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Thermal and Hydrodynamic Performance Analysis of a Shell and Tube Heat Exchanger Using the AHP Multicriteria Method

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Abstract. The goal of this work is to identify the best alternatives that allow for improving the thermal efficiency of a shell and tube heat exchanger in real operating conditions. The main motivation for carrying out the research is based on the need identified, together with the oil, natural gas, and alternative energy industry, to analyze and learn about the main criteria that directly impact the thermal efficiency of a heat exchanger. The applied methodology was based on the AHP (Analytic Hierarchy Process) multicriteria method. Three relevant criteria were identified: Thermodynamic, Hydrodynamic, and Economic. Additionally, a complete analysis of 9 sub-criteria (i.e. energy and exergetic analysis of the process, analysis of the thermodynamic properties of the fluids; pressure drop, volumetric flow of hot and cold fluids; energy costs, maintenance, operation and geometry of the heat exchanger) allowed us to conclude that the best strategy to increase the thermal efficiency of a heat exchanger in real operating conditions consists of using innovative online cleaning prototypes that use abrasive spheres. This will allow the heat exchanger to be cleaned simultaneously with its operation, reducing downtime and maintenance times/costs.

Keywords: AHP; Hydrodynamic performance; MCDM; Shell-and-tube heat exchanger; Thermal efficiency

1. Introduction

Shell and tube heat exchangers are devices that transfer thermal energy from a hot medium to a colder medium within a system. This allows the generation of large exchange areas in small spaces. These have long-term importance in the industry, already constant that, since their appearance, have allowed optimization in thermal and production processes thanks to the different models, designs, and configurations that have emerged according to our needs. The accumulation of deposits in heat exchangers is strongly aggravated by the presence of microorganisms present in cooling water, especially those

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originating from storage tanks and seawater. Furthermore, such exchangers lose, over time, the power to cool the bearings and moving components of industrial equipment. The thermal efficiency, which is subject to the characteristics in the parameters of a heat exchanger, is frequently affected by mechanical phenomena such as corrosion, overpressure in the fluid transport duct, biofouling or chemical fouling. This greatly compromises the thermal and hydrodynamic performance of the heat exchanger. After an exhaustive bibliographic review, it is observed that multiple models of the multicriteria method have been implemented in decision-making, such as the evaluation study between a helical exchanger and a plate exchanger for nuclear reactors. Sabharwall, Kim, and Patterson (2012) applied the integration between MOEA and AHP for advanced heat exchanger concepts in industrial equipment. In Tahmasebzadehbaie *et al.* (2017) realized the integration between the FUZZY failure mode, the FMEA FUZZY, and AHP responded to the study of risk analysis and mitigation in order to proper strategies for improving the thermal efficiency and environmental emission of a gas-turbine cycle. Two years later, Mano *et al.* (2019) published a study of the costs associated with the environmental impacts caused by energy generation and the construction of equipment incorporated in the synthesis of the Heat Exchanger. The analyses were carried out through the integration of the FUZZY and AHP model. In Roy and Majumder (2019), realized a study of the productivity performance of a shell and tube heat exchanger using the NBO multicriteria model. In the same year, the efficiency improvement in natural gas boiler systems was studied using the AHP model (Cui *et al.*, 2019). The results of both researches confirmed the importance of applying the decision-maker method in order to know the performance of the heat exchanger in the industrial sector. In that same year, 2019, Wicaksono *et al.* (2019) studied the effect of changes in the surface area of a heat exchanger and its impact on its thermal efficiency in order to assess whether geometric and structural changes of an exchanger are really significant in relation to its thermal efficiency. The results confirmed that a larger heat exchange surface area produced a greater cooling load and a greater temperature difference between the working fluids, thus favoring an increase in the system's thermal efficiency and confirming the importance of the geometry of the exchanger in the heat transfer process.

