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Multi-Objective Optimization of a Multilayer Wire-on-Tube Condenser: Case Study R134a, R600a, and R513A

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Abstract: This study presents the optimization of a multilayer wire-on-tube condenser exposed to forced convection, using the Optimized Multi-objective Particle Swarm Optimization (OMOPSO) algorithm. The maximization of the heat transfer and the minimization of the heat exchange area were defined as objective functions. In the optimization process, the variations of eight geometric parameters of the condenser were analyzed, and the Multi-objective Evolutionary Algorithm based on Decomposition (MOEAD), Non-dominated Sorting Genetic Algorithm-II (NSGAII), and OMOPSO algorithms were statistically explored. Furthermore, the condenser optimization analysis was extended to the use of alternative refrigerants to R134a such as R600a and R513A. Among the relevant results, it can be commented that the OMOPSO algorithm presented the best option from the statistical point of view compared to the other two algorithms. Thus, optimal designs for the wire-on-tube condenser were defined for three proposed study cases and for each refrigerant, providing an overview of compact designs. Likewise, the reduction of the condenser area was analyzed in more detail, presenting a maximum reduction of 15% for the use of R134a compared to for the current design. Finally, the crossflow condition was studied with respect to the current one, concluding in a greater heat transfer and a smaller heat exchange surface.

Keywords: domestic refrigerator; MOEAD; NSGAII; OMOPSO; refrigerants

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1. Introduction

Heat exchangers are widely used equipment in different sectors such as industrial, transportation, pharmaceutical, refrigeration, and air conditioning. They represent a key role in the efficiency of each system of which they are part. In recent years, there has been great interest in implementing various optimization methods to improve the design of the equipment. Increasing heat transfer per unit area, reducing manufacturing costs [1], and saving energy consumption [2] are among the main objectives for optimizing heat exchangers. For example, the optimization methodologies are specifically applied to wire-on-tube heat exchangers such as the one developed by Bansal and Chin [3], in which they proposed an optimization factor based on the thermal capacity per unit weight of a wire-on-tube condenser. That study was based on the development of a mathematical model, obtaining a 3% gain in thermal capacity and a 6% reduction in the condenser weight. Zhang et al. [4] experimentally developed the optimization of the airflow field of a spiral wire-on-tube condenser by forced convection. In doing so, they achieved a 2.37% reduction in energy consumption.

On the other hand, multi-objective optimization is one of the applications in the engineering of genetic algorithms. This can be evidenced in a previous study [5], in which a multi-objective optimization applied to a plate heat exchanger was proposed in order to maximize the overall heat transfer coefficient and minimize the pressure drop by analyzing eight geometric variables. Imran et al. [6] performed a thermo-hydraulic optimization by analyzing different geometrical parameters. The authors obtained that the heat transfer and the pressure drop increase with the increase in the horizontal port center distance and the number of plates. Kumar et al. [7] developed an optimization technique by implementing the MOWO meta-heuristic algorithm. The authors demonstrated the effectiveness of this algorithm in thermal and hydraulic optimization. Sodagar-Abardeh et al. [8] determined the optimal geometry and flow conditions of plate heat exchangers based on the entropy generation minimization approach.

Other multi-objective algorithms found in the literature and applied to the optimization of heat exchangers are the bat algorithm [9], MOGA [10], Bees algorithm [11], NSGAII [12], constructal theory [13], MOHTS [14], cohort intelligence [15], and FOA [16]; all of them involving objectives such as cost minimization, efficiency increase, and reduced pressure drop. One of the most widely used algorithms in optimization studies is the NSGAII, proposed by Deb et al. [17], with the purpose to improve some characteristics such as computational complexity, non-elitism approaches, and the need to specify a distribution parameter. In this regard, Sanaye and Hajabdollahi [18] presented a mathematical model using the ε-NTU thermal analysis method for compact heat exchangers. They considered the variation of six geometric parameters and used the NSGAII algorithm to achieve the maximum effectiveness and the minimum annual investment and operating cost. Rodríguez et al. [19] proposed a flexible optimization procedure using NSGAII for several types of fluids and for multiple shell and tube heat exchanger designs. They concluded that the length of the tube had the greatest influence, not only on the value of the ecological function, but also on the cost. Liu et al. [20] performed a combination of CFD simulation and multi-objective optimization to improve the performance of a heat exchanger by optimizing the Colburn factor and the friction factor.

OMOPSO is another multi-objective optimization algorithm presented by Sierra and Coello [21]. With this algorithm, the exploration and exploitation capacity were improved during the search process by dividing the population into sub-swarms of equal size and adapting each of them to a different mutation operator. Although it has been little used in heat exchangers optimization, comparisons between NSGAII and OMOPSO can be found in different works [22,23], in which it is reported that the OMOPSO algorithm presents better results with a lower error rate. The main motivation for the use of genetic algorithms in multi-objective problem solving is that they can return a set of non-dominated solutions that converge to a Pareto optimal front, providing the possibility of searching in limited spaces.

