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Mathematical simulation of a vehicle radiator by genetic algorithm method and comparison with experimental data

R. Mehdipour[1], Z. Baniamerian[2], B. Sakhaei[3*]

[1]*Tafresh University, Tafresh, Iran, mehdipour@tafreshu.ac.ir*
[2]*Tafresh University, Tafresh, Iran, baniamerian@tafreshu.ac.ir*
[3]*Irankhodro Powertrain Company (IPCO), Tehran, Iran, b_sakhaei@ip-co.com*
[*]*Corresponding Author, Phone Number: +98-912-2775798*

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ABSTRACT

In many industrial processes, heat exchangers play the important role of the cooling function. The effective heat transfer rate in a specific process strongly depends on the heat exchanger design. The most popular type of heat exchangers commonly used in the automotive industry, is called "radiator". In engines, radiators play the important role of the cooling process.

The present study is devoted to develop a mathematical model for the simulation of the vehicle radiator by utilizing the genetic algorithm method. Beside available experimental/analytical studies for studying the behavior of heat exchangers, an analytical model to predict and simulate their performance is of great worth. In the present study, we are going to use results of experimental data to obtain a general correlation, which can simulate the performance of heat exchangers. In this regard, a program is written to develop a mathematical model applying experimental data as inputs. The model is based on thermodynamic and heat transfer calculations and calculates cooling rate in each time step with deviation of 1.68%.

1) Introduction

Heat exchangers have been widely applied in most industries supplying heat transfer between two fluids flowing at different temperatures, having been separated by a solid wall. Some types of heat exchangers have been used in thermal engineering applications such as power plants, automotive industry, heating/cooling systems, gas turbines, refrigeration, HVAC systems, cryogenic systems and some other industries. Various types of pipe cross-sections have been used for different applications of heat exchangers. Many researches in this field have been aimed at improving the productivity of heat exchangers.

The most popular type of heat exchangers commonly used in automotive industry, is called radiator. In most types of engine processes in vehicles, radiators play the important role of cooling processes. Heat transfer from the engine is an important issue which should be optimized in order to reach the most effective performance. Many optimization methods and algorithms have been suggested lately to improve radiators performance. Genetic Algorithm and Neural Networking Methods are two examples of mentioned optimization approaches.

First pioneered by John Holland in 60s, Genetic Algorithm (GA) has been widely applied in many fields of engineering. GA method surpasses other traditional methods in most of optimization problems. Finding optimal parameters and shape design is subject of many engineering problems [1-6], that is complicated by using traditional methods of optimization while can be simply accomplished using GAs. However, because of its significant performance in optimization, GA has been erroneously concerned just as a function optimizer.

Many experimental and numerical studies have been conducted on airside heat transfer performance of heat exchangers. Wang et al. (1997, 1999) [7,8] made extensive experiments on the heat transfer and pressure drop characteristics of tube heat exchangers.

Somchai and Yutasak [9] experimentally investigated the effect of the fin pitch and number of the tube rows on the air side thermal performance of the herringbone wavy fin and the tube heat exchanger.

Yan and Ping [10] in 2013, simulated radiators in two different ways, first by considering heat blocks in the radiator and second by applying IGBT power components. Radiator performance is then compared inn two cases. Lianfa et al. [11] have analyzed influence of the flow velocity of the inlet fluid and thermal convection of air on the outlet temperature of fluid in a typical radiator applying the commercial software ANSYS. In addition, they have discussed thermal deformation of the water-cooling flow channel in common conditions. Peyghambarzadeh et al. [12] have evaluated the heat transfer performance of the automobile radiator experimentally in case of employing nano-fluid in cooling passages. They have then evaluated thermal performance of the radiator for different types of nano-particles.

