optima [19]. Table 1 lists the parameters used for the implementation of the PSO algorithm in this study.

Table 1: Parameters for the PSO algorithm. Source: authors' own work.

Name	Value
Maximum inertia	0.7
Minimum inertia	0.001
Cognitive component	1.494
Social component	1.494
Maximum speed value	0.01
Number of particles	30

Genetic Algorithm

GAs are classical optimization techniques. They have been used multiple times to solve continuous optimization problems (such as the optimization of nonlinear continuous functions and second-order borderline differential equations) with satisfactory results. A GA starts with the creation of an initial population whose individuals evaluate the objective function. Subsequently, new populations are generated and, by means of selection, mutation, and recombination, the algorithm moves within the solution space to determine the best configurations [20]. It should be noted that GAs solves optimization problems by transforming a restricted problem into a conditional one. That means that the mathematical model (which contains a set of constraints that depend on the conditions under analysis) is evaluated at each iteration [21]. The purpose of the previous step is that a sizing configuration that violates one constraint of the problem can still be considered a good solution [22]. Table 2 below lists the parameters used for the implementation of the GA.

Table 2: Parameters for the GA.

Name	Value
Individuals per tournament	2
Population	50
Mutation parameter	0.5

Generalized Algebraic Modelling System (GAMS)

GAMS is a commercial optimization tool that can be used to solve complex and large-scale problems in different research areas employing linear and nonlinear equation systems with low computational cost [23]. This tool comprises a compiled language and a series of optimization solvers, which are different in the demo and professional licensed versions. Users can select from a group of different solvers to explore the solutions the software can provide.

Basic knowledge about programming languages and mathematical modeling is necessary to use this software [24].

The implementation of any optimization problem using GAMS requires at least of the following steps by employing some reserved words:

a) Definition of scalars and parameters that will remain constant and will be necessary to solve the equations.

b) Declaration of the variables in the model, which will take the values in the pre-established intervals.

c) Declaration of dependent variables, which will be calculated at each iteration depending on the values of the variables to be optimized.

d) Limits and intervals are fixed; the solution space is defined.

e) Equations used to solve the problem and analyze the constraints.

f) The solution is produced, defining the variables to be shown, which represent the optimal solution to the problem.

To review general concepts about mathematical optimization using GAMS refer to [24] and [25].

General Parameters

In order to solve the mathematical model, it is necessary to define the upper and lower bounds (which were taken from [15] and [16]) and some parameters used by the three strategies implemented in this work. They are listed in Table 3.

Parameters of the mathematical model

Table 4 lists the values of the properties for this study case. They were taken from Minton's work.

RESULTS AND DISCUSSION

In this section are presented the results obtained by the purposed method GAMS employed to solve the maximization of the overall heat transfer coefficient, and the numerical simulation of the optimization techniques PSO and GA, which were used as comparison methods e in terms of quality and computational times, mentioned algorithms were programmed in MATLAB® on an HP Z600 Workstation with 12Gb of RAM and a six-core processor. In addition, were used the results reported in the specialized literature where was employed the same mathematical model described above, the mentioned methods correspond to the conventional design method developed by *Minton* [15] and the metaheuristic technique Tuned Wind-Drive Optimizer (TWDO) [16].

Fig. 3 shows the value of the overall heat transfer coefficients of the solutions found by the optimization methods and techniques previously mentioned. The data indicate that GAMS obtained the best solution among the comparison methods, with the highest overall heat transfer coefficient (258.084 W/m^2 K) which is 0,8% higher that the TWDO followed by the PSO with a difference of 2.18%. Such solution found by GAMS meet the set of constraints achieving a heat duty of 186.482 kW of transferred heat and the pressure drops of the hot and cold fluids reach 1.31 kPa and 1.19 kPa, respectively, while the maximum limit is 6.894 kPa, proving that the solution developed by the purposed method guarantee a reliable and safe design, which respects the set of constraints and solution space.

Table 5 shows the values of the main variables, objective function and heat duty obtained by the evaluated methods.

Table 3: Bounds and general conditions. Source: authors' own work.

