Determination of a Pareto set for the corrugated channel heat exchangers using genetic algorithm procedure

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Abstract
In the study, optimum parameters including geometries and flow characteristics related to the heat exchangers with corrugated channels were determined using the genetic algorithm technique. The optimum solutions or Pareto set obtained from the multi-objective optimization process. Any change in the heat exchanger can lead to an increase in pressure drop and subsequently an increase in pumping energy. Therefore, the Nusselt number (Nu) and pressure drop (ΔP) were considered as optimization objects. The investigated geometrical parameters of the wavy channels are amplitude ratio (b/H), phase shift (φ), and number of waves (N_w). The obtained optimum values provide a trade-off between heat transfer coefficient and pressure drop in the channels. The designer can select optimum values according to the required design factors.

Keywords: Heat transfer, Pressure drop, Wavy channels, Multi-objective optimization, Genetic algorithm

Introduction
The thermal and flow characteristics in channels with various shapes have been discussed in many articles [1]. Using the wavy channels in heat exchangers leads to a significant heat transfer enhancement (HTE) and reduce the size of the heat exchangers. This increase in heat transfer will be accompanied by an increase in pressure drop. Therefore, both factors need to be considered together.
An experimental setup was provided by Nakhchi [2] to study the effects of geometrical parameters of wavy channels on heat transfer rate and pressure drop of the fluid. The response surface methodology (RSM) procedure was used to evaluate the studied wavy channels. Khan et al. [3] used a three-dimensional simulation using computational fluid dynamics (CFD) to study the heat transfer performance of the wavy channels. Baik et al. [4] provide a numerical analysis to investigate heat transfer in the wavy-channeled printed circuit heat exchangers (PCHEs) compared with the straight-channeled PCHEs. Chiam et al. [5] performed an empirical and numerical investigation for the novel wavy microchannels.
The genetic algorithm (GA) is a well-known subgroup of artificial intelligence (AI) which is usually employed to optimize the engineering systems [6]. The GA technique can be considered for energy and cost optimization [7] or developing the predictive equations by means of adjusting the constants of the equations [8,9]. Beigzadeh et al. [10] proposed new empirical equations to estimate and optimize the geometries of the heat exchangers with

coiled tubes. Tarafder et al. [11] optimized the design parameters related to an industrial ethylene reactor by the genetic algorithm multi- objective optimization.

In the present work, the GA method based on multi-objective optimization was used to determine a collection of optimal answers of geometric parameters of the wavy channels. Two empirical correlations related to the Nusselt number (Nu) and pressure drop (ΔP) of the wavy channels were employed as objective functions.

Data collection and empirical correletions

The empirical data related to the Nu and ΔP in the corrugated channels with different geometrical parameters including amplitude ratio (b/H), phase shift (φ), and number of waves (N_w) were collected for multi-objective optimization. Fig. 1 illustrates a schematic view of the investigated wavy channel with the geometrical parameter details. The features of the experimental setup and procedure are described by Nakshi [2]. The amplitude ratio (b/H) of 0.2, 0.4, and 0.6, three phase shifts (φ) of 0º, 90º, and 180º between the upper and lower channel walls, and three waves number (N_w) of 5, 10, and 15 were tested in the experiments. A range between 1106 and 2530 was assigned for Reynolds number (Re). The Nu and ΔP were calculated by measuring temperatures, pressures, and flow rates.

Two empirical correlations were applied to predict target variables and were used as objective functions [12]:

$$Nu = 0.089 Re^{0.76}\left(1 + N_w^{0.925}\left(\frac{\varphi}{\pi}\right)^{0.278}\left(\frac{b}{H}\right)^{7.069}\right) \quad (1)$$

$$\Delta P = 0.001 Re^{1.304}\left(1 + N_w^{0.169}\left(\frac{\varphi}{\pi}\right)^{1.265}\left(\frac{b}{H}\right)^{1.572}\right) \quad (2)$$

The constants of the above correlations were obtained using the GA technique in the previous work [12].