In the present study a model is developed capable of simulating radiator performance as well as estimating radiator treatment for different operating conditions. A program is written, taking experimental data as input, to finally determine a mathematical relation ruling over the input data. The proposed method in this study is GA. The proposed model is precise, simple and has low computation costs. The method is then exerted on a typical automobile made by IKCO for its performance to be evaluated. The mentioned experimental data are obtained by applying the experiment in a wind tunnel [13] on a Peugeot radiator. Figure 1 demonstrates a schematic of a wind tunnel similar to which has been used in the experiment. The computer program is based on Genetic Algorithm method which surpasses experimental and CFD methods from the viewpoints of costs and CPU time. The program inputs are experimental data, and the aim is to simulate experimental performance mathematically.

2) Mathematical simulation of the heat exchanger

The logarithmic mean temperature difference method is used for analyzing the performance of the radiator as a heat exchanger [15].

$$\begin{cases} Q = UAF\ \Delta T_{Lm.cf} \\ \Delta T_{Lm.cf} = \dfrac{(T_{h2} - T_{C1}) - (T_{h1} - T_{c2})}{Ln[(T_{n2} - T_{c1})/(T_{n1} - T_{c2})]} \end{cases} \quad (1)$$

In some conditions, when the heat exchanger is not exactly a counter flow or a parallel flow one, a correction factor, *F*, would be defined. There are some curves and tables to define this factor. These tables have been obtained by Boumen et al. [16]. The factor is available for most common heat exchangers.

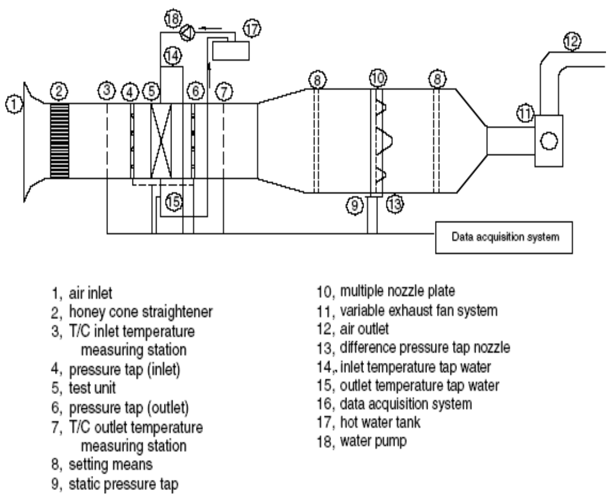

Figure 1: Schematic of a wind tunnel system [14]

The aforementioned correction factor depends on flow type parameters and also *R*, *P* arrangement. Total heat transfer coefficient, between hot water and air stream, in the last relation is defined as below [15]:

$$UA = \frac{1}{\frac{1}{n_i h_i A_i} + \frac{R_{fi}}{n_i A_i} + Rw + \frac{R_{fo}}{n_o A_o} + \frac{1}{n_o h_o A_o}} \tag{2}$$

It can be shown that the flow within the radiator is turbulent. h_i can be determined if the *Nu* number is known. Most of experimental relations for the *Nu* number of the fluid flowing in a pipe, which are suggested in different handbooks, have the similar form as following:

$$Nu_i = a^*(R_{eb}^{b^*} - C^*)P_{rb}^{d^*} \tag{3}$$

Where, a^*, b^*, c^* are variables of different magnitudes depending on flow conditions. For instance for a fluid of following characteristics, $0.5<Pr_b<500$ and $3*10^3<Re<10^6$, Nu_b is calculated by use of the equation (4) [15].

$$Nu_b = 0.012(R_{eb}^{0.87} - 280)\,\mathrm{Pr}_b^{0.4} \tag{4}$$

Since temperature differences in radiator will not exceed 10˚C, most physical parameters can be assumed constant.

As the pipe section is oval, the diameter shown in the above equations is the hydraulic diameter of the section. It has been perceived experimentally that using hydraulic diameter in the mentioned equations may cause a deviation of ±15%, ±10% from real value for friction coefficient and *Nu* number, respectively.

Magnitude of h_o is also unknown which should be determined to obtain *UA* value from equation (2). Despite many studies devoted to heat exchangers, no unique correlation for h_o has been developed so far. This issue can be due to the great variety of heat exchangers, owing to their different shapes and fins profiles.

