J Ther Eng, Vol. 8, No. 1, pp. 29–37, January 2022

Journal of Thermal Engineering
Web page info: https://jten.yildiz.edu.tr
DOI: 10.18186/thermal.1066993

Research Article

Mini-channel heat exchanger optimization using genetic algorithm and multiple-criteria decision making

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ARTICLE INFO

Article history
Received: 10 June 2021
Accepted: 21 September 2021

Keywords:
Mini-channel, Heat Exchanger, Heat Transfer, Optimization, Genetic Algorithm, VIKOR

ABSTRACT

This study aims to apply an integrated optimization approach that combines Multi-objective Optimization (MOO) and Multiple-criteria Decision-making (MCDM) to optimize a multiport mini-channel having 2D sawtooth micro fins under laminar, transitional, and turbulent flow conditions. Water was considered as working fluid. The Reynolds number (*Re*), fin height (H_f), fin width (W_f), the number of micro-fins in each mini-channel (*N*), and the distance between the successive fins (S1) were selected as design and flow parameters and the Nusselt number (*Nu*) and the Poiseuille number (*Po*) were selected as objective functions. A Genetic Algorithm based MOO study was conducted using the correlations available in the literature aiming to find the optimum values of design and flow parameters that maximize *Nu* and minimize *Po*. Then, the VIsekriterijumska Optimizacija I Kompromisno Resenje (VIKOR) method was employed to help designers to select an optimum design among the Pareto optimal solution set which is the output of MOO. Finally, the optimization results obtained were compared with those obtained by the 1st Law of Thermodynamics based Performance Evaluation Criteria (PEC). The advantages and disadvantages of these methods were discussed in detail. It is revealed that the integrated approach is a more comprehensive and flexible approach that also covers the results of PEC.

Cite this article as: Abdussamet S. Mini-channel heat exchanger optimization using genetic algorithm and multiple-criteria decision making. J Ther Eng 2022;8(1):29–37.

INTRODUCTION

Depending on the technological developments, heat generation in electronic devices has been increased dramatically over the years [1–3]. Moreover, these devices have been getting smaller day by day. These facts necessitate removing excess heat from the system effectively within a limited space due to maintaining reliable operating conditions [4–7]. Mini-channels have become one of the most promising solutions for meeting these needs due to their low material, working fluid, and space needs, as well as their high surface area/volume ratio [8].

There is a plethora on the studies aiming to improve the performance and optimization of mini-channel heat

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This paper was recommended for publication in revised form by Associate Editor Naime Filiz Ozdil

Published by Yıldız Technical University Press, İstanbul, Turkey

exchangers. Some of the studies on mini-channel heat exchangers are summarized below. In their numerical study, Pang et al. [9] selected the temperature uniformity, entropy generation, maximum temperature of mini-channel heat sink, and pumping work as the objective functions while they selected geometrical parameters of mini-channel heat sink as design parameters. They employed Multi Objective Genetic Algorithm (MOGA) to solve the MOO problem. Finally, they concluded that entropy generation and maximum temperature of mini-channel heat sink have the same effect on optimization results, and there is not a unique optimum. Selleri et al. [10] obtained a mathematical model for a mini-channel heat exchanger under laminar flow conditions using the analytical and numerical results available in the literature aiming to find optimal mini-channel exchanger design for various operating conditions. Then, they validated these mathematical models and used them for optimization problem definition. They selected overall heat transfer coefficient and overall pressure drop as objective functions and determined various geometric variables as design parameters. They used the Genetic Algorithm to solve the MOO problem. They reported that the MOO provides a wide variety of optimum solutions for the design problem handled, allowing the user to select the one that best meets the project requirements. Kilic and Senturk [11] used Taguchi Method and Computational Fluid Dynamics (CFD) simulations to find the optimum cold plate design under developing laminar flow conditions. They considered a water-cooled cold plate having mini-channels. The geometrical parameters of the mini-channel considered as design variables and the maximum surface temperature and the pressure drop were determined as objective functions. They also examined the effect of channel material on hydro-thermal performance. They found the optimum values of channel height, channel width, wall thickness, and base thickness as 9 mm, 0.6 mm, 0.3 mm, and 0.3 mm respectively. In their experimental study, Vajravel et al. [4] proposed a new mini-channel heat sink design for laminar flow conditions. Then, they compared the performance of their new design with the conventional mini-channel heat sink. They reported that a significant reduction in thermal resistance was achieved with the new design and a reduction in substrate temperature gradient around 60% was obtained. In their numerical study, Li et al. [12] investigated the design optimization of a liquid-cooled mini-channel heat exchanger used in an electric vehicle. In the multi-objective design optimization, they considered structural analysis, fluid dynamics, and thermodynamics respects and determined four objectives as minimization of battery pack volume, pressure drop, standard temperature difference, and temperature difference. They determined some geometrical parameters of the mini-channel heat exchanger as design parameters. They conducted some CFD simulations based on an experimental plan obtained through a Design of Experiment (DoE) method. Then, they obtained surrogate models of objective functions using the CFD results and used these models in the MOO problem definition. They solved the MOO problem using MOGA and visualized the optimization results as a Pareto front. Alipour and Kizilel [13] investigated the effect of design parameters of mini-channel aluminum plates on multilayer 20Ah $LiFePO_4$/Graphite cell thermal behavior numerically. They considered the width of the channel, the number of channel passes, and the heat transfer medium as design parameters, and pressure drop and power consumption as objectives. Then, they compared the performance of air- and water-cooling. They reported that the water-cooling reveals better hydro-thermal performance. In their experimental study, Al-Tae'y et al. [14] examined the influence of heat flux oscillation on the buoyancy-driven convection in an ethylene glycol cooled mini-channel heat sink under laminar flow conditions. In the experiments, They considered four different heat flux frequencies with constant and continuous heat flux. They concluded that in general, the fluid outlet temperature rises until it reaches the fluid outlet temperature for a constant and continuous heat flux situation when the heat flow frequency decreases. In their numerical study, Zhang et al. [15] investigated the MOO of the cooling performance of a mini-channel with boot-shaped ribs in transcritical regions using the Response Surface Method (RSM) and Multi-objective Genetic Algorithm (MOGA). They considered four design parameters as rib height, rib width, rib pitch, and the Reynolds number and the average temperature of the heated wall, and the pressure drop along the channel as outputs. The objective functions were obtained using the RSM and the MOO problem was solved using MOGA. They selected an optimum design among the Pareto solution set without using any method.