In 2020, a study realized by (Wu *et al.*, 2020) confirmed that the thermodynamic variations between an integrated energy system with an organic Rankine cycle could be analyzed by focusing on the MADM model. On the other hand, the selection of a sustainable renewable energy source in India was achieved through the implementation of the TOPSIS analysis for the selection of nanomaterials in the heat exchanger application (Krishankumar *et al.*, 2021). In Maisuria, Sonar, and Rathod (2021), considered that different nanofluids are characterized by suspensions of nanometric-sized nanoparticles in the fluid, and based on these nanoparticles, the thermal performance of a heat exchanger can be improved. Thus, the authors used the AHP model to determine the weights of the criteria and, subsequently, used the TOPSIS model to classify the best alternatives that allowed them to select the appropriate nanoparticles for a heat exchanger. Thus, confirming the studies by Wicaksono *et al.* (2019) regarding the impact of geometry on the heat exchanger, in Shukla, Bhabhor, and Jani (2022a) published an experimental work and a review of the literature where they detail the study carried out on a shell and tube heat exchanger (STHE) with variations in the types of baffles (Shukla, Bhabhor, and Jani, 2022a; Shukla, Bhabhor, and Jani, 2022b). During the experiments, they used various types and angles of baffles that allowed them a wide range of possibilities regarding the analysis of the geometric impact on the thermal efficiency of the exchanger. The authors confirmed that the efficiency of the tube heat exchanger increased significantly as the baffles were varied. Furthermore, it was confirmed that the type of material used and the number of baffles used greatly impact the change in the heat transfer coefficient and rate.

Regarding the pressure gradient, the authors confirmed that it is affected by changes in the material and the number of baffles inside the shell. Moreover, in Zhang, Yi, and Xie (2022), using the AHP multicriteria method, designed and put into operation a two-stage heat exchanger. The authors analyzed the heat transfer characteristics under different flow rates. In addition, they propose some optimization procedures. The authors concluded that the performance of the heat exchanger under a flow rate ratio of 1.72 to 3.72 increased the effectiveness of the heat exchanger. Thus, the results of the experimental model confirmed that the hydrodynamic criteria are the most relevant when analyzing the thermal effectiveness of the heat exchanger. He *et al.* (2022) propose alternative methods that allow for increasing the thermal efficiency of a heat pump. To achieve this goal, they adopted the dip coating method. During the experiments, they analyzed three types of absorbent compounds and applied the AHP multicriteria method to evaluate the thermal performance of the heat pump. The results confirmed that the thermal criterion associated with the mass transfer during the absorption process is the most important to consider since it directly impacts the thermal performance of the heat pump. Hazza *et al.* (2022), in the area of production and selection of suppliers for industrial equipment, using the integration of the Delphi and AHP multicriteria methods, carried out a study for the selection of suppliers of small and medium-sized companies. During the investigation, the authors identified five main criteria: price, delivery time, rejection number, flexibility, and online classification. Where after implementing the Delphi method twice, the specialists reached a consensus. The results confirmed that 43.84% of the price of suppliers of industrial equipment (engines, heat exchangers, etc.) is the most relevant for the industrial sector. This recent work confirms that the economic factor is a relevant criterion when evaluating a heat exchanger and its direct impacts on thermal efficiency.

On the other hand, Keklikcioglu *et al.* (2022) carried out an investigation where they studied the main hydrodynamic impacts in a heat exchanger. They evaluated the separation of the boundary layer inside the duct and the importance of evaluating the Reynolds number. Additionally, hydrodynamic losses due to pressure drop and heat transfer mechanisms by conduction and convection were considered. All these criteria were evaluated using the AHP-TOPSIS hybrid method. During the experiments, the authors evaluated six different Reynolds numbers to know the influence of the flow regime on the thermal efficiency of the heat exchanger. Based on the thermal criteria, the authors evaluated the Nusselt number and its impact on the thermal and hydrodynamic performance of the heat exchanger. As a contribution of the research, the authors affirm that the variation of the input parameters generates changes in the performance parameters, such as the friction factor, the Nusselt number, and the thermo-hydraulic performance factor. In the same line of research initiated by Keklikcioglu *et al.* (2022), in order to evaluate and improve the thermal effectiveness of a shell and tube heat exchanger, Gowri *et al.* (2022) proposed a study modifying the geometry of the heat exchanger. To analyze the problem, they used a multi-objective genetic algorithm (GA) in addition to applying the FAHP-VIKOR hybrid multicriteria method. In this way, the authors selected the best geometric model that optimized the thermal effectiveness of the heat exchanger. In this study, it was concluded that the Nusselt number increases with increasing Reynolds number. The Nusselt number of the slotted tube confirmed an increase of up to 56% in the heat transfer flux of the process.