In the present study, we are going to find a mathematical correlation for h_o, by use of experimental results. Looking through the curves resulted from experimental studies [15,17], it is revealed that all curves are logarithmic and can be simply written as the suggested equation (5):

$$\frac{h_o}{Gc_p}\mathrm{Pr}^{\frac{3}{2}} = a + bLn(\mathrm{Re}) \tag{5}$$

This suggested equation, forms a curve which well fits the results taken from reference [15,17]. The heat transfer coefficient that is plotted in reference [15], is demonstrated in Figure 2. The only task to complete the Equation (5) for calculating h_o is to find constants "*a*" and "*b*".

By definition of the parameter σ and *G* as below:

$$\sigma = \frac{A_{min}}{A_{fr}} \tag{6}$$

$$G = \frac{\rho\, u_\infty A_{fr}}{A_{min}} = \frac{pu_\infty}{\sigma} \tag{7}$$

Re number is written as:

$$\mathrm{Re} = \frac{GD_h}{m} \tag{8}$$

Based on the above equations and by choosing a suitable value for "*a*" and "*b*", h_o can be calculated by applying the following relation:

$$h_o = \frac{N}{G\,C_p}\mathrm{Pr}^{\frac{2}{3}} \approx a + b\;Ln(\mathrm{Re}) \tag{9}$$

For example, the best values for "*a*" and "*b*", for the radiator of ref [15] (radiator 9.68-0.87-R) are:

$a = 0.020267 \quad , \quad b = -1.937e-3$

It should be noted that these values are given specifically for the radiator of reference [15] and varied by the type of radiator. Values of simulation parameters for some different heat exchangers with different types of plate finned tubes are listed in Table 1. These values can be applied as initial estimation of optimization procedure that will be mentioned at section 6.

3) Calculation of *UA* in the mentioned radiator model

At this section, *UA* is calculated by Equation (2). Except *UA*, all other parameters in Equation (1) are known from the results of wind tunnel experiment [13].

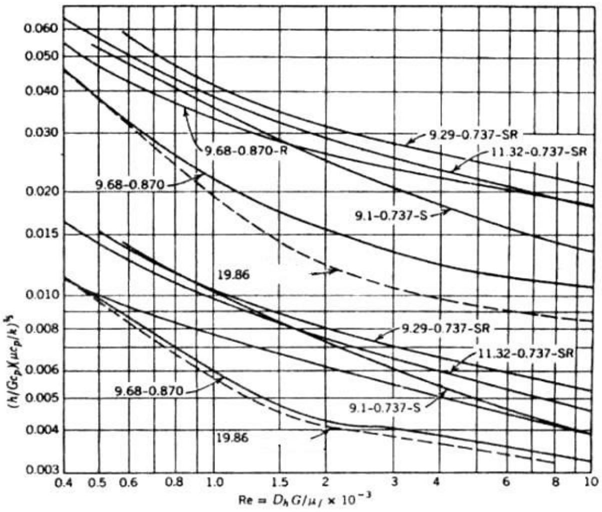

Figure 2: Heat transfer and friction: coefficients for fluid flowing through different types of plate finned tubes [15]

Table 1: Values of simulation parameters for a typical heat exchanger with plate finned tubes of different type [15]

Conditions	σ	D_{hm}	*a*	*B*
Plate finned tubes of type 0.87-9.68	0.697	0.299	0.02026	-1.93E+03
Plate finned tubes of type 0.737-9.1	0.788	0.356	0.0214	-1.95E+03
Plate finned tubes of type 0.737-9.1R	0.788	0.356	0.0362	-3.63E+03
Plate finned tubes of type 0.737-9.29R	0.788	0.315	0.0329	-3.12E+03
Plate finned tubes of type 0.737-11.32SR	0.78	0.343	0.3069	-2.91E+03

Table 2: Radiator performance test governed on Peugeot radiator [13]