It is clear from the above-mentioned literature review that various optimization methods have been employed to optimize mini-channel heat exchangers. However, it is still unclear which one is superior to the others. Therefore, this study is dedicated to employ a recently proposed integrated optimization approach that combines Multi-objective Optimization (MOO) and Multiple-criteria Decision-making (MCDM) to optimize a multiport mini-channel having 2D sawtooth micro fins under laminar, transitional, and turbulent flow conditions. In the present study, correlations for the Nusselt number (*Nu*) and the friction factor (*f*) obtained by Zhang et al. [16] were used in the definition of the optimization problem. In their experiments, Zhang et al. [16] were used water as working fluid. A MOO study was conducted aiming to find the optimum values of selected design and flow parameters that maximize *Nu* and minimizes the Poiseuille number (*Po*) simultaneously. Then, the VIsekriterijumska Optimizacija I Kompromisno Resenje (VIKOR) method-based MCDM analysis was conducted to help designers to select the optimum design among the Pareto optimal solutions which are the output of the MOO. Finally, the results were compared with those obtained by

1st Law of Thermodynamics based Performance Evaluation Criteria (PEC), and the advantages and disadvantages of these methods were discussed in detail.

PROBLEM DESCRIPTION

In the present study, the optimization of a multiport mini-channel heat exchanger investigated by Zhang et al. [16] was done using an integrated optimization methodology recently proposed by Subasi and Erdem [17]. Then, the optimization results were compared with those obtained by Zhang et al. [16] using PEC. The mini-channel heat exchanger experimentally investigated by Zhang et al. [16] have 11 independent mini-channels with symmetrically distributed 2D sawtoothed fins on upper and lower surfaces of each mini-channel as shown in Figure 1. In the experiments, they used water as working fluid.

Zhang et al. [16] selected the Reynolds number (*Re*), fin height (H_f), fin width (W_f), the number of micro-fins in each mini-channel (*N*), and the distance between the successive fins (S_1) as design parameters and investigated the effects of 14 different types of micro-fin designs on heat transfer and pressure drop. They selected *Nu* and *f* as a measure of heat transfer and pressure drop respectively. Based on 283 and 470 experimental data for *Nu* and *f* respectively, they obtained the correlations for *Nu* and *f* given in Equations 1 and 2.

$$Nu = 0.0412Re^{0.68}\left(\frac{H_f}{D_h}\right)^{0.205}\left(\frac{W_f}{D_h}\right)^{-0.304}\left(\frac{S}{D_h}\right)^{-0.177}Pr^{0.1} \tag{1}$$

$$f = 1.139Re^{-0.54}\left(\frac{H_f}{D_h}\right)^{0.178}\left(\frac{W_f}{D_h}\right)^{-0.491}\left(\frac{S}{D_h}\right)^{-0.293} \tag{2}$$

The hydraulic diameter D_h and the average space *S* in Equations 1 and 2 are defined in Equations 3 and 4 respectively.

$$D_h = \frac{2H_cW_c}{H_c + W_c} \tag{3}$$

$$S = \frac{W_c - \frac{N}{2}W_f}{\frac{N}{2}+1} \tag{4}$$

H_c and W_c in Equations 3 and 4 are the mini-channel height and weight respectively. The correlations in Equations 1 and 2 were used in the optimization problem definition in the present study. The integrated methodology consists of MOO and MCDM methods. The details and application of the methodology are given in the next section.