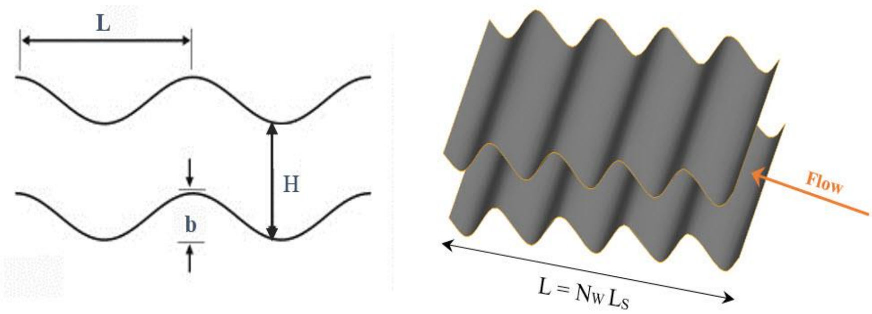

Fig 1. Schematic view of a corrugated channel with its main geometrical parameters.

Genetic algorithm-based multi-objective optimization

The genetic algorithm (GA) is a very important optimization procedure inspired by the principles of Darwin's biological evolution. GA has become one of the most popular methods for optimization in the chemical engineering systems [13]. The optimization process used an initial group of random answers (population) and develops by iterations (generations) to reach better answers. The key mechanisms of the GA are fitness evaluation, parent choice, elitism, crossover, and mutation. The mentioned steps in the GA process described in [14].

The multi-objective optimization is a simultaneous optimization of two or more objective functions. In the multi-objective optimization, the main aim is to discover a group of answers which known as Pareto optimum answers. In the present research, multi-objective based GA is developed to achieve optimum geometrical parameters and Reynolds number (Re) in the sinusoidal wavy channels. The optimal solutions lead to minimizing pressure drops and maximizing heat transfer coefficients (Nu). So, the two objective optimization functions considered as follows:

$$OF_1\left(\frac{b}{H}, \frac{\phi}{\pi}, N_w, Re\right) = -Nu \tag{3}$$

$$OF_1\left(\frac{b}{H}, \frac{\phi}{\pi}, N_w, Re\right) = \Delta P \tag{4}$$

The above objective functions lead to the maximum Nu and the minimum ΔP.
In the GA optimization, 200 chromosomes were considered as population size with 400 generations. Moreover, the crossover probability and mutation possibility of 0.8 and 0.01, respectively, were employed in the method.

Results and discussion

In the study, we tried to use the genetic algorithm technique based on multi-objective optimization to obtain operating parameters of a wavy channel heat exchanger. A higher pressure drop in the investigated channels leads to a higher required pumping power which is an undesirable effect. Therefore, the process was employed to optimize the design parameters which lead to the greatest possible amount of heat transfer rate and the least pressure drop of the fluid flow. Fig. 2 illustrates the results related to the Pareto optimum curve. Minimizing the two objective functions lead to the Pareto optimum answers like a concave front. The figure obviously shows the conflict between two objectives functions (-Nu and ΔP). Changes in geometrical dimensions that lead to increased heat transfer rate or Nu will increase pressure drop and vice versa. This proves the necessity for multi-objective optimization for obtaining the optimal design for the wavy channel heat exchangers.
Any value of the geometric parameters can be selected depending on the target and application. In order to make this clear, a group of the selected optimum design parameters and resultant Nu and ΔP related to the Pareto set, are presented in Table 1. As can be seen in the table, the obtained values of b/H and N_w are more tend to its upper limit due to the higher value of powers in the Nu correlation (Eq. 1). There is no answer out of these Pareto optimum answers superior to any other in both objective functions because every answer in the obtained Pareto set is global optimum results.