Number of horizontal pipes	1		Number of vertical pipes		41
Dimensions of window	620*360		Surface area		0.2232
Surface has been painted or not	Yes		enclosure type		Plastic
Number of fine per inch	18		Basis type		Metal
Aero dynamic test					
w (rev.)	*V* (m/s)	*dP* (Pa)	*Q* (kW)		*Q* (kW)
0	22.2	649.7	56.9		71.9
70	14.6	305.3	47.7		58.3
90	7.8	97.7	33.5		39.8
100	4.8	46.4	24.5		28.9
Hydraulic test					
H_i (mmHg)	385	350	310	265	220
H_o (mmHg)	515	545	583	625	675
dP (kPa)	16	24	33.9	44.4	56.1
q (lit/hour)	2400	3000	3600	4200	2800

The magnitude of the variables which are required for calculating *UA* value from Equation (2), are the known results of our mentioned experiment [13]. These results are tabulated in Tables 2 and 3.
Heat resistance can be calculated by substituting the above parameters into Equation (1) while considering data in Table 1, the magnitude of *UA* is obtained 1.19E+3. Similar calculations should be done on each value of Table 3 to derive values of Table 4.
The mentioned process can be applied in order to obtain the values of *UA* in the experiment. These values are tabulated in Table 4. The data in the last column of mentioned table are utilized to constitute the objective function which is mentioned in Section 5.

4) Computer program algorithm

Pipe section of the radiator, considered in the present study, is an oval with diameters of $R_1 = 5.5mm$ and $R_2 = 21mm$.
NU number can be calculated by Equation (10). As previously mentioned, a^*, b^*, c^*, d^* are variables which take different magnitudes in different flow conditions.

$$Nu_b = a^*\left(\mathrm{Re}_{eb}^{b^*} - c^*\right)\mathrm{Pr}_b^{d^*} \tag{10}$$

At the beginning we are to find exact values of a^*, b^*, c^*, d^*. If suitable constants of a^*, b^*, c^*, d^* are defined, the rest of calculations can be continued as:

$$R_{eb} = \frac{\rho u_\infty D_H}{m} \tag{11}$$

The following relation can be applied in order to obtain $u_\infty = u_{WR}$

$$u_{WR} = \frac{4Q_d}{\pi D_H^2} \tag{12}$$

Specification of the geometry can lead to the calculation of *Nu* applying Equation (10). Determination of *Nu* number is enough to obtain h_i:

$$h_i = \frac{Nu_R \times k}{D_H} \tag{13}$$

Thus far, the parameter h_i, has been formulated. In order to reach *a* formula for h_o, the following mathematical process is applied.
At first step σ is calculated by Equation (6). A_{fr} in this equation can be determined from geometry measurements. Hydraulic diameter in air-cooled radiators is defined as following:

$$D_h = 4\frac{L_e A_{\min}}{A_t} \tag{14}$$

L_e in the above equation is total length of radiator pipes, which is measured 0.02 m for the radiator considered in the present study.
Air mass flow rate can be calculated by the following equation:

$$G = \frac{Pu\infty A_{fr}}{A_{\min}} = \frac{Pu\infty}{\sigma},\ R_e = \frac{GD_n}{M} \tag{15}$$

Then h_o can be obtained by having suitable values for "*a*" and "*b*":

$$h_o = \frac{N}{G\,C_p}\mathrm{Pr}^{\frac{2}{3}} \approx a + b\,Ln(\mathrm{Re}) \tag{16}$$

Measuring A_{fr} , L_e and estimating suitable values for D_h, b, a and σ, results in determination of h_o, A_t and finally *UA*.

$$\frac{1}{U\ A} = \frac{1}{h_i A_i} + R_t + \frac{1}{n_o h_o A_o} \tag{17}$$

The magnitude of R_t in the above equation, is too small compared with $h_i A_i$ and $h_o A_o$.