According to the literature review, it can be seen that most of the studies focus on optimization of the compact, plate, and shell-and-tube heat exchangers, concentrating on the optimization of costs and geometric parameters to improve their thermo-hydraulic behavior. Therefore, the studies of wire-on-tube heat exchangers focused on optimization are limited. In the domestic refrigeration industry, one of the most widely used heat exchanger designs is the wire-on-tube heat exchanger design, mainly due to its low cost and ease of manufacture [24].

In the present work, the optimization of a multilayer wire-on-tube condenser used in domestic refrigeration was proposed, where the analysis of eight geometric parameters on the thermal behavior of the heat exchanger was suggested. In addition, the use of alternative refrigerants such as R600a and R513A as substitutes for R134a was experimentally studied. These refrigerants had similar thermophysical properties to R134a. In addition to this, R513A had a 56% reduction in its GWP compared to R134a. R600a had a GWP of 10 and was considered a long-term solution. Therefore, these refrigerants were taken as alternatives, because they presented a reduction in the direct impact on the environment with respect to R134a.

The results presented the optimal geometric configurations that maximized heat transfer with a reduction in the heat exchanger area for all three refrigerants. Thus, the main objective of this work was to explore the application of fully documented multi-objective algorithms (NSGAII, OMOPSO, and MOEAD) in the optimization of a multilayer wire-on-tube condenser used in domestic refrigeration.

The results presented the optimal geometric configurations that maximized heat transfer with a reduction in heat exchanger area for all three refrigerants, with respect to the operating point obtained experimentally for each refrigerant. In addition to this, this work was proposed as a guideline to obtaining design parameters for the construction of new equipment that present a better thermal performance under different established operating conditions.

In this work, the multilayer wire-on-tube condenser used was described, the objective functions were defined, and the basic concepts of the algorithms used were defined. Then, a qualitative and statistical comparison is presented for the selection of the multi-objective optimization algorithm; finally, the results obtained and the main conclusions of the work are presented.

2. General Aspects and Optimization

2.1. Multilayer Wire-on-Tube Condenser

The wire-on-tube condenser considered in this work is shown schematically in Figure 1, where its particular design and the most representative geometric parameters are observed. Normally, this type of heat exchangers operates under forced convection conditions, using a fan with a 0.11 m diameter, obtaining a maximum airspeed of 5 m/s, thus facilitating the increase in the heat transfer with respect to the area of this equipment. The air speed was measured with an anemometer with an uncertainty of ±3% of the reading. This heat exchanger consists of wires welded to the wall of the tube through which the refrigerant passes, thus forming different layers; these wires serve as fins for increased heat transfer. This condenser is made of carbon steel with a conductivity of 45 W/mK and painted black on its outer surface. Table 1 indicates the geometric parameters considered in this study for the optimization of the heat exchanger, their reference values, as well as the evaluation range of each one of them. The geometry of the condenser represents an original design with an area of 0.3714 m^2 and a mass of 1.216 kg. The range selection in the variation of the eight geometric parameters was defined taking into consideration the commercial dimensions of both the tube and the wire, as well as the limitations in the space where the multilayer wire-on-tube condenser is located, and the typical values found in the literature.

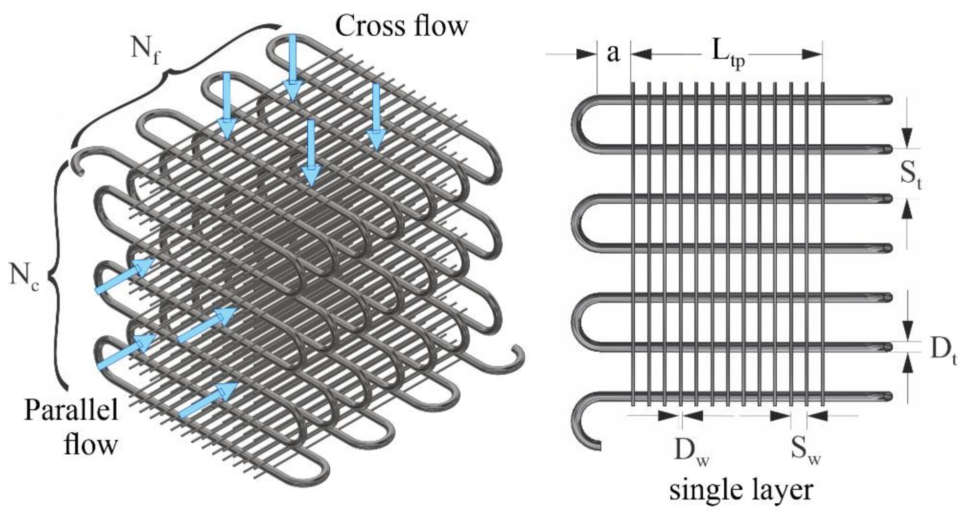

Figure 1. Schematic representation of the multilayer wire-on-tube condenser.

Table 1. Geometric parameters of the multilayer wire-on-tube condenser.