RESULTS AND DISCUSSION

Multi-objective Optimization (MOO)

The Nusselt number (*Nu*) and the Poiseuille number (*Po*) were selected as objective functions. The aim of the optimization in the present study is to find the optimum values of selected design and flow parameters, which minimize *Po* and maximize *Nu* simultaneously within the

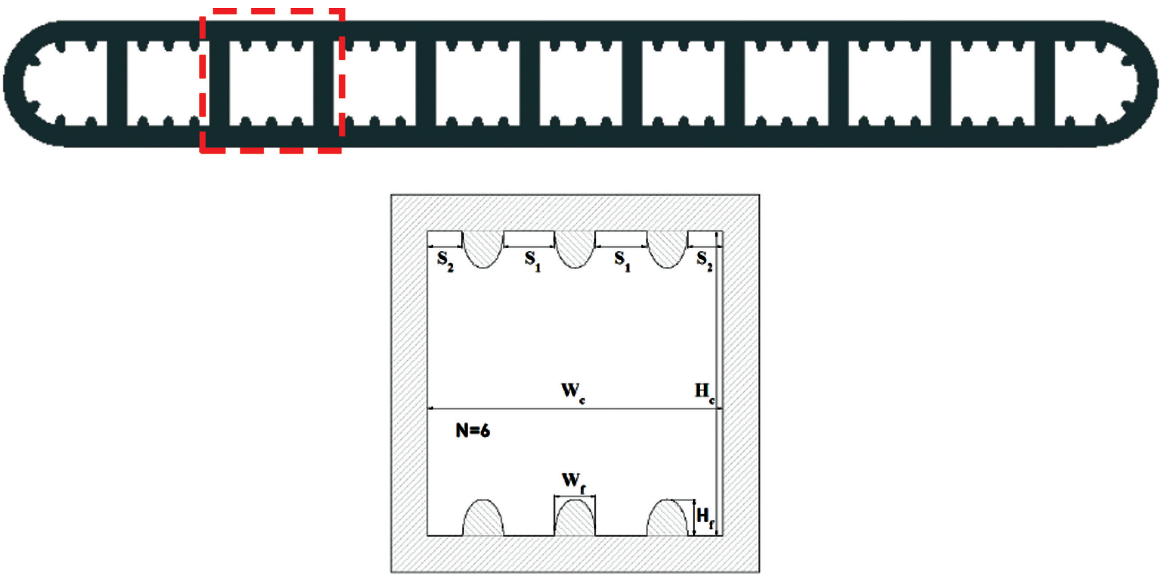

Figure 1. Schematic description of the multiport mini-channel heat exchanger.

studied range. This forms a MOO problem which is defined in Equation 5

$$\begin{cases} \min_{\vec{X}} \vec{F}(\vec{X}) \\ Subject\ \ to \quad 128 \le X(1) \le 5645 \\ 0.028 \le X(2) \le 0.211 \\ 0.078 \le X(3) \le 0.190 \\ 0.088 \le X(4) \le 0.429 \\ 5.430 \le X(5) \le 6.990 \end{cases} \tag{5}$$

where $\vec{F}(\vec{X}) = [Po(\vec{X}), -Nu(\vec{X})]^T$ and $\vec{X} = [Re, H_f/D_h, W_f/D_h, S/D_h, Pr]^T$. The negative sign in front of *Nu* is due to transforming all objective functions to a minimization form to make the optimization problem easier. The result of a MOO problem is different from a single-optimization problem. In single-optimization problems, there is one optimum but a set of optimum solutions called Pareto optimal set exists in the MOO problems. The Pareto optimal set consists of Pareto optimal solutions which form the Pareto front [17,18].

The correlations given in Equations 1 and 2 obtained by Zhang et al. [16] were used as objective functions, and the optimization problem in Equation 5 was solved using the Genetic Algortihm implemented in MATLAB. Further details can be found in Matlab's Global Optimization Toolbox User's Guide [19]. Pareto optimal solutions were given in Figure 2. Each Pareto optimal solution in Figure 2 satisfies the optimization problem defined in Equation 5 equally. Therefore, any of them can be selected as optimum solution.

