Applying NSGA-II to Shell-and-Tube Heat Exchangers: Insights from the Exergetic Optimization Perspective

Qusay K. Mojar Alshamusi1*, Layth S. Jasim Al-Hayder2, Hassan A. Habeeb Alshamsi3

1Directorate General of Education Baghdad Rusafa / 3
2Department of Chemistry, College of Education, University of Al-Qadisiyah, Diwaniya
3Department of Chemistry, College of Education, University of Al-Qadisiyah, Diwaniya

Abstract--This study employed a genetic algorithm technique to examine and predict how shell-and-tube heat exchangers’ performance regarding heat recovery could be improved. In particular, a multi-objective energy-based optimization algorithm was employed. Two major parameters that were investigated in relation to their potential moderating effect included cost and energy efficiency. Regarding the cost, the study examined specific parameters such as operating cost (energy expenditure accruing from pumping) and equipment capital spending (the surface area of the heat exchanger). Regarding the design parameters, issues that were analyzed included baffle cut ratio, baffle spacing ratio, tube length, tube pitch ratio, tube diameters, and tube arrangement. To ensure that an optimal heat exchange was designed, aspects of the coefficient of heat transfer and pressure drop were estimated using Bell-Delaware procedure and the ε – NTU method. To ensure that minimum total cost, minimum energy destruction, and maximum energy efficiency were obtained, NSGA-II algorithm was applied. In turn, Pareto optimal solutions were reported in the results. From the findings, it was evident that two objective functions conflicted and that a change in geometrical properties would decrease the exergy destruction (or increase the exergy efficiency), leading to increased total cost. In exergy destruction, the heat exchanger optimization relative to exergy analysis indicated that irreversibility such as high temperature differences between the cold and hot steam and pressure drop affect the nature of exergy destruction. As such, it was concluded that when the heat exchanger’s component efficiency is increased, its cost increases.

1. Introduction

In industrial power generation firms, shell-and-tube heat exchangers have gained increasing use. Also, the heat exchangers have gained wide application in petroleum, petrochemical, and chemical plants [1]. The role of the exchangers lies in the transfer of heat between two or more fluids. They also transfer heat between fluids and solid surfaces, as well as fluids and solid particulates [2]. The transfer, which occurs through thermal contact, takes place at different temperatures [3]. Hence, there are no work or external heat interactions [4]. Effective parameters that shape the performance of the heat exchangers have also been documented. Some of these parameters include baffle spacing, tube arrangement, tube length, and tube numbers, which are worth considering during the heat exchanger design [5, 6]. In most of the previous studies, parameters that have been commonly considered include capital investment or heat transfer surface area cost and entropy generation as objective functions [7-10]. In a quest to address the role of additional parameters and how they could be shaped during heat exchanger design to achieve optimal outcomes, this study strived to investigate the subject of exergy destruction and total cost minimization, as well as exergy efficiency maximization. To establish a set of Pareto optimal solutions, the study implemented a genetic algorithm. To determine the total cost arising from heat exchanger design changes and optimal values of exergy destruction and exergy efficiency, a sensitivity analysis was performed.
2. Materials and Methods

Regarding the analysis of heat transfer, the study relied on an E-type TEMA shell.

![Figure 1: The TEMA E shell-and-tube heat exchanger employed in the study](image)

Also, an estimation of the effectiveness of the heat exchanger was performed using:

\[ \varepsilon = \frac{2}{(1 + C^*) + (1 + C^{*2})^{0.5} \coth \left( \frac{NYL}{2(1 + C^{*2})^{0.5}} \right)} \]

In relation to the exergy analysis, it is worth indicating that the parameter refers to a system’s state departure from the rest of the environment [9]. Also, exergy refers to the maximum work obtainable after combining the environment and the system [10]. Hence, exergy deviates from energy in such a way that it is not conserved [3]. Rather, irreversibilities destroy it [6]. In a given process, there is a proportional association between entropy generation and exergy destruction – arising from the irreversibilities [6-8]. In the study, the specific exergy and exergy efficiency were determined by:

\[ e = (h - h_0) - T_o(S - S_0) + \frac{V^2}{2} + gz \]

\[ \eta_{ex,AP} = 1 - \sum_{i,HEx} \frac{E_{x,D,HEx}}{E_{x}} \]

Upon employing a genetic algorithm, the study proceeded to the stage of multi-objective optimization. Some of the specific procedures that were conducted (and parameters considered) included non-dominated sorting, tournament selection, controlled elitism sort, crowding distance, crossover and mutation, and case analysis.

3. Results and Discussion

One of the initial steps involved verifying the model and optimization. For the modeling results, they were verified by comparing the simulation output with previous results documented in the literature. From the findings, this study established that the modeling output results’ difference percentage points were acceptable. Upon verification, specific optimization results were examined. In particular, seven design parameters were selected in a quest to minimize the exergy destruction and total cost – while maximizing the exergy efficiency. Specific parameters that were considered included baffle cut ratio, baffle spacing ratio, tube number, tube length, tube pitch ratio, tube diameters, and tube arrangement.
In relation to genetic algorithm optimization, with 100 generations selected, other variables that were analyzed and applied were specified in such a way that the controlled elitism value $c = 0.6500$, gene mutation probability $p_m = 0.0350$, crossover probability $p_c = 0.90$, and population size $M = 100$ individuals. The figure below highlights the Pareto-optimal front results.