Thus, considering the cited literature, it is found that the specialized literature is not clear in presenting an investigative work that analyzes various aspects related to the heat transfer process. These aspects are related to economic, environmental, social, and technical criteria, among others, and their interrelation with the thermal efficiency of a shell and tube heat exchanger, which is widely used in the industrial sector and, mainly, in hydroelectric plants, for the generation of electrical energy from hydraulic energy.

In this context of state of art, the specialized literature confirms the importance of using multicriteria decision support methods to evaluate the thermal performance of a heat exchanger. In specific terms, using the AHP model, this work proposes to evaluate the best strategies that increase the thermal effectiveness of a shell and tube heat exchanger in light of thermal, hydrodynamic, and economic criteria.

2. Methodology applying the AHP multicriteria method

The AHP (Analytic Hierarchy Process) multicriteria method is a widely used decision-making tool to determine priorities between different criteria, sub-criteria, and alternatives. It was introduced and defined by Saaty (1977) as an effective tool to deal with complex decision-making that can help the decision-maker set priorities and make the best decision. The basis of the AHP method is the decomposition and synthesis of the relationships between the criteria. Therefore, it is possible to achieve a prioritization of the criteria, which will be closer to the best single measurement response (Satty, 1991; 1990; 1985; 1977). Briefly, the theory's central idea is the study of systems from a sequence of pairwise comparisons. It allows you to generate weights for each evaluation criterion based on paired comparisons provided by the experts/judges of these criteria (Kadoi, Re-ep, and Divjak, 2017; Thomas and Vargas, 2006). In its initial formulation, AHP assumes four hypotheses (reciprocity, homogeneity, hierarchies and systems with dependencies, and expectations) and uses a hierarchy as a structure to model the problem, in which the elements of a level did not depend on the descendants or the criteria of the same level. At the top level of the hierarchy (level 0), the global goal or mission considered for the problem is placed, and at the successive levels (1,2,3...), the other relevant aspects. In the simplest case of hierarchy (only two additional levels), the considered criteria are included in the next level (level 1) and the alternatives in the last (level 2). This simplified model can be completed as much as necessary to achieve a realistic representation of the problem, including different levels for the scenarios. The resulting hierarchy must be complete, representative (includes all relevant attributes), non-redundant, and minimal (does not include irrelevant aspects). Its construction is the most creative part of the resolution process, and opposing positions may appear between the different participants. In this sense, an agreement between the parties involved is necessary before proceeding with the resolution. This way of modeling the problem includes all the relevant aspects in a single hierarchy. However, when enough information about the problem is available, it is possible to break down the initial hierarchy into more detailed or precise ones.

In mathematical terms, the value function for each alternative is given by Equation (1):

$$\boldsymbol{F(a) = \sum_{j=1}^{n} w_j v_j(a)} \tag{1}$$

In this equation:
$F(a)$: indicates the final value of alternative a;
w_j: denotes the weight of the j-th criterion
v_j: denotes the performance of the alternative in relation to the j-th criterion.

Considering that $x = (x_1, x_2, \dots x_n)$ and $y = (y_1, y_2, \dots, y_n)$ can be written in matrix notation $A \cdot x = y$, where A is the judgment matrix, given by:

$$A = \begin{bmatrix} \frac{w_1}{w_1} & \frac{w_1}{w_2} & & \frac{w_1}{w_n} \\ \frac{w_2}{w_1} & \frac{w_2}{w_2} & \cdots & \frac{w_2}{w_n} \\ \vdots & & \ddots & \vdots \\ \frac{w_n}{w_1} & \frac{w_n}{w_2} & \cdots & \frac{w_n}{w_n} \end{bmatrix} \tag{2}$$

Algebraically this operation can be represented by Equation (3):

$$\sum_{j=0}^{n} a_{ij} \cdot x_i = y_i \qquad \therefore \qquad i = 1, 2, 3, \dots, n \tag{3}$$

since $a_{ij} = \frac{w_j}{w_i}$, we get:

$$a_{ij} \frac{w_j}{w_i} = 1 \qquad \therefore \qquad i, j = 1, 2, 3, \dots, n \tag{4}$$

therefore:

$$\sum_{j=0}^{n} a_{ij} \cdot w_j \frac{1}{w_i} = n \qquad \therefore \qquad i = 1, 2, 3, \dots, n \tag{5}$$

or:

$$\sum_{j=0}^{n} a_{ij} \cdot w_j = n w_i \qquad \therefore \qquad i = 1, 2, 3, \dots, n \tag{6}$$