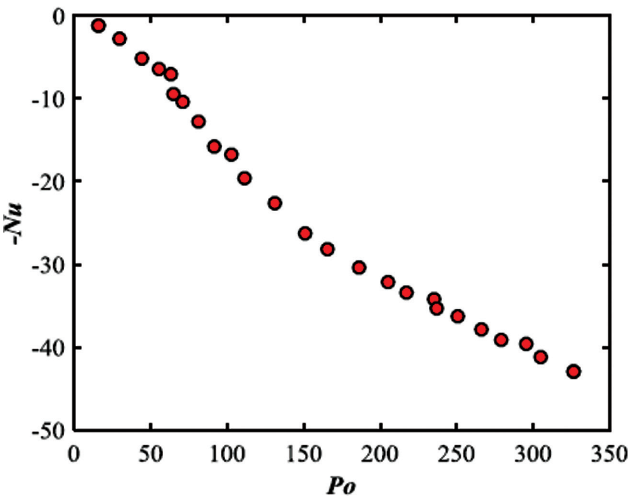

Figure 2. Pareto optimal set.

Table 1 shows the Pareto optimal solutions and corresponding values of the design parameters. It can be observed from the Table 1 that *Po* increases with increasing *Nu*. This can be explained such that *Nu* and *Po* are two conflicting objectives. In Pareto optimality, the only way to improve an objective function is to giving concessions from other objective function(s). There are 34 optimum listed in Table 1. Any optimum in Table 1 has no superiority over one another and therefore designers have freedom to select any of them in the decision stage. As it is seen from Table 1, the optimum values of the design and flow parameters namely *Re*, H_f/D_h, W_f/D_h, S/D_h, and *Pr* varies for each optimum. For example; *Re* varies a broad range between 133.999 and 5424.344. Some of the design parameters such as H_f/D_h, W_f/D_h and S/D_h require geometric modifications in the design while *Re* is related to the pumping power. Therefore, the selection of an optimum among the Pareto solution set is not an easy task. This forms a typical MCDM problem that will be discussed in the next section.

Multiple-criteria Decision-Making (MCDM)

Being one of the popular MCDM methods the VIsekriterijumska Optimizacija I Kompromisno Resenje (VIKOR) method [20] was used to evaluate the alternatives obtained as a result of the MOO study and to help designers to select the best optimum that meets their requirements among the Pareto solution set listed in Table 1. A flowchart depicting the VIKOR method's steps is shown in Figure 3.

In the calculation of *Q*, *v* is the weight of the strategy of maximum group utility. It can be selected for "voting by majority" as $v>0.5$, for "consensus" as $v=0.5$, and for "vote" as $v<0.5$. In the present study, "consensus" case was considered and *v* was selected as 0.5.

The MCDM problem handled in the present study has two criteria and thirty-four alternatives as listed in Table 1. Figure 4 shows the hierarchical structure that is the graphical representation of how many criteria and alternatives having in the MCDM problem. *Po* was converted to benefit criteria by taking its inverse. Therefore, in the MCDM problem, *Nu* and *1/Po* have been considered as two benefit criteria. It is determined taking into account experts' opinion that the two criteria are of equal importance and therefore the criteria weights were determined as $w(Nu; 1/Po) = (0.5; 0.5)$.

It is found as the result of the MCDM problem that a set of alternatives which are $A^{(10)}$, $A^{(9)}$, and $A^{(8)}$ was found as the best choices. This implies that $A^{(10)}$, $A^{(9)}$, and $A^{(8)}$ have no superiority over another and therefore one of them can be regarded as optimum solution. These alternatives are highlighted in Table 1. It can be concluded with a careful examination of the values of design and flow parameters which correspond these alternatives that there is a remarkable difference for *Re* and H_f/D_h values while there is not a marignal difference between the optimum values of other