5) Simulation of radiator by Genetic Algorithm Method

As mentioned previously, the computer program is written based on GA method. The objective of the computer program is to find a mathematical relation which well fits on the experimental data. In the other word, the intention is to simulate experimental data, by a mathematical relation. By performing such simulation, the total physical process of a radiator has been modeled, while behavior of the radiator can be estimated in different operating conditions. To achieve the mentioned objective, if *n*, *b*, *a*, *D*, *d*, *a**, *b**, *c**, *d**, and *σ* are definite, *UA* can be obtained at each temperature. Therefore the only task is to determine the values of *n*, *b*, *a*, *D*, *d*, *a**, *b**, *c**, *d**, and, *σ*, etc. some initial estimations for *a**, *b**, *c**, *d** are demonstrated in Table 5.

The mentioned parameters can be determined using iterative algorithm of GA. The following objective function is minimized during the iteration:

$$SE = \sum \left| UA_{\exp} - UA_{\mathrm{mod}\,el} \right| \tag{18}$$

5.1) Why has genetic algorithm method been used?

There are two dominant purposes for applying GA Method; the first is due to several numbers of effective variants on radiator simulation and the second is that the CPU time for radiator modeling is not of great significance in the present study.

Neural network method can also be applied in the present modeling procedure but it can be claimed that GA Method is much simpler and more rapid in comparison with neural network method.

Problems of these types usually involved with several parameters and therefore state space of several partial minimums. Derivative optimization methods and also least square method accompany with severe problems as they commonly trap in between partial minimums. In this study, the method of bi conjugate gradient, before GA, was employed that led to non-proper conditions.

5.2) Stages of computer program for simulation of the radiator using genetic algorithm method

Genetic algorithm method which is used for simulating radiator performance, consists of some steps.

Let's remark about each one:

A) As the first step, a set of 100 chromosomes should be used as input for the computer program. Each Chromosome consists of 9 parameters in order to have 100 suitable chromosomes as initial ones, the first set can be directly derived from standard tables, which 9 initial gens n_0, *b*, *a*, D_{HM}, *d*, *a**, *b**, *c**, *d**, and *σ*.

B) At the second stage, the objective function is defined by Equation 18. By using that function, the error value is calculated for each Chromosome. Then all 100 chromosomes are sorted due to increasing objective function values.

C) At the third step, 100 compound chromosomes can be produced by combination of 100 chromosomes from the previous step.

For example, the chromosomes number 101 can be produced by combination of the first Chromosome with second one. In the other word a new Chromosome is obtained by using five gens of first Chromosome and four gens of second Chromosome. A similar algorithm can be exerted on all other chromosomes to produce 100 new chromosomes. The chromosomes produced in mentioned method are called compound chromosomes.

Table 3: Radiator performance test governed on Peugeot radiator [13]

V (m/s)	H_{to} (mm)	H_{rt} (mm)	T_{air} (˚C)	Q (lit/h)	$T_{water,out}$ (˚C)	$T_{water,in}$ (˚C)	W (rev.)
23.03	147	14	17.3	2400	60.9	82	0
				2400	60.1	81	0
				2400	59.1	80	0
22.34	146	13	17.4	4800	68.5	82	0
				4800	67.6	81	0
				4800	66.8	80	0
14.63	183	120	18.2	2400	64.3	82	70
				2400	63.7	81	70
				2400	62.5	80	70
14.58	183	120	17.7	4800	71.1	82	70
				4800	70.2	81	70
				4800	69.3	80	70
7.75	205	185	18.8	2400	68.9	82	90
				2400	68.4	81	90
				2400	67.7	80	90
7.85	207	187	18.9	4800	74.4	82	90
				4800	73.5	81	90
				4800	72.7	80	90
4.84	210	201	18.8	2400	73.3	82	100
				2400	71.6	81	100
				2400	71	80	100
4.75	211	201	19	4800	76.3	82	100
				4800	75.5	81	100
				4800	74.7	80	100