Name	Value
Maximum width	1.5 m
Minimum width	0.5 m
Maximum length	20 m
Minimum length	10 m
Maximum channel spacing	0.032 m
Minimum channel spacing	0.005 m
Maximum wall thickness	0.0079 m
Minimum wall thickness	0.0032 m
Stopping criterion	Convergence
Maximum number of iterations	500
Dimensions of the problem	4
Penalty criterion	1.5

An analysis of Table 5 reveals that GAMS produced a 17.14% increase in the overall heat transfer coefficient compared to the original design, 14.78% with respect to the GA, and a 2.18% regarding PSO. This is because an optimization technique or method was not applied to find the size of the exchanger in the original design. In terms of processing time, the proposed method exhibits the best computation time to solve the problem, being less than 1e-4 s, which is significantly shorter than the GA (0.58 s) and PSO (0.42 s). It is worth mentioning that the processing times of the traditional solution method reported by Minton and the TWDO were not reported; moreover, computation times are not included in that study. As a result, the computational capacity needed to evaluate that strategy cannot be determined. Those results show that GAMS is an efficient and fast tool to find an optimal solution that meets all the constraints and requirements specified in the problem addressed with a low computational cost, this due to the operation of the software GAMS which employs a variety of tuned optimization techniques, while in the comparison methods are used parameters which are not optimized, for this reason the exploration and exploitation in the solution space is less efficient.

When the results above are compared to those in [15], it can be seen that the dimensions of the exchanger found in the latter do not meet the minimum heat duty and,

Table 4: Parameters of the mathematical model. Source: [15].

Variable	Name	Hot stream	Cold stream
Mass flow	*m* (kg/s)	0.7844	0.7466
Inlet temperature	T_i (K)	473.15	333.15
Outlet temperature	T_o (K)	393.15	423.55
Density	ρ (kg/m^3)	843	843
Specific heat	*Cp* (J/kg K)	2973	2763
Viscosity	μ (Pa s)	0.00335	0.008
Thermal conductivity	*k* (W/m K)	0.348	0.322
Fouling resistance	*Rf* (m^2 K/W)	1.0567e-4	
Thermal conductivity of the surface material	k_p (W/m K)	14.53	14.53
Maximum pressure drop	ΔP_{max} (kPa)	6.894	6.894

Table 5. Solutions found by the algorithms. Source: authors' own work.

Var	Original design [15]	GA	PSO	TWDO [16]	VORTEX
U	220	217.361	252.459	256.01	258.084
B	0.6100	0.5390	0.6000	0.5011	0.5000
L	12.741	14.331	12.822	10.000	14.28
Sh,c	0.0063	0.0056	0.0050	0.0050	0.0050
t	0.0032	0.0061	0.0032	0.0032	0.0068
Ds	0.5941	0.6868	0.5571	0.5011	0.5650
Q	164.744	183.573	189.533	141.086	186.482
time	---	0.58	0.42	-	0.0001

Fig. 3. Overall heat transfer coefficients found by different optimization methods. Source: authors' own work.

therefore, that solution is infeasible. Nevertheless, such work is the starting point of the sizing because it defines a comprehensive model to calculate this type of heat exchangers. Furthermore, an analysis of the results in [16] reveals that the solution found by the TWDO does not meet the heat duty either because it does not feature an adequate ratio between the overall heat transfer coefficient and the transfer area. In that case, the solution represents a more economical exchanger, but it does not meet the minimal technical specifications of the problem. Nevertheless, the potential of the tool and the analysis in that study should not be dismissed.

CONCLUSIONS

The problem of sizing heat exchangers represents an exhaustive task due to the considerable number of variables and parameters in the system. Finding an adequate, efficient, and low-cost design means long hours completing a manual iterative process. As a result, designers should use optimization algorithms to manipulate input parameters and the properties of the fluid to solve each specific problem.

This work proposed the use of GAMS, which demonstrated to be a fast and efficient optimization tool to solve this type of nonlinear problems. It provided a single solution and produced the best results compared to other algorithms that were used for comparison. The differences between the purposed method and the comparison methods are related to the quality of the programming because GAMS is an optimization solver, which uses different algorithms to find the one that best suits the nature of the problem. While the proposed algorithms have different methods of analysis of the solution space where its exploration and exploitation are less efficient.

The maximization of the overall heat transfer coefficient improves the efficiency of the exchanger and enables a faster heat transfer rate; furthermore, a smaller transfer area is required as a result. Future work will include a model integrating the cost of the exchanger (considering its useful life prediction) to define the exchanger and its construction parameters.

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