Which is equivalent to the matrix equation:

$$Aw = nw. \tag{7}$$

A measure of consistency called the Consistency Index (CI), given by equation (8), is used to calculate the deviation of λ_{max} in relation to n since the use of the scale for the sentences generates variations in a_{ij}, altering the value of λ_{max}:

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{8}$$

The Consistency Relation (CR) is given by the following expression:

$$CR = \frac{CI}{RI} \tag{9}$$

The RI parameter, also known as Random Index, denotes the consistency index of a randomly generated reciprocal matrix, based on the scale from 1 to 9, as forced reciprocals (Saaty, 1977). The final evaluation of the statement's consistency occurs by comparing the value of CR. For the development of the research, the following considerations are made: CR≤0.1: it consists of a coherent judgment; 0.1 <CR< 0.2: Questionable judgment; CR≥0.2: Incoherent sentence. It indicates that the paired comparisons of that stage generated a high inconsistency rate, and the expert must redo their judgments.

In summary, the calculation methodology is based on the following structure: (i) define a clear objective; (ii) define the criteria, sub-criteria, and alternatives; (iii) establish the weight of the criteria and sub-criteria; (iv) calculate the Consistency Index; (v) calculate the Consistency Relation; (vi) establish the weight and ranking of the alternatives.

3. Results and Discussion

From the information available in the specialized literature on publications by different authors in the research area (Table 1), it was perceived that the study of the thermal efficiency of heat exchangers considers the energetic, thermodynamic, hydrodynamic, economic, and environmental, among others. In all cases, the Consistency Ratio (CR) calculated did not exceed the value of 0.1. In the subsequent sections, for each of the criteria and sub-criteria evaluated, this CR value is found at the bottom of the tables. It can be seen that, although there is significant subjectivity in the responses associated with each specialist, the consistency index does not exceed the maximum value established in the model, which confirms the robustness of the associated hypotheses defined for the application of the model AHP.

Table 1 Criteria adopted in published research and available in the literature

Authors	Criteria
Gowri *et al.* (2022)	Energetic
Keklikcioglu *et al.* (2022)	Thermodynamic, Mechanical
Zhang, Yi, and Xie (2022)	Thermodynamic, Hydrodynamic, Mechanical.
He *et al.* (2022), Wicaksono *et al.* (2019)	Thermodynamic, Energetic, Geometric Design.
Maisuria, Sonar, and Rathod (2021)	Thermodynamic, Economic.
Wu *et al.* (2020)	Energetic, economical
Roy and Majumder (2019)	Uncertainty, Economic, Energy, Environmental.
Mano *et al.* (2019)	Thermodynamic, Environmental, and Economic
Sabharwalla, Kim, and Patterson (2012)	Thermodynamic, Geometric Design, Economic, Operational, Materials, Hydrodynamic, Structural

From the information collected and consolidated in Table 1, three criteria were selected, which are widely cited in the specialized literature, these are (i) Thermodynamic, (ii) Hydrodynamic, and (iii) Economic. Concerning the data collection and evaluation process, the research instrument considered nine topics in the analysis of the efficiency of a shell and tube heat exchanger, taking into account the inherent characteristics of the different thermal and hydrodynamic parameters that impact the heat transfer process as well as the criteria and sub-criteria of analysis adopted. Table 2 summarizes the themes and dimensions considered in the research.

Table 2 Criteria and Sub criteria

CRITERIA	SUBCRITERIA	
Thermodynamic	T1	Energy balance based on the first law
	T2	Thermodynamic properties: density, specific heat, and thermal conductivity
	T3	Exergy analysis of the process
Hydrodynamic	H1	Pressure difference between hot and cold fluids
	H2	Volumetric flow of hot and cold fluids
	H3	Cold fluid pressure drops through the exchanger ducts
Economic	E1	Energy cost
	E2	Cost of maintenance and operation
	E3	Cost of redesign and manufacturing of new heat exchanger components

The following table summarizes the proposed alternatives to meet the objective of increasing the thermal efficiency of the heat exchanger:

Table 3 Proposed solution alternatives

ALTERNATIVES		DESCRIPTION
Alternative #1	A1	Increase the straight sections of the exchanger through which the liquid water flows and, in this way, guarantee a constant velocity profile during the heat transfer process.
Alternative #2	A2	Perform the calibration of temperature, pressure, and flow meter sensors to make corrections to the measurement indicated by the instruments. Thus, it is possible to calculate thermal efficiency with corrected and reliable values.
Alternative #3	A3	Implement a mathematical model that allows predicting the cleaning and shutdown periods of the heat exchanger based on the calculation of the Fouling Factor.
Alternative #4	A4	Use innovative online cleaning prototypes that use abrasive spheres. This will allow the heat exchanger to be cleaned simultaneously with its operation, reducing downtime and maintenance times/costs.
Alternative #5	A5	Implement a data acquisition and measurement system in real-time. This will allow the control of the process during the 24 hours of the day and identify variations, as well as fluctuations presented throughout a day of operation.

The results showed that the Consistency Relation (CR) for the criteria and sub-criteria matrices meets the condition of CR ≤ 0.10. The results associated with the investigation are tabulated and will be presented in the subsequent sections. It is important to note that the last column, "Priorities" corresponds to the weight of the criterion and/or sub-criterion depending on the case analyzed and is an absolute value of the percentage value. The numbers or fractions defined for the relationship of each criterion and/or sub-criteria were made based on the specialized literature proposed by Saaty (1977).

Thus, Table 4 presents the results of the matrices obtained in relation to the criteria, highlighting in bold the Thermodynamic criterion, which, in the light of the specialists consulted, is the criterion with the greatest impact on the thermal efficiency of a heat exchanger:

Table 4 Criteria comparison matrix

CRITERIA	Thermodynamic	Hydrodynamic	Economic	Priorities
Thermodynamic	**1**	**1**	**3**	**0.4429**
Hydrodynamic	1	1	2	0.3873
Economic	1/3	1/2	1	0.1698

*Consistency Ratio calculated as 0.016

The results of the previous table confirmed that, in 44.29%, the thermodynamic criterion is more relevant in relation to the thermal efficiency of a shell and tube heat exchanger, followed by the hydrodynamic criterion with 38.73% and, finally, the economic criterion. With 16.98%. It can be seen that the Consistency Ratio was calculated as 0.016, which confirms the consistency of the matrix. This result is in line with the fundamentals established in the specialized literature (Saaty, 1977) since the thermal efficiency is based on the measurements of the inlet and outlet temperatures of the air and water fluids. In a heat exchanger system, these temperatures are typically measured using Pt-100 type platen resistance meters.

Considering each criterion, a paired comparison was made between the respective sub-criteria. For the case of the thermodynamic criterion, Table 5 confirms that the one with the greatest weight corresponds to the exergy analysis of the process with 52.47% (highlighted in bold). This result is explained because an exergy analysis (second law of thermodynamics) necessarily includes an energy analysis (first law of thermodynamics). In this way, in order to know the best alternatives that allow increasing the thermal efficiency of a heat exchanger, it is necessary to know not only the energy generated but also how much of that generated energy is useful for the system, that is, it requires knowledge of the exergy of the heat transfer process.

Table 5 Comparison matrix: Thermodynamic sub-criterion.

Criterion: Thermodynamic	Energy balance based on the first law	Thermodynamic properties: density, specific heat and thermal conductivity	Exergy analysis of the process	Priorities
Energy balance based on the first law	1	1/3	1/3	0.1416
Thermodynamic properties: density, specific heat, and thermal conductivity	3	1	1/2	0.3338
Exergy analysis of the process	**3**	**2**	**1**	**0.5247**

*Consistency Ratio calculated as 0.046

For the situation where the sub-criteria of the hydrodynamic criterion were analyzed, the consolidated results of Table 6 show that the Volumetric flow of hot and cold fluids, with 58.13%, is the most relevant when analyzing the thermal efficiency of a heat exchanger (highlighted in bold, Table 6). Specialists agree that the heat flow is a function of the mass or volumetric flow of fluids ($\dot{Q} = \dot{m}C_p\Delta T$). In this context, the mass or volumetric flow of the water in the heat exchanger under study is measured by a Krohne Optisonic 6000/UFC 300W converter whose calibration was carried out in the LC-Controls Metrologia laboratory (accredited by the General Coordination of Accreditation of Inmetro - Brazil, CGCRE). As the mass flow increases, maintaining a constant temperature variation, the heat exchanger between the working fluids (water and air) will be greater. Consequently, the thermal efficiency of the system will be greater.