Table 4: UA calculation for the experiment

T_{c1} (˚C)	T_{h1} (˚C)	Velocity air (m/s)	Water flow (lit/hour)	*UA* (W/K)
17.3	82	22.04	2400	1.18E+03
17.3	80	22.03	2400	1.21E+03
17.4	82	22.34	4800	1.43E+03
17.4	80	22.34	4800	1.44E+03
18.2	82	14.63	2400	1.01E+03
18.2	80	14.63	2400	1.04E+03
17.7	82	14.58	4800	1.17E+03
17.7	80	14.58	4800	1.19E+03
18.8	82	7.75	2400	7.70E+02
18.8	80	7.75	2400	7.32E+02
18.9	82	7.85	4800	8.45E+02
18.9	80	7.85	4800	8.37E+02
18.8	82	4.84	2400	5.61E+02
19	82	4.75	4800	6.60E+02
18.8	80	4.84	2400	5.20E+02
19	80	4.75	4800	6.24E+02

Table 5: Initial values for a^*, b^*, c^*, d^*

N	a^*	b^*	c^*	d^*
1	0.0120	0.87	280	0.400
2	0.0214	0.80	100	0.400
3	0.0220	0.80	0	0.500
4	0.0210	0.80	0	0.400
5	0.0150	0.88	0	0.333
6	0.1890	0.63	0	0.360

D) At this step, 100 casual chromosomes would be produced by random. For example, the 201st Chromosome can be obtained by multiplying the first Chromosome parameters by a number between 0.1 and 10 (This number is randomly selected) 100 other chromosomes can be produced in similar way.

E) Till the present stage, 300 chromosomes have been produced. At this step, after applying error value calculations, these chromosomes should be sorted via increasing the error value and then 100 dominant chromosomes be separated.

6. The new 100 chromosomes, which were obtained in the previous step, are used for the computer program as input and all mentioned steps are repeated again.

6) Results and discussions

There are several unknown variables which dominantly affect the radiator performance in the suggested correlation; therefore the iterative method of genetic algorithm is utilized to define the mentioned variables.

The experiment is exerted on the radiator of Peugeot. After 1000 iteration a precise model with deviation of 1.68% is obtained. The precision of 10 dominant chromosomes can be seen in Table 6. Magnitudes of dominant chromosome parameters, (the gens of dominant chromosome) are shown in Table 7. Variation of air pressure drop via the air velocity is shown in Figure 3. This curve is obtained from the experimental results.

Figure 4 demonstrates heat transfer changes via the air velocity. Figure 4 shows a comparison between experimental results and final model obtained from computer program.

It is obvious from the last figure that there is a good agreement between the experimental results and the mathematical model.

Table 6: Precision of the simulation for 10 dominant chromosomes (results of computer program after 1000 iterations)

Chromosome No.	*Se*	Error function (%)
1	255.30	1.678
2	255.40	1.678
3	255.40	1.678
4	255.50	1.679
5	255.70	1.680
6	255.70	1.680
7	255.70	1.680
8	255.80	1.681
9	255.90	1.682
10	256.20	1.684

Table 7: Magnitude of dominant chromosome parameters

a^*	1.13E-1
b^*	4.32E-1
c^*	1.65E+1
d^*	0.00E+0
σ	1.09E-3
D_{hm}	3.16E-1
A	1.13E-1
B	-3.79E-3
n_o	9.30E-1

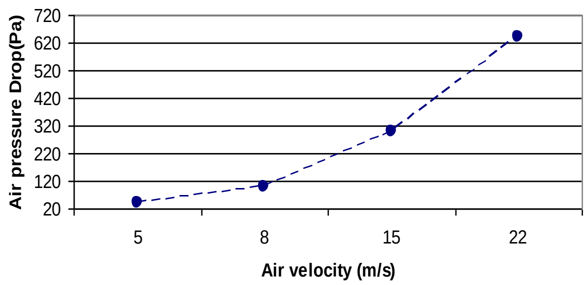

Figure 3: The air pressure drop via air velocity resulted from the experiment governed on Peugeot radiator