Variable	Nomenclature	Type of Variable	Reference	Lower Limit	Upper Limit
Tube diameter (mm)	D_t	Continuous	4.76	4	6
Wire diameter (mm)	D_w	Continuous	1.30	1	2
Tube pitch (mm)	S_t	Continuous	25.4	20	30
Wire pitch (mm)	S_w	Continuous	4.06	4	5
Length with a wire (mm)	L_{tp}	Continuous	101.6	80	120
Length without a wire (mm)	a	Continuous	16.72	12	18
Number of layers	N_c	Discrete	7	6	8
Number of rows	N_f	Discrete	7	6	8

In Figure 2, the scheme of the model used as a reference for the optimization analysis is presented and was validated with stationary experimental data obtained with a real refrigerator. This model was developed in a previous study [25], in which the ε-NTU thermal analysis method and empirical correlations were used, considered as input variables the geometric parameters (Table 1) and the operating conditions of the condenser, as shown in Table 2. The thermal capacity, the air outlet temperature, and the refrigerant outlet temperature were obtained as outputs. Notice that our interest is in the thermal analysis of the condenser, so the hydraulic model was not considered in this study. The model predicted the thermal behavior adequately, since the output parameters of the model represented a maximum error of ±5% for heat transfer and ±0.5 K for the outlet temperatures of the refrigerant and air.

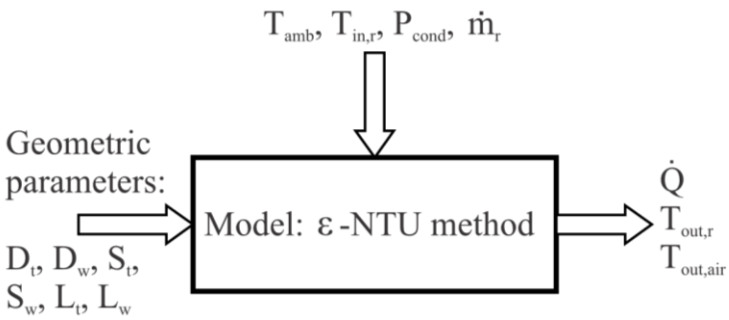

Figure 2. Input−output model structure of the multilayer wire-on-tube condenser.

Table 2. Operating condition for refrigerants R134a, R600a, and R513A.

	R134a	R600a	R513A
P_{cond} (bar)	9.2	5.3	11.4
$T_{in,r}$ (°C)	44.5	45.1	50.2
T_{amb} (°C)	30	30	30
$\dot{m}_r$ (kg/s)	0.0013	0.0006	0.0013

2.2. Operating Conditions

Table 2 shows the operating conditions that were taken as a reference for the optimization of the multilayer wire-on-tube condenser. These values were obtained experimentally in a real domestic refrigerator, instrumented with respect to NOM-015-ENER-2018 standard. The condensing pressure was measured using a pressure transducer with a measurement range of 0–25 bar and an uncertainty of ±1%, and K-type thermocouples with uncertainty of ±0.03 °C were used for temperature measurement. The mass flow rate was measured by a Coriolis-effect flowmeter with an uncertainty of ±0.22%.

The signals generated by the measurement devices were stored in a PC-based compact RIO data acquisition system using LabView software. Each point used in validation was determined by averaging the temperature over the last 20 min of an ON period. The following conditions were taken into account: in this period of operation, the pressures and temperatures of the inlet and the outlet of the air and the refrigerant in the condenser were known.

2.3. Proposed Objective Functions

The multi-objective optimization considered in this work is defined in a general way by the following equation:

$$F_{1,2}\ (x) = [f_1(x),\ f_2(x) \ldots f_n(x)], \tag{1}$$

where $F(x)$ represents the objective functions to maximize/minimize the heat transfer, and $f(x)$ are the geometric optimization parameters mentioned in Table 1, n represents the number of parameters. For this case study, n = 8. Considering the maximization of the heat transfer and the minimization of the exchanger area, a multiple set of optimal solutions, known as Pareto optimal solutions, are obtained.

According to the model developed for the wire-on-tube condenser [25], the two objective functions that were defined in this work are shown in Equations (2) and (3). The total heat transfer of the condenser, $\dot{Q}$, was estimated considering three zones with respect to the refrigerant state, desuperheating, condensation, and subcooling. In each zone, an energy balance is applied between both fluids (the refrigerant and the air). While exchange area, A_T, is provided by the wire area and the tube area:

$$\dot{Q} = \dot{Q}_{dsh} + \dot{Q}_{cond} + \dot{Q}_{sub}, \tag{2}$$

$$A_T = A_w + A_t, \tag{3}$$

$$A_w = \pi D_w L_w N_w, \tag{4}$$

$$A_t = \pi D_t L_t. \tag{5}$$

The relationships shown in Equations (6)–(8) are defined to obtain the total exchanger area as a function of the geometric design parameters:

$$L_t = \left(L_{tp} + 2a\right) N_f N_c + \frac{\pi S_t}{2}\left(\left(N_f - 1\right) + N_f(N_c - 1)\right), \tag{6}$$

$$N_w = 2N_c\left(\frac{L_{tp}}{S_w} + 1\right), \tag{7}$$

$$L_w = S_t\left(N_f - 1\right) + \frac{S_t}{2}. \tag{8}$$

In this work, different operating conditions were evaluated for the thermal behavior of the wire-on-tube condenser, which is mounted in a domestic refrigerator [25].