Table 6 Comparison matrix: Hydrodynamic sub-criteria

Criterion: Hydrodynamic	Pressure difference between hot and cold fluids	Volumetric flow of hot and cold fluids	Cold fluid pressure drops through the exchanger ducts	Priorities
Pressure difference between hot and cold fluids	1	1/2	3	0.3092
Volumetric flow of hot and cold fluids	**2**	**1**	**5**	**0.5813**
Cold fluid pressure drops through the exchanger ducts	1/3	1/5	1	0.1096

*Consistency Ratio calculated as 0.0032

In relation to the economic criterion, with 70.14% (highlighted in bold in Table 7), the specialists agree that the Cost of maintenance and operation is the most relevant when considering an increase in the thermal efficiency of a heat exchanger.

In this context, a high maintenance cost indicates that the Fouling Factor (FF) increases exponentially. From the specialized literature (Susmiati *et al.*, 2022; Susanto *et al.*, 2020; Frota, 2019), it is known that the FF is a parameter whose behavior is inverse to thermal efficiency. That is, an increase in FF necessarily implies a decrease in thermal efficiency. During its operation in a hydroelectric plant, a heat exchanger is exposed to various impurities, suspended solids, and algae from the river. This favors energy losses, economic losses in operation, and increased maintenance costs. The mean time between failures begins to decrease, and the undesirable maintenance stops begin to be more and more frequent. For this reason, specialists agree that, unquestionably, from an economic point of view, the Cost of maintenance and operation directly impacts the thermal efficiency of a heat exchanger. The results from the paired comparison of the alternatives based on each sub-criterion are shown below. Note that, based on each sub-criterion, a given alternative was identified as the best solution. However, at the end of applying the AHP method, these alternatives must be weighted to finally be able to perform a ranking and identify the ideal solution. For the situation where the sub-criteria associated with the thermodynamic criterion were analyzed (Table 8), it is observed that the best alternatives correspond to A4 (42.27%) for the case of the sub-criterion Energy balance based on the first law; A2 (29.30%) for the case of the sub-criterion Thermodynamic properties: density, specific heat and thermal conductivity and A3 (42.29%) for the case of the sub-criterion Exergy analysis of the process. It is interesting to note that the specialists consider that when carrying out the energy balance based on the first law, the use of innovative prototypes that allow the cleaning of the heat exchanger simultaneously with its operation improves the effectiveness of the equipment and reduces economic costs. Associated with the process. Already in the situation where the thermodynamic properties of the working fluids (density, specific heat and thermal conductivity) are analyzed, the specialists agree that the best alternative is to have properly calibrated instrumentation in order to correct the temperature measurements, pressure and volumetric flow. These measurements can be corrected by applying analytical methods, the concept of systematic error, or the calibration certificate. In all cases, there will be a high metrological reliability of the measurements made and, consequently, of the calculation of the thermodynamic properties dependent on these measurements. In relation to exergetic analysis, specialists agree that establishing analytical models that allow cleaning periods to be identified and predicted will increase the useful energy of the process. Unquestionably, establishing longer cleaning periods, that is, increasing the mean time between failures due to the Fouling Factor, translates into energy use of the system. Therefore, an analysis based on the second law of thermodynamics is the most recommended to know the scope of this improvement.

Table 7 Comparison matrix: Economic sub-criteria

Criterion: Economic	Energy cost	Cost of maintenance and operation	Cost of redesign and manufacturing of new heat exchanger components	Priorities
Energy cost	1	1/4	3	0.2132
Cost of maintenance and operation	**4**	**1**	**7**	**0.7014**
Cost of redesign and manufacturing of new heat exchanger components	1/3	1/7	1	0.0853