Table 1. Pareto optimal solutions

Alternatives	*Design Parameters*					*Objective functions*	
	Re	H_f/D_h	W_f/D_h	S/D_h	*Pr*	*Nu*	*Po*
$\mathbf{A}^{(1)}$	133.999	0.0280	0.1897	0.4286	6.9455	1.294	16.629
$\mathbf{A}^{(2)}$	169.575	0.0826	0.1891	0.3221	6.1579	1.971	24.467
$\mathbf{A}^{(3)}$	258.486	0.1293	0.1540	0.4157	6.3610	2.938	33.017
$\mathbf{A}^{(4)}$	592.696	0.0521	0.1734	0.4140	6.3031	4.135	38.864
$\mathbf{A}^{(5)}$	695.066	0.0908	0.1888	0.3978	6.0670	5.049	44.792
$\mathbf{A}^{(6)}$	642.521	0.1431	0.1508	0.3288	6.7104	5.876	55.299
$\mathbf{A}^{(7)}$	1479.147	0.0633	0.1813	0.4141	6.6106	7.945	59.944
$\mathbf{A}^{(8)}$	1876.622	0.0528	0.1857	0.4091	6.4992	8.937	64.211
$\mathbf{A}^{(9)}$	2156.072	0.0735	0.1853	0.4154	6.2038	10.442	72.362
$\mathbf{A}^{(10)}$	3334.393	0.0283	0.1881	0.4178	6.6316	11.562	73.938
$\mathbf{A}^{(11)}$	2268.097	0.1342	0.1867	0.3860	6.7974	12.470	83.907
$\mathbf{A}^{(12)}$	4532.048	0.0286	0.1869	0.4133	6.3940	14.275	85.825
$\mathbf{A}^{(13)}$	4586.537	0.0450	0.1886	0.4218	6.7385	15.776	92.588
$\mathbf{A}^{(14)}$	4900.374	0.0604	0.1885	0.4175	6.7569	17.572	100.936
$\mathbf{A}^{(15)}$	4352.150	0.1105	0.1613	0.4016	6.7273	19.360	116.193
$\mathbf{A}^{(16)}$	5084.765	0.1201	0.1784	0.3909	6.6126	21.295	121.519
$\mathbf{A}^{(17)}$	4635.672	0.1755	0.1705	0.3561	6.5588	22.260	130.917
$\mathbf{A}^{(18)}$	5112.374	0.1824	0.1496	0.3534	6.7387	25.057	147.385
$\mathbf{A}^{(19)}$	5304.607	0.1561	0.1654	0.2394	6.7959	25.883	155.573
$\mathbf{A}^{(20)}$	4947.440	0.1611	0.1368	0.2607	6.7098	25.893	162.213
$\mathbf{A}^{(21)}$	5179.843	0.1811	0.1309	0.2593	6.8502	27.814	173.108
$\mathbf{A}^{(22)}$	5265.506	0.1889	0.1293	0.2341	6.8755	29.006	182.162
$\mathbf{A}^{(23)}$	5148.898	0.1839	0.1089	0.2285	6.9283	30.091	196.675
$\mathbf{A}^{(24)}$	5408.925	0.2017	0.1000	0.2529	6.9303	31.959	206.954
$\mathbf{A}^{(25)}$	5384.978	0.2006	0.1093	0.1866	6.8924	32.670	215.887
$\mathbf{A}^{(26)}$	5390.234	0.2024	0.1028	0.1943	6.4272	32.902	220.336
$\mathbf{A}^{(27)}$	5290.942	0.1891	0.1021	0.1400	6.8128	34.227	238.453
$\mathbf{A}^{(28)}$	5401.355	0.2058	0.0867	0.1596	6.7994	36.259	254.810
$\mathbf{A}^{(29)}$	5411.615	0.2023	0.0881	0.1228	6.8784	37.752	272.366
$\mathbf{A}^{(30)}$	5407.330	0.1989	0.0826	0.1180	6.8249	38.596	283.586
$\mathbf{A}^{(31)}$	5413.789	0.2054	0.0859	0.1038	6.9004	39.342	290.571
$\mathbf{A}^{(32)}$	5412.495	0.2097	0.0793	0.1040	6.8992	40.464	303.165
$\mathbf{A}^{(33)}$	5416.276	0.1927	0.0782	0.0894	6.4616	40.766	314.324
$\mathbf{A}^{(34)}$	5424.344	0.2110	0.0782	0.0890	6.9432	41.914	320.178

design parameters. Therefore, the designer can select an optimum considering these differences between the alternatives. It should also be mentioned that the MCDM problem can be extended to help designers in the decision phase by adding new criteria such as the weight of heat exchanger, ease of manufacturing, and cost. These additional criteria did not considered in the present study due to be able to compare the optimization results with the other optimization method applied by Zhang et al. [16].

In the MCDM analyses, it is important to investigate the effects of the weight of each criterion that shows the relative importance of the criteria on the results. Therefore, in the present study, a sensitivity analysis was conducted by changing the weight of each criteria giving consideration to their sum must be equal to 1. Figure 5 shows the result of sensitivity analysis. The horizontal and vertical axes of Figure 5 represent cases having various criteria weights, and ranking of alternatives respectively, and the lines correspond to