2.4. Algorithms

The NSGA-II algorithm [26] is presented as an improved version of the NSGA. NSGA-II uses an elitist principle, whereby the elites of a population are given an opportunity to be carried to the next generation. It is computationally more efficient than the NSGA, and it is a highly competitive algorithm in convergence. In addition, it uses an explicit diversity-preserving mechanism (crowding distance) and highlights non-dominated solutions. The OMOPSO algorithm [27] develops an approach based on Pareto dominance and the use of an agglomeration factor for the selection of leaders, which is used to filter the number of leaders when this exceeds the maximum limit imposed. These leaders are retained considering the best crowding values. It also uses two external files, with one to store the best positions of the current iteration and the other to store the non-dominated solutions. Finally, the MOEAD algorithm [28] decomposes multi-objective optimization problems into a series of single-objective optimization subproblems, by applying decomposition approaches. Then, these subproblems are simultaneously optimized by using evolutionary algorithms. The set of Pareto-oppressed solutions is obtained, because each solution corresponds to the optimal solution of each single-objective optimization subproblem. This method has a great advantage of maintaining the distribution of solutions, and optimization by analyzing information from adjacent problems can avoid falling into a local optimum due to the existence of de-composition operations.

2.5. Case Study

To contribute with a broader view on the use of algorithms, this study initially proposed the evaluation of three algorithms: NSGAII, OMOPSO, and MOEAD, with a search population size of 100 individuals, a maximum of 250 iterations, and a mutation probability of 0.125. A statistical comparison was made between the proposed algorithms by evaluating the R134a, R600a, and R513A refrigerants used in the wire-on-tube condenser, the above under the same simulation parameters, looking for the best response, that is, with the lowest statistical variation of the results obtained for each refrigerant with respect to the proposed objective functions.

As our first solver, we decided to use the 2001 version of NSGAII, because it is historically one of the most widely applied algorithms to a variety of continuous multi-objective problems with reasonably good results in the literature. This algorithm was only the initial approach to our experiments. The main idea of using this algorithm was to initially explore the performance of a multilayer wire-on-tube condenser optimized by heuristic algorithms. Once we obtained encouraging results, we applied more sophisticated algorithms, namely, OMOPSO and MOEAD.

Once the algorithm based on the statistical results has been selected, three study cases related to the geometric design of the heat exchanger were proposed. In these cases, the number of layers, N_c, and the number of rows, N_f, were kept fixed, and the other geometric parameters were varied considering the two objective functions, the minimization of the area and the maximization of the heat transfer. These three cases were defined as follows: case 1: $N_c = N_f = 6$; case 2: $N_c = N_f = 7$; and case 3: $N_c = N_f = 8$. Notice that a square ($N_c = N_f$) condenser section (exchanger side) was maintained, mainly considering the limitations in the space of the refrigerator where the multilayer wire-on-tube condenser was installed.

3. Results and Discussion

3.1. Analysis of the Optimization Algorithm

Figure 3 presents a qualitative comparison using boxplots obtained using the data analysis software R Studio, for the three optimization algorithms initially proposed in this work (NSGAII, OMOPSO, and MOEAD). The information was obtained by running 35 simulations for each algorithm and for each of the three refrigerants analyzed. Figure 3a,c,e shows the distribution of the data obtained for the minimization of the heat transfer area, and Figure 3b,d,f illustrates the data distribution for the maximization of the heat transfer, which were for the experimentally tested refrigerants.

Analyzing Figure 3a, a greater data dispersion was observed for the MOEAD and NSGAII algorithms, while for the OMOPSO algorithm there was a lower dispersion. In Figure 3c, for R600a refrigerant, it was observed that the MOEAD and OMOPSO algorithms presented a lower data dispersion, including defining a smaller heat transfer area with respect to the NSGAII algorithm. As for Figure 3e, for the R513A refrigerant, it was observed that the data dispersion was not very different between the algorithms; however, the NSGAII reflected the minimal heat transfer area. In the previous figures, some atypical points were observed.

Regarding heat transfer and for the evaluation of R134a and R600a refrigerants, as shown in Figure 3b,d, respectively, it was observed that there was not dispersion in the data obtained with the three algorithms, since the results did not present any variation. Although in the analysis for R513A refrigerant (Figure 3f), the MOEAD and OMOPSO algorithms are similar, they did not present any dispersion in the results obtained. With respect to the NSGAII algorithm, a slight reduction of 0.06% in heat transfer was observed.

Although Figure 3f presents a minimum dispersion of data, this gives us a guideline from the statistical analysis to make the selection of the optimization algorithm.