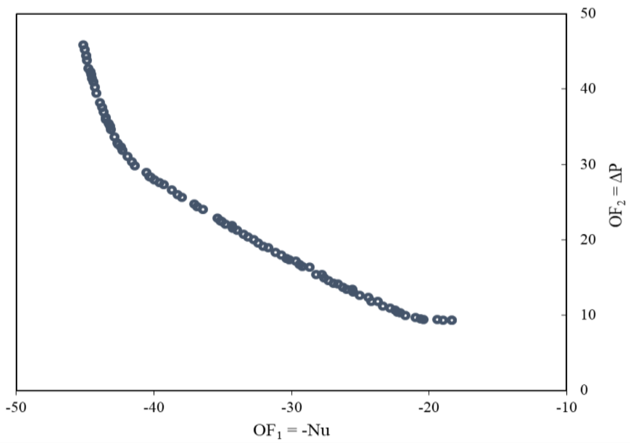

Fig. 2. The Pareto optimal solutions.

Table 1 Some of the optimum values of the Pareto set.

Re	N_w	φ/Π	b/H	Nu	ΔP
1106.0	5	0.0000	0.6000	18.31	9.31
2495.7	15	0.9947	0.5996	45.14	45.81
1113.3	13	0.0804	0.5998	20.97	9.66
1112.7	13	0.0407	0.5997	20.62	9.50
1155.4	14	0.1040	0.5998	22.07	10.25
2495.3	15	0.3983	0.5996	42.63	32.84
2177.1	15	0.2085	0.5996	37.07	24.71
1222.2	15	0.1244	0.5995	23.33	11.14
2187.0	15	0.1679	0.5995	36.84	24.33
1541.4	13	0.1622	0.5996	27.79	15.35
2012.4	15	0.1891	0.5995	34.76	22.07
1487.6	15	0.1510	0.5996	27.29	14.59
2488.2	15	0.2334	0.5996	41.34	29.81
1113.4	14	0.1353	0.5996	21.72	9.92
1420.3	15	0.1404	0.5995	26.26	13.66
2491.0	15	0.9421	0.5996	44.89	44.44
2481.3	15	0.2703	0.5996	41.57	30.32
1457.4	15	0.1522	0.5997	26.90	14.21
1106.9	6	0.0399	0.5999	19.39	9.42
1993.8	15	0.1634	0.5996	34.25	21.51
2418.9	15	0.2425	0.5995	40.52	28.88
2495.0	15	0.7552	0.5996	44.29	40.23
2495.8	15	0.8049	0.5997	44.49	41.37
1911.6	15	0.1593	0.5995	33.13	20.32
2441.4	15	0.1587	0.5996	39.97	27.95
2483.7	15	0.3806	0.5996	42.36	32.31
2302.8	15	0.2109	0.5996	38.67	26.62
1109.9	14	0.0267	0.5998	20.41	9.42
2028.6	15	0.1943	0.5996	35.02	22.36
1834.6	15	0.2317	0.5996	32.71	20.01
1106.0	6	0.0088	0.5998	18.97	9.33
1685.4	15	0.1876	0.5995	30.37	17.50
1229.3	13	0.2214	0.5996	23.69	11.79
2494.4	15	0.5713	0.5996	43.50	36.25
1164.2	14	0.1064	0.5998	22.28	10.37
1766.3	15	0.1551	0.5997	31.16	18.29
1327.4	15	0.2181	0.5996	25.49	13.03
2277.5	15	0.1662	0.5996	37.92	25.62
2494.9	15	0.9695	0.5997	45.01	45.18
2370.7	15	0.2063	0.5996	39.59	27.58

Conclusions

The ability of the genetic algorithm to optimize heat and flow characteristics including Nusselt number and pressure drop in corrugated channels was investigated. The optimum operating values of the wavy heat exchangers, which results in a trade-off between Nu and ΔP, are founded by using the multi-objective GA optimization scheme. A Pareto set related to the geometrical parameters of the wavy channels including amplitude ratio (b/H), phase shift (φ), and number of waves (N_w) and flow characteristic (Re) was presented. A designer of the heat exchanger selected operating values based on the ideal operating conditions includes lower pressure drop or higher heat transfer. The GA multi-objective optimization technique can be used as an advantageous procedure in the design of heat transfer systems.

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