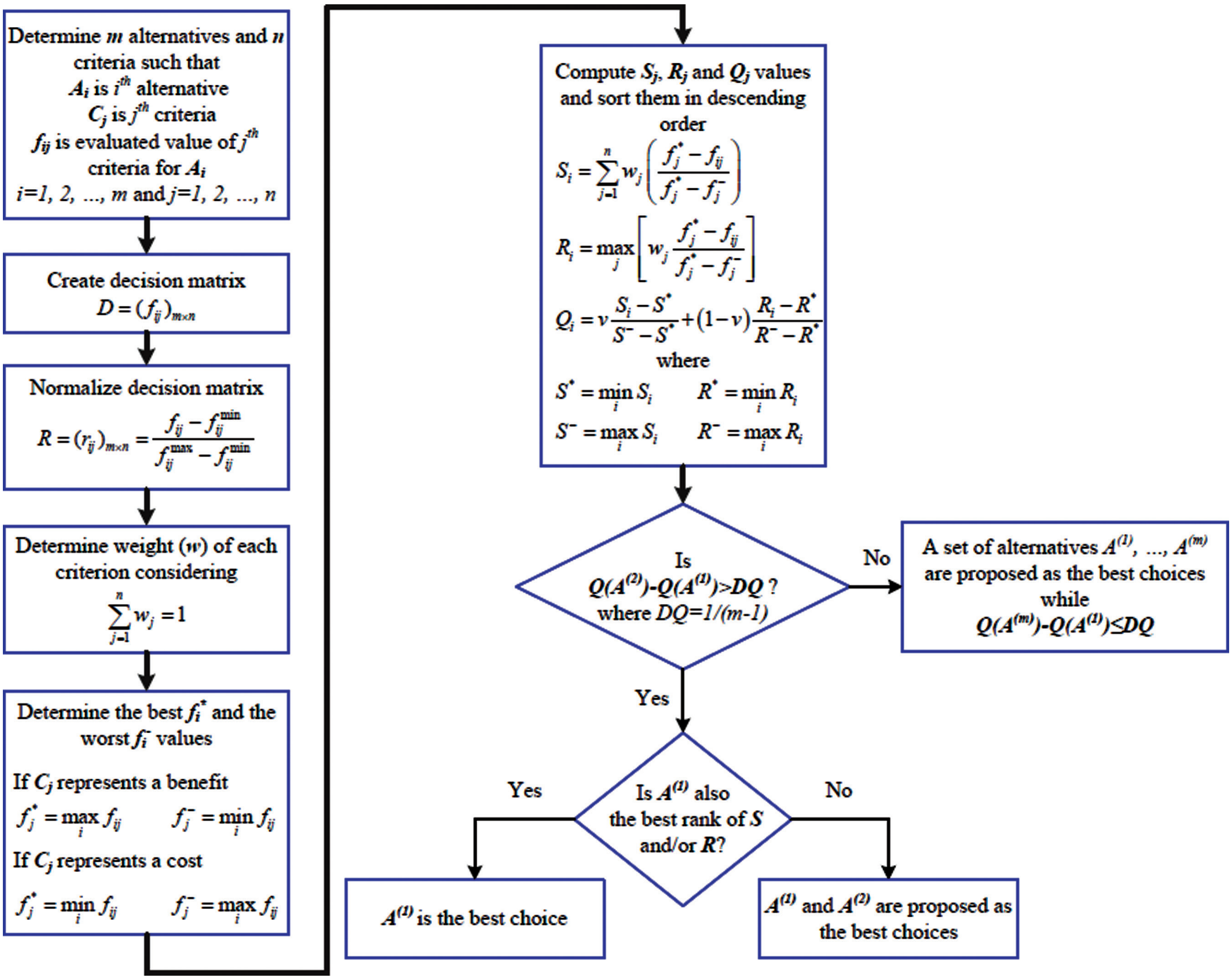

Figure 3. Flowchart of the VIKOR method.

the alternatives indicated in the legend. It can be concluded from Figure 5 that the criteria weights have great importance in the ranking of alternatives. It can also be observed from Figure 5 that there is turning points after *w(Nu; 1/Po) = (0.4; 0.6)* and *w(Nu; 1/Po) = (0.6; 0.4)*. This is due to the fact that two conflicting criteria were considered here, and thus the change of criteria weights marginally affects the ranking order at these criteria weight combinations. It is concluded with the sensitivity analysis that the ranking order of alternatives is affected by the criteria weights, and therefore they need to be determined carefully by designers considering their needs.

Comparison of optimization methods

In this section, the results of two optimization methods are compared in detail. The first optimization method is the combination of Genetic Algorithm based MOO and the VIKOR based MCDM. The second method is PEC which is commonly used in heat transfer enhancement studies. The PEC given in Equation 6 is calculated based on the constant pumping power.

$$PEC=\frac{Nu/Nu_{ref}}{\left(f/f_{ref}\right)^{1/3}} \tag{6}$$

It is known that most of the heat transfer enhancement methods such as extended surfaces lead to an increase in heat transfer and pressure drop. However, the increment in pressure drop is not desired while an increment in the heat transfer is the main motivation in heat transfer enhancement studies. Therefore, PEC is used to evaluate the performance of the applied heat transfer enhancement method with reference to the base case at the same pumping power. In their study, Zhang et al. [16] used PEC to investigate the