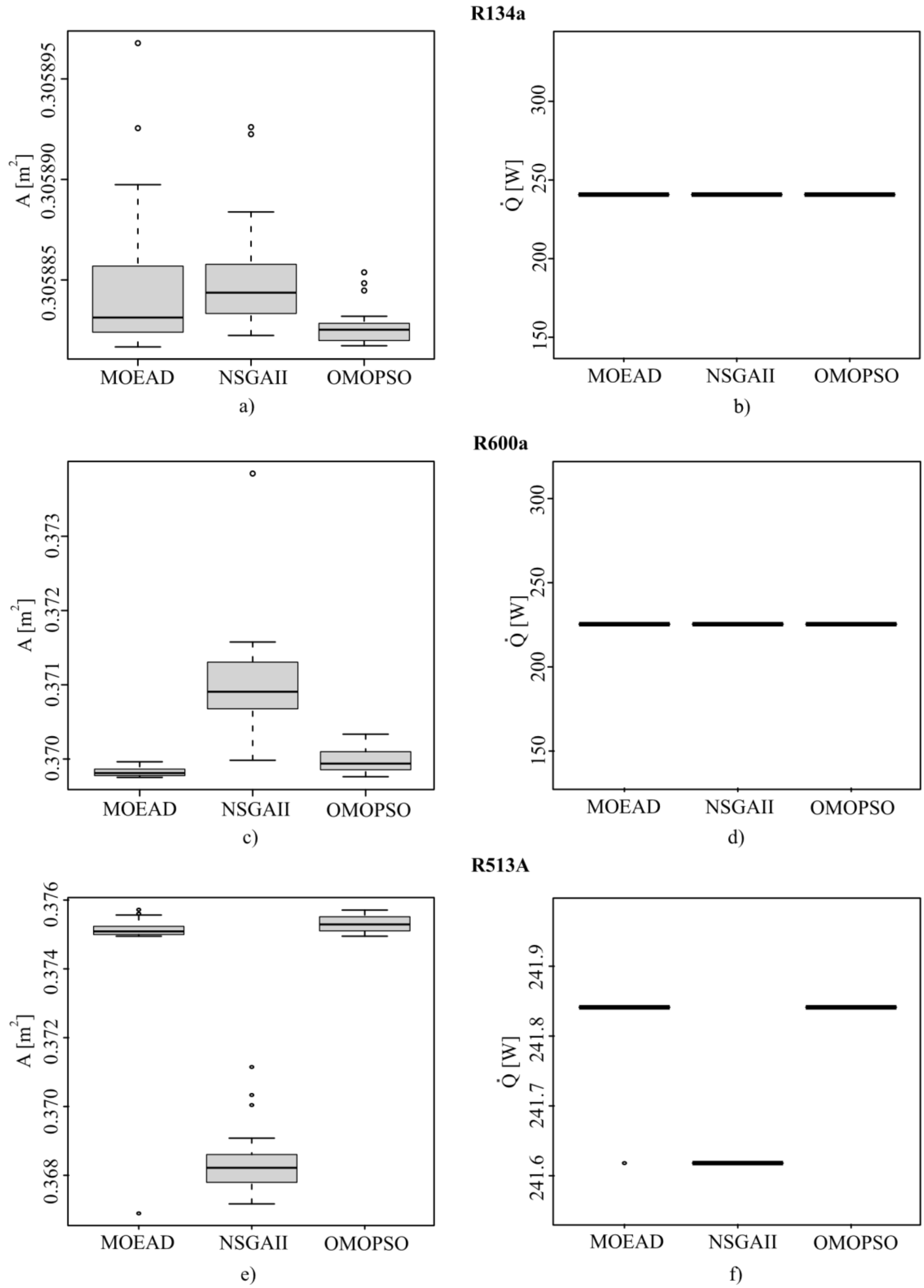

Figure 3. Statistical comparison between NSGAII, OMOPSO, and MOEAD algorithms. (**a**,**c**,**e**) heat transfer area; (**b**,**d**,**f**) heat transfer.

Based on the analysis and the inspection of the box plots, this work proposed an optimization of the multilayer wire-on-tube condenser by using the OMOPSO algorithm, since it is relatively better and consistently outperforms the NSGAII and MOEAD algorithms.

To substantiate the use of the OMOPSO algorithm in this work and under the conditions of the model [25], Table 3 presents a summary of the statistical comparison, through the Tukey HSD pairwise test, among the algorithms presented in Figure 3, which was a specific case for the heat transfer surface. In the first column, the evaluated refrigerant was defined, and in the second column, a grouping of algorithms was proposed for their respective comparisons. The Diff column indicates the mean between the lower limit, *lwr*, and the upper limit, *upr*, of each confidence interval calculated at 95%. Finally, the value of *p adj* indicates whether there was a significant difference in the use of the algorithms. A *p adj* value of >0.05 means that there was not a statistically significant difference between the compared algorithms.

Table 3. Statistical results between algorithms for R134a, R600a, and R513A refrigerants.