*Consistency Ratio calculated as 0.028

For the situation where the sub-criteria associated with the hydrodynamic criterion were analyzed (Table 9), the alternatives A1 (42.52%), A2 (40.62%), and A4 (41.75%) were the ones that obtained the greatest weight. Regarding the “Pressure difference between hot and cold fluids” sub-criterion, specialists agree on the importance of guaranteeing a fully developed flow for the hydrodynamic analysis of the system. For this purpose, it is important to guarantee a section of straight section not less than 80 times the internal diameter of the duct (80D). This will allow a greater hydrodynamic length for the parabolic development of the velocity profile in accordance with Newtonian fluid mechanics theory. Unquestionably, this solution directly implies a new configuration of the heat exchanger system, and the economic impacts, analyzed in the next criterion, must be taken into account. In the case of the “Volumetric flow of hot and cold fluids” sub-criterion, the specialists confirm that the best alternative is to guarantee the metrological reliability of the measurement system through the calibration of the instruments connected to the heat exchanger. In the case of the heat exchanger analyzed, the airflow is not measured but calculated from an energy balance. In this context, the hydrodynamic behavior of the heat exchanger has shown an inconsistency in the calculation of the airflow from the mass balance. The airflow is controlled by a motor with constant RPM. Thus, theoretically, the mass flow of the air must be constant throughout the entire process. However, in the calculation of the airflow, very high values have been obtained. Different throughout the day. These values vary from 7000 m^3/h to 22000 m^3/h. Different works carried out in the research area (Frota, 2019; Frota, 2021a; Frota, 2021b) have confirmed that there is a difficulty in measuring the air outlet temperature, which ends up having a direct impact on the metrological reliability of the system and, consequently, on the flow calculation. From airflow, the correction was performed using the median of the calculated values, which allowed for obtaining a more homogeneous and representative heat exchanger efficiency curve of the physical nature of the problem (Frota, 2019). In this way, the volumetric flow of the working fluids (water/air) must be strongly controlled based on the calibration of the measuring instruments connected to the heat exchanger. Finally, in relation to the "Cold fluid pressure drops through the exchanger", it is a parameter directly related to the thermal efficiency of the heat exchanger. A higher pressure drop translates into the higher energy consumption of the industrial equipment connected to the hydro-generator system (motors, pumps, etc.). In addition, it is an indicator of an increase in the Fouling Factor, and it is required to carry out a maintenance stop to clean the system. Thus, the best alternative is to use innovative cleaning prototypes that allow, simultaneously the operation and cleaning of the heat exchanger.

Table 8 “Thermodynamic sub-criteria” from all Alternatives

Sub-Criterion	Alternatives	A1	A2	A3	A4	A5	Priorities
Energy balance based on the first law	A1	1	1/4	1/3	1/4	1/3	0.0614
	A2	4	1	3	1/2	4	0.2794
	A3	3	1/3	1	1/6	1/3	0.0947
	A4	**4**	**2**	**6**	**1**	**4**	**0.4227**
	A5	3	1/4	3	1/4	1	0.1418
Thermodynamic properties: density, specific heat and thermal conductivity	A1	1	1/4	1/3	1/4	1/4	0.0554
	A2	**4**	**1**	**4**	**1/2**	**2**	**0.2930**
	A3	3	1/4	1	1/3	1/3	0.1003
	A4	4	2	3	1	1/2	0.2764
	A5	4	1/2	3	2	1	0.2749
Exergy analysis of the process	A1	1	3	1/3	2	2	0.2144
	A2	1/3	1	1/3	1/3	3	0.1150
	A3	**3**	**3**	**1**	**3**	**5**	**0.4229**
	A4	1/2	3	1/3	1	3	0.1800
	A5	1/2	1/3	1/5	1/3	1	0.0677

For the situation where the sub-criteria associated with the Economic criterion were analyzed (Table 10), alternatives A4 (41.75% for the Energy Cost sub-criterion and 38.14% for the Cost of maintenance and operation sub-criterion) and A1 (40.59%) were the who gained more weight. In the case of the "Energy cost" and "Cost of maintenance and operation" sub-criteria, the specialists consider that the best alternative is associated with using an innovative online cleaning prototype. The literature confirms that the use of this equipment reduces the costs associated with operation, maintenance, and, consequently, energy costs. Finally, in relation to the sub-criterion "Cost of redesign and manufacturing of new heat exchanger components", it necessarily impacts the economic part of the process since it includes the performance of manufacturing actions and metalworking activities that seek to guarantee the hydrodynamic operation of the process. The fundamental objective of this alternative is to guarantee a constant velocity profile of the cold fluid (water) through the implementation of a straight section that allows an adequate hydrodynamic length to have a fully developed flow in the process. From this velocity profile, carrying out an energy balance that includes the full effects of conduction and convection will be possible. That is, viscous dissipation and the impact of linear momentum in the convective heat transfer process are considered. In this way, unquestionably, redesigning the heat exchanger is intrinsically related to the technical and operational gains of the industrial equipment.