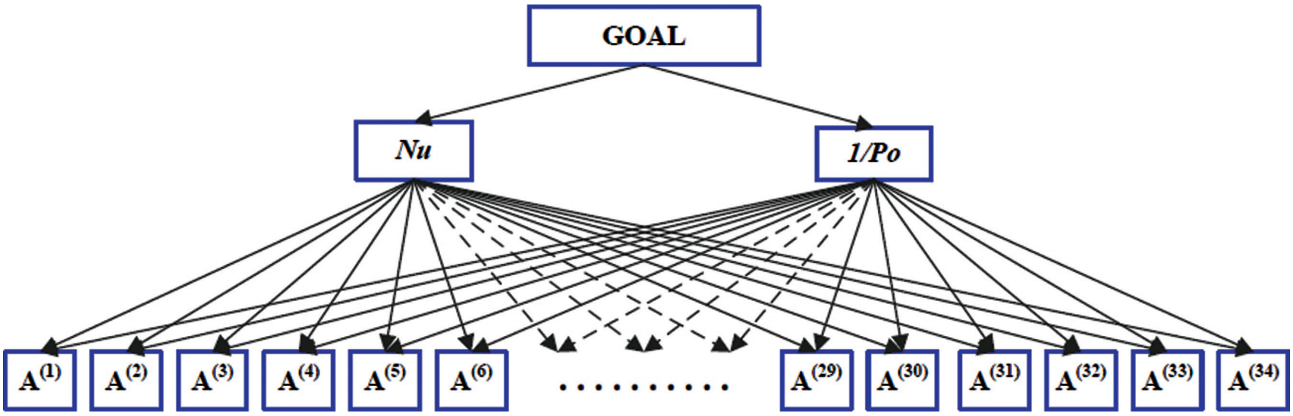

Figure 4. Hierarchical structure used in the MCDM problem.

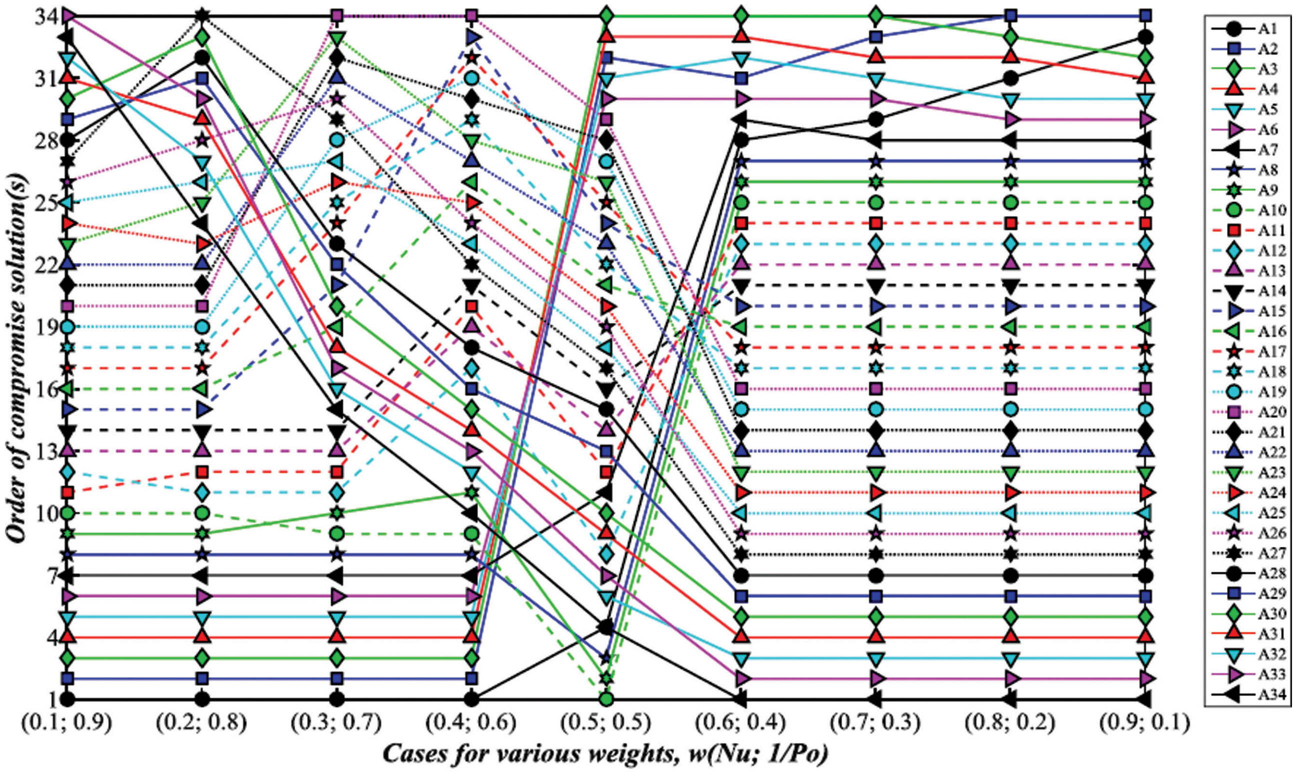

Figure 5. Sensitivity analysis.