Refrigerant	Algorithm	Diff	*lwr*	*upr*	*p adj*
R134a	NSGAII-MOEAD	0.000000466	−0.000000902	0.000001833	0.6976122
	OMOPSO-MOEAD	−0.000001939	−0.000003307	−0.000000572	0.0029952
	OMOPSO-NSGAII	−0.000002405	−0.000003773	−0.000001038	0.0001789
R600a	NSGAII-MOEAD	0.001188397	0.000970156	0.001406639	0.0000000
	OMOPSO-MOEAD	0.000159179	−0.000059061	0.000377421	0.1973007
	OMOPSO-NSGAII	−0.001029218	−0.001247459	−0.000810977	0.0000000
R513A	NSGAII-MOEAD	−0.006567517	−0.007110653	−0.006024381	0.0000000
	OMOPSO-MOEAD	0.000395047	−0.000148089	0.000938183	0.1990515
	OMOPSO-NSGAII	0.006962564	0.006419428	0.007505700	0.0000000

For the case of R134a, a *p adj* value of >0.05 was observed in the comparison of the NSGAII and MOEAD algorithms, which confirmed that there was not a significant difference between the two algorithms. In the comparison between the OMOPSO and the MOEAD algorithms, a *p adj* value of <0.05 was observed, showing in this case that the two algorithms were statistically different, presenting better results with the OMOPSO algorithm (see Figure 3a), a similar case to that presented in the comparison between the OMOPSO and NSGAII algorithms. With respect to the R600a refrigerant, it was observed that the OMOPSO and MOEAD algorithms reflected the lowest dispersion of data, where they did not show up significant differences ($p\ adj > 0.05$). For the case of the analysis with refrigerant R513A, the OMOPSO and MOEAD algorithms were statistically similar ($p\ adj > 0.05$); therefore, there was no significant difference between the results with the use of both algorithms.

3.2. Optimization Results

This section presents the main results of the multilayer wire-on-tube condenser optimization process. The jMetalPy [29] and Python software were used to develop the optimization scenarios [30]. Thus, Figures 4–6 show the Pareto front obtained from the optimization using the OMOPSO algorithm for the refrigerants R134a, R600a, and R513A, respectively. The graphs in each figure show the behaviors for the three geometric cases proposed in this work, varying the number of layers and the number of rows. In addition, each graph also represents the current operating point for each refrigerant, which is marked by crossing the dotted lines.

In the case of the wire-on-tube condenser using R134a (Figure 4), a significant reduction in the heat exchanger area can be observed compared to the current state (line crossing) and a slight increase in the heat transfer of the equipment. Cases 2 and 3 presented very similar Pareto fronts compared to the case where a smaller number of layers and rows were defined. For the analysis of the heat exchanger using R600a (Figure 5), a greater variation in behavior was shown for the three cases under study. However, a quick inspection showed that there were conditions for an area close to the current one where greater heat transfer can be obtained (cases 2 and 3). Regarding the behavior of R513A (Figure 6), the geometric configurations of cases 2 and 3 presented a very similar Pareto front, observing favorable conditions for a greater heat transfer with a smaller exchange surface.

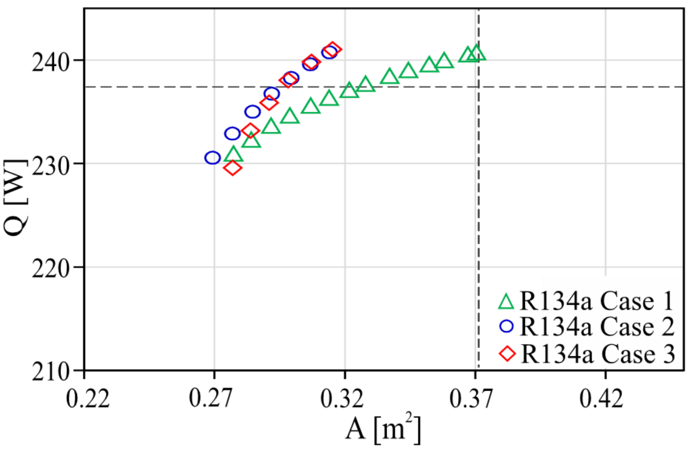

Figure 4. Results of the optimization of the wire-on-tube condenser using R134a.

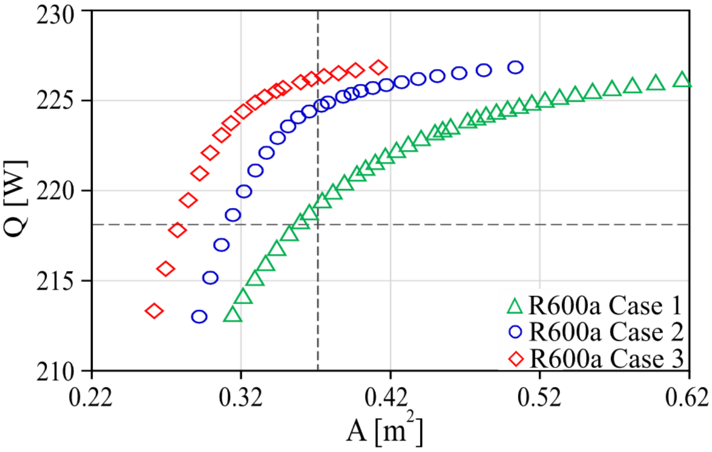

Figure 5. Results of the optimization of the wire-on-tube condenser using R600a.