![Figure 2: Pareto-optimal front results in relation to multi-objective optimization](image)

In relation to specific results that were obtained relative to variable interactions, this study established that for all design points, the total cost decreased with an increase in $pt/\text{do}$, with similar results also obtained regarding exergy efficiency whereby its increase caused a decrease in the total cost for the selected design points. It is also notable that the increase in the parameters increased exergy destruction. The resultant inference was that in heat exchangers, a conflict between two objectives arises from variations in the tube pitch ratio.

In relation to the tube length, the study established that an increase in this variable caused an increase in the total cost and exergy efficiency for the selected design points in the entirety. Hence, it was concluded that as the tube length of the heat exchanger varies, two objective functions experience a conflict. The tube number as also investigated to determine how it would affect the intended variables. Indeed, similar results were obtained as those established when the tube length was examined. Particularly, both the total cost and exergy efficiency increased with an increase in the tube number. It is also notable that as the tube number increased, there was a decrease in exergy destruction for the selected design points in the entirety.

For baffle spacing ratio, an increase in this variable caused a conflict between two objective functions. Lastly, an increase in the baffle cut ratio caused a decrease in both the total cost and exergy efficiency. However, the latter correlation was not direct. Similarly, the impact of baffle cut ratio on these parameters was not statistically significant. It is also imperative to highlight that as the baffle cut ratio was increased, there was change in exergy destruction for all the design points. However, this change was not statistically significant.
4. Conclusion and Future Directions

In summary, this study employed a genetic algorithm to conduct a multi-objective exergy-based optimization. The motivation was to steer improvements in relation to the performance of shell-and-tube heat recovery exchangers. Notably, two key parameters were considered. These parameters included cost and exergy efficiency. The decision variables or design parameters included baffle spacing ratio, tube number, tube length, tube pitch ratio, baffle cut ratio, and tube arrangement. Also, the investigation considered the moderating effects of 20 standard tubes containing definite outer and inner diameters. From the optimization problem, two objective functions that were considered included the total cost and exergy destruction (or the energy efficiency). With the interactions among these variables analyzed, the eventuality is that the total cost and exergy destruction were minimized while maximizing exergy efficiency. Specific results demonstrated that an increase in the exergy efficiency causes an increase in the heat exchanger’s total cost. As such, when exergy efficiency of a heat exchanger is increased, the resultant product is more efficient both thermo-economically and thermodynamically. Should exergy efficiency be decreased, the total cost increases respectively. The implication for industrial application is that this study’s results were relevant in such a way that they increased the understanding that when there is irreversibility such as high temperature difference and pressure drop between hot and cold steam, exergy destruction is affected. Also, the study led to the understanding that the parameter of tube arrangement has little or no effect on the two optimized objective functions’ conflict while important design parameters with a significant effect include baffle spacing ratio, tube number, tube length, and tube pitch ratio.

5. References

[1]. Costa, L. H., and Queiroz, M., Design Optimization of Shell-and-Tube Heat Exchangers, Applied Thermal Engineering, vol. 28, pp. 1798–1805, 2008.
[2]. Johannessen, E., Nummedal, L., and Kjelstrup, S., Minimizing the entropy production in heat exchange, International Journal of Heat and Mass Transfer, vol. 45, pp. 2649–2654, 2002.
[3]. Caputo, A. C., Pelagagge, P. M., and Salini, P., Heat Exchanger Design Based on Economic Optimization, Applied Thermal Engineering, vol. 28, pp. 1151–1159, 2008.
[4]. Ozcelik, Y., Exergetic Optimization of Shell and Tube Heat Exchangers Using a Genetic Based Algorithm, Applied Thermal Engineering, vol. 27, pp. 1849-1856, 2007.
[5]. Agarwal, A., and Gupta, S. K., Jumping Gene Adaptations of NSGA-II and Their Use in the Multi-Objective Optimal Design of Shell and Tube Heat Exchangers, Chemical Engineering Research and Design, vol. 86, pp. 123–139, 2008.
[6]. Shah, R. K., and Sekulic, P., Fundamentals of Heat Exchanger Design, John Wiley & Sons, Hoboken, NJ, 2003.
[7]. Dincer, I., and Rosen, M. A., Exergy, Elsevier Science, Ltd., Oxford, 454 p., 2007.
[8]. Haseli, Y., Dincer, I., and Naterer, G. F., Optimum Temperatures in a Shell and Tube Condenser With Respect to Exergy, International Journal of Heat and Mass Transfer, vol. 51, pp. 2462–2470, 2008.
[9]. Fesanghary, M., Damangir, E., and Soleimani, I., Design Optimization of Shell and Tube Heat Exchangers Using Global Sensitivity Analysis and Harmony Search Algorithm, Applied Thermal Engineering, vol. 29, pp. 1026–1031, 2009.
[10]. Ponce-Ortega, J. M., Serna-Gonzalez, M., Rico, V., and Jiménez, A., Use of Genetic Algorithms for the Optimal Design of Shell-and-Tube Heat Exchangers, Applied Thermal Engineering, vol. 29, pp. 203–209, 2009.