Table 2. Comparison of the optimum solutions of two methods

Alternatives	*Design Parameters*					*Objective functions*	
	Re	H_f/D_h	W_f/D_h	S/D_h	*Pr*	*Nu*	*Po*
MOO	1876.622	0.0528	0.1857	0.4091	6.4992	8.937	64.211
+	2156.072	0.0735	0.1853	0.4154	6.2038	10.442	72.362
MCMD	3334.393	0.0283	0.1881	0.4178	6.6316	11.562	73.938
PEC [16]	2000.000	0.2110	0.1420	0.2370	6.4444	14.804	113.278

performance of 2D sawtoothed fins in comparison with the smooth mini-channel. In the present study, a recently proposed optimization methodology was applied to find optimum 2D sawtoothed fin configuration. The comparison of the optimization results is given in Table 2.

The combination of optimum values of ($Re; H_f/D_h; W_f/D_h; S/D_h; Pr$) that maximizes PEC was found by Zhang et al. [16] as (2000; 0.2110; 0.1420; 0.2370; 6.4444). This combination of parameters performs PEC, *Nu*, and *Po* as 1.9, 14.804, and 113.278 respectively. As to the results of the combined optimization method, a compromise solution set was found and listed in Table 2. It can be concluded by examining Tables 1 and 2 that $A^{(10)}$ gives the most competitive results compared to PEC. The optimum value combination of ($Re; H_f/D_h; W_f/D_h; S/D_h; Pr$) for $A^{(10)}$ is (3334.393; 0.0283; 0.1881; 0.4178; 6.6316). The combined method provides around 28% and 53.2% less *Nu* and *Po* respectively when compared to PEC. This means that the designer can have a decrement around 53.2% from *Po* by sacrificing 28% from *Nu*. The combined method allows designers to be flexible by providing a set of Pareto optimal solutions and allowing them to select various objective functions and the importance of criteria.

CONCLUSION

An application of a recently proposed integrated optimization methodology for design optimization of a mini-channel heat exchanger was done in the present study. In this context, the combination of the Genetic Algorithm based MOO and the VIKOR based MCDM was applied to find the optimum values of design and flow parameters that maximizes *Nu* and minimizes *Po*. Then, the results were compared with the results obtained applying PEC. The main findings can be summarized as follows.

- Within the studied range of design and flow parameters, the combination of optimum values of ($Re; H_f/D_h; W_f/D_h; S/D_h; Pr$) using PEC and the combined optimization approach was found as (2000; 0.2110; 0.1420; 0.2370; 6.4444) and (3334.393; 0.0283; 0.1881; 0.4178; 6.6316), respectively.
- The sensitivity analysis revealed that the criteria weights used in the MCDM have a remarkable impact on the order of alternatives. Therefore, designers should be careful in determining the relative importance of the criteria.
- The MOO part of the combined optimization approach allows designers to select their own objective functions. However, the combination of *Nu* and *f* need to be used in PEC. In the present study, *Nu* and *Po* were selected as objective functions but other objective functions can also be defined such as thermal resistance, pumping power, friction factor, etc. Moreover, some constraints can also be included in the optimization problem definition.
- Some additional criteria can also be added such as cost, weight of heat exchanger, ease of manufacturing, etc. in the MCDM stage of the combined optimization approach.
- The combined optimization approach results cover PEC results and therefore it can be regarded as a more comprehensive and flexible method.

NOMENCLATURE

A_i	i^{th} alternative
CFD	Computational Fluid Dynamics
C_j	j^{th} criteria
D	Decision matrix
D_h	Hydraulic diameter, m
f	Friction factor
f_{ij}	Evaluated value of j^{th} criteria for A_i
H_f	Fin height, m
m	Number of alternatives
MCDM	Multiple-criteria Decision-making
MOGA	Multi Objective Genetic Algorithm
MOO	Multi-objective Optimization
N	Number of micro-fins in each mini-channel
n	Number of criteria
Nu	Nusselt number
PEC	Performance Evaluation Criteria
Po	Poiseuille number
R	Normalized decision matrix
Re	Reynolds number
RSM	Response Surface Method
S	Average space, m
S_1	Distance between the successive fins, m
v	Weight of the strategy of maximum group utility
VIKOR	VIsekriterijumska Optimizacija I Kompromisno Resenje
w	Weight of each criterion
W_f	Fin width, m
F	Objective function(s)
Pr	Prandtl number
X	Design parameter(s)

Subscripts

ref	Reference

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

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