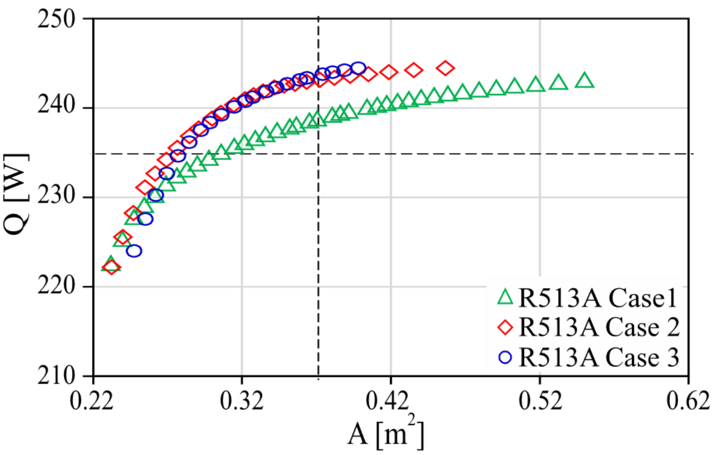

Figure 6. Results of the optimization of the wire-on-tube condenser using R513A.

On the other hand, Table 4 indicates the optimal solution for each case analyzed, where the geometric design of the wire-on-tube condenser for each refrigerant was defined, as well as the total volume of the condenser and the respective mass that each design produces. The optimal point corresponded to the Euclidean distance of the Pareto front points concerning the current operating point calculated for each refrigerant. Thus, Table 4 provides an overview of different optimal designs using different refrigerants. Through a quick inspection of the table, it can be observed, for the cases proposed in this work and for the different refrigerants, that there was indeed a reduction in the heat exchange surface with respect to the reference surface (0.3714 m^2) of the condenser. This was also reflected in a decrease in the mass of the heat exchanger, where the reference mass was 1.216 kg.

Table 4. Optimal geometric designs of the three respective refrigerants for each case analyzed.

Refrigerant	R134a			R600a			R513A		
	Case 1	**Case 2**	**Case 3**	**Case 1**	**Case 2**	**Case 3**	**Case 1**	**Case 2**	**Case 3**
$\dot{Q}$ (W)	240.53	240.72	240.72	218.80	221.10	222.25	238.58	242.92	243.14
A (m^2)	0.36723	0.31415	0.31268	0.36570	0.32961	0.36189	0.36512	0.36334	0.35886
D_w (mm)	1.3	1.0	1.0	1.3	1.0	1.0	1.2	1.0	1.0
S_w (mm)	4.0	5.0	5.0	4.0	5.0	5.0	4.0	5.0	5.0
D_t (mm)	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	4.8
S_t (mm)	21.5	20.0	20.0	21.7	20.0	20.0	27.1	22.2	20.0
L_{tp} (mm)	120.0	105.1	80.0	120.0	111.3	80.0	120.0	120.0	116.0
N_c (-)	6	7	8	6	7	8	6	7	8
N_f (-)	6	7	8	6	7	8	6	7	8
a (mm)	18.0	15.4	10.0	18.0	16.0	14.1	18.0	18.0	18.0
L_t (mm)	6716.0	8070.0	8269.0	6721.0	8437.0	8787.0	6998.0	9211.0	11,597.0
N_w (-)	361.0	295.2	257.0	361.0	312.6	257.0	361.0	338.7	372.2
L_w (mm)	118.5	130.0	150.0	119.1	130.0	150.0	148.9	144.1	150.0
Volume (m^3)	0.000144	0.000130	0.000132	0.000142	0.000136	0.000139	0.000146	0.000152	0.000154
Mass (kg)	1.1205	1.0202	1.0376	1.1184	1.0698	1.0910	1.1449	1.1951	1.2094

For refrigerants R134a and R600a, it was observed that, as the lateral section of the exchanger increased ($N_c = N_f$), there was a decrease in the length of the tube without a wire, a, as well as a decrease in the tube with a wire, L_{tp}. While in the case of R513A a different situation was presented, for the three study cases the length without a wire was kept constant and practically the length with a wire remained unchanged. In fact, for this refrigerant, the largest designs of the condenser were presented, being reflected in a greater surface and a greater mass of the heat exchanger. Finally, it was noted that the results returned a wires number, N_w, that did not correspond to integer values, so rounding to the nearest value could be assumed.

Continuing with the results of this study, Figure 7 shows the percentage reduction in the area of the wire-on-tube condenser for each refrigerant according to the arrangement of the number of rows and the number of layers. For the above, it was considered that the current exchange area was 0.3714 m^2, which was considered 100%. In each case, the condenser optimization was conducted using each of the refrigerants and starting from the current surface. Thus, in Figure 7, it can be seen that for the geometric arrangement of case 1, there was practically no reduction of the area in the heat exchange equipment for any refrigerant. However, for cases 2 and 3, a reduction in area can be seen, thus showing a more compact wire-on-tube condenser. In fact, the use of R134 showed the greatest area reduction, in the order of 15% compared to the current heat exchanger design.