Table 9 "Hydrodynamic sub-criteria" from all Alternatives

Sub-Criteria	Alternatives	A1	A2	A3	A4	A5	Priorities
Pressure difference between hot and cold fluids	**A1**	**1**	**4**	**4**	**3**	**3**	**0.4252**
	A2	1/4	1	1/2	1/3	2	0.0957
	A3	1/4	2	1	1/3	3	0.1404
	A4	1/3	3	3	1	5	0.2684
	A5	1/3	1/2	1/3	1/5	1	0.0703
Volumetric flow of hot and cold fluids	A1	1	1/4	1/3	1/3	1/3	0.0654
	A2	**4**	**1**	**3**	**3**	**3**	**0.4062**
	A3	3	1/3	1	1/3	1/4	0.1106
	A4	3	1/3	3	1	2	0.2249
	A5	3	1/3	4	1/2	1	0.1928
Cold fluid pressure drops through the exchanger ducts	A1	1	1/3	1/2	1/4	2	0.1056
	A2	3	1	3	1/2	3	0.2659
	A3	2	1/3	1	1/4	1/2	0.1056
	A4	**4**	**2**	**4**	**1**	**4**	**0.4175**
	A5	1/2	1/3	2	1/4	1	0.1056

Table 10 "Economic sub-criteria" from all Alternatives

Sub-Criteria	Alternatives	A1	A2	A3	A4	A5	Priorities
Energy cost	A1	1	1/3	1/2	1/4	2	0.1056
	A2	3	1	3	1/2	3	0.2659
	A3	2	1/3	1	1/4	1/2	0.1056
	A4	**4**	**2**	**4**	**1**	**4**	**0.4175**
	A5	1/2	1/3	2	1/4	1	0.1056
Cost of maintenance and operation	A1	1	1/3	1/4	1/4	1/3	0.0646
	A2	3	1	2	1/2	3	0.2545
	A3	4	1/2	1	1/3	1/2	0.1419
	A4	**4**	**2**	**3**	**1**	**3**	**0.3814**
	A5	3	1/3	2	1/3	1	0.1576
Cost of redesign and manufacturing of new heat exchanger components	**A1**	**1**	**3**	**5**	**3**	**3**	**0.4059**
	A2	1/3	1	4	1/3	3	0.1705
	A3	1/5	1/4	1	1/4	1/3	0.0528
	A4	1/3	3	4	1	4	0.2685
	A5	1/3	1/3	3	1/4	1	0.1024

The consolidated results in Figure 1c allowed for establishing a ranking of the strategies that seek to establish the best strategies that allow increasing the thermal efficiency of a heat exchanger.

Table 11 Ranking of alternatives

Alternatives	Priorities
A4	0.263
A2	0.244
A3	0.187
A1	0.162
A5	0.144

4. Conclusions

This work allowed, applying the AHP multicriteria method, to establish a ranking of the best strategies that increase the thermal efficiency of a shell and tube heat exchanger. The consolidated results allowed us to establish that the best alternative to improve the efficiency of an exchanger is A4 (26.3%), which consists of using innovative online cleaning prototypes that use abrasive spheres. This will allow the heat exchanger to be cleaned simultaneously with its operation, reducing downtime and maintenance times/costs. Next, alternative A2 (24.4%) proves to be the second most appropriate option. This alternative is related to the calibration of temperature, pressure, and flow meter sensors, with the purpose of making corrections to the measurement indicated by the instruments. Thus, it is possible to calculate thermal efficiency with corrected and reliable values. As a third alternative, alternative A3 (18.7%) appears, which consists of implementing a mathematical model that allows predicting the cleaning and shutdown periods of the heat exchanger based on the calculation of the Fouling Factor. The fourth option, A1 with 16.2%, is related to increasing the straight sections of the exchanger through which the liquid water flows and, in this way, guaranteeing a constant velocity profile during the heat transfer process. Finally, the fifth option relates to A5 (14.4%) and consists of implementing a real-time data acquisition and measurement system. This will allow the control of the process during the 24 hours of the day and identify variations, as well as fluctuations presented throughout a day of operation.

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