The airflow direction is another important parameter in the operability of the heat exchange equipment. Thus, with the modeling of the wire-on-tube condenser and through the optimization process, Figure 8 shows Pareto fronts comparing the crossflow conditions and the current operating conditions of the condenser for the three refrigerants. For this case, a constant airflow velocity of 5 m/s was considered for both flow conditions.

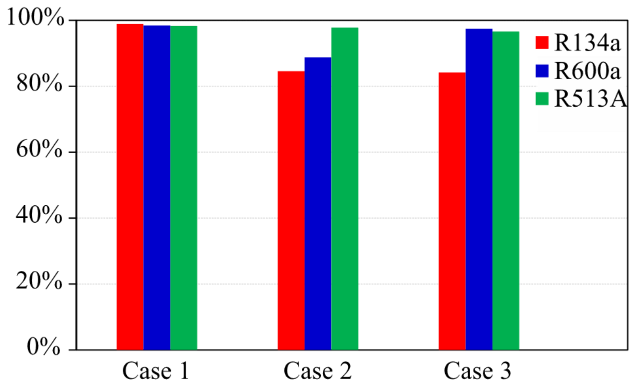

Figure 7. Reductions of the wire-on-tube condenser area for the use of the three refrigerants.

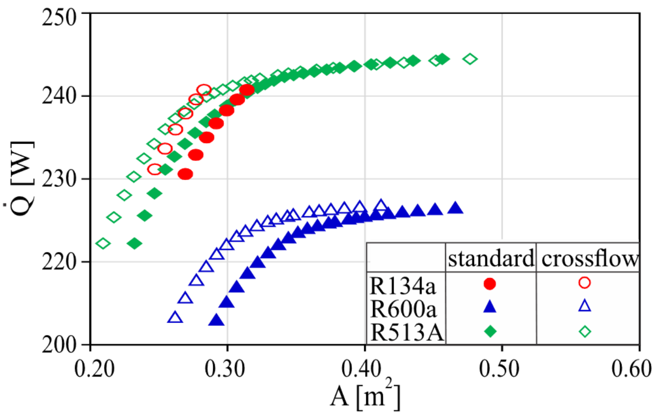

Figure 8. Heat transfers for the current and crossflow conditions.

A quick inspection of Figure 8 shows a clear reduction in the heat exchange surface for the crossflow condition for a defined heat transfer. Considering the optimum point of each Pareto front for the crossflow with respect to the current condition of the condenser, it can be deduced that for the case of R134a there were an increase in heat transfer of 1.4% and a reduction in the area of the 24%. In the case of R600a, an area reduction of 17% was obtained for a heat transfer increase of 2.3%. Finally, the R513A refrigerant presented a reduction in the exchange surface of 2.4% and an increase in the heat transfer of 5%.

4. Conclusions

In this work, the optimization of a multilayer wire-on-tube condenser was conducted considering the maximization of the heat transfer and the reduction of the condenser area as objective functions. In addition, through the statistical analysis performed for the evaluation and selection of the best algorithm, it was obtained that OMOPSO presented statistically better results compared to the NSGAII and MOEAD algorithms.

By using the OMOPSO multi-objective optimization algorithm and evaluating eight geometric parameters, the Pareto front graphs were obtained for three case studies and for three refrigerants R134a, R600a, and R513A, obtaining for each case the current operating conditions and the optimization proposal. Through the optimization process, a considerable improvement in the design of the multilayer wire-on-tube condenser was obtained using the refrigerants evaluated in this work.

Since R600a and R513A refrigerants are considered low GWP alternatives for domestic refrigeration systems, in this case, the use of R600a presented greater benefits in terms of reduction of the condenser heat exchange area. On the other hand, the operation of the wire-on-tube condenser under crossflow conditions considerably improved the heat transfer, thus allowing a greater reduction in the condenser area.

Finally, this type of study allows expanding the knowledge of the use of heuristic optimization algorithms in multi-objective optimization processes for heat exchange equipment and helps design engineers or manufacturers to present better, more compact designs with greater heat transfers.

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Nomenclature

a	length without wires (mm)
A	area (m^2)
CFD	computational fluid dynamics
D	diameter (mm)
FOA	Falcon Optimization Algorithm
GWP	Global Warming Potential
L	length (mm)
L_{tp}	length with wire (mm)
$\dot{m}$	mass flow rate (kg/s)
MOEAD	Multi-objective Evolutionary Algorithm based on Decomposition
MOGA	Multi-objective Genetic Algorithm
MOHTS	Multi-objective Heat Transfer Search
MOWO	Multi-objective Wale Optimization
N_c	layers number (-)
N_f	rows number (-)
N_w	wires number (-)
NSGAII	Non-dominated Sorting Genetic Algorithm-II
NTU	number of transfer units (-)
OMOPSO	Optimized Multi-objective Particle Swarm Optimization
P	pressure (bar)
$\dot{Q}$	heat transfer rate (W)
S	pitch (mm)
T	temperature (K)
Subscripts	
amb	ambient
air	air
cond	Condensation and condenser
dsh	desuperheating
in	inlet
out	outlet
r	refrigerant
sub	subcooling
T	total
t	tube
w	wire

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