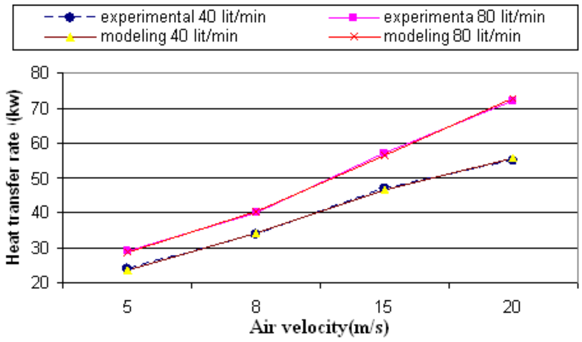

Figure 4: Comparison between experimental results and results of final model obtained from computer program

7) Conclusions

Heat transfer rate in the engine, strongly depends on radiator performance. Therefore it is necessary to have a precise simulation for the radiator. Most of researches related to heat exchangers are confined to experimental works and there is no mathematical model to specifically simulate the radiator performance. In the present study the experimental results have been applied to derive a mathematical correlation which can predict the radiator performance with an acceptable precision. The model generates a correlation for simulation of thermal behavior in the radiator by using a relation in similar form to empirical ones. The exact form of the correlation obtained by employing GA method. The model is then compared with experimental results and showed a good precision (1.68% deviation).

List of Symbols

A_i	Inside area (m^2)
A_o	Outside area (m^2)
dT_m	Partial temperature difference between inside and outside of radiator pipe ($^\circ C$)
D_h	Pipe hydraulic diameter (m)
L	Total length of radiator pipe (m)
$(\dot{m}C_p)_c$	Thermal capacity of cold fluid zone (kJ/K)
$(\dot{m}C_p)_h$	Thermal capacity of hot fluid zone (kJ/K)
n_i	Inner fin efficiency
n_o	Outer fin efficiency
Nu_b	Nuselt Number
P	Inner circumference of tube (m)
R_{fi}	Thermal resistance of inner fouling (K/W)
R_{fo}	Thermal resistance of outer fouling (K/W)
R_w	Wall thermal resistance (K/W)
T_{c1}	Water temperature at radiator outlet ($^\circ C$)
T_{c2}	Water temperature at radiator inlet ($^\circ C$)
T_{h1}	Air temperature at radiator outlet ($^\circ C$)
T_{h2}	Air temperature at radiator inlet ($^\circ C$)
ΔT_{lm}	Logarithmic mean temperature difference ($^\circ C$)

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شبیه‌سازی ریاضی مبدل حرارتی خودرو با روش وراثت و مقایسهٔ آن با نتایج تجربی

رامین مهدی پور[1]، زهرا بنی عامریان[2]، بابک سخایی[3*]

[1] *دانشگاه تفرش، تفرش، ایران،* mehdipour@tafreshu.ac.ir
[2] *دانشگاه تفرش، تفرش، ایران،* baniamerian@tafreshu.ac.ir
[3] *شرکت تحقیق، طراحی و تولید موتور ایران‌خودرو (ایپکو)، تهران، ایران،* b_sakhaei@ip-co.com
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چکیده

مبدل‌های حرارتی هواخنک در صنایع متنوعی استفاده می‌شوند و عملکرد مناسب مجموعه وابسته به عملکرد سامانهٔ خنک‌کاری است. مبدل حرارتی خودرو تاثیر شدیدی در سامانهٔ خنک‌کاری موتور دارد.

بر همین اساس، در این مقاله شبیه‌سازی ریاضی مبدل حرارتی با استفاده از روش وراثت انجام شده است. علیرغم مطالعات تجربی متعددی که برای بررسی رفتار مبدل‌های حرارتی صورت گرفته است، هیچ شبیه‌سازی تحلیلی واحدی برای شبیه‌سازی عملکرد مبدل حرارتی موجود نیست. در این تحقیق، با استفاده از نتایج تجربی معادله‌ای عمومی برای شبیه‌سازی عملکرد مبدل حرارتی ارائه شده است. بر این اساس، یک برنامهٔ رایانه‌ای تدوین شد که با استفاده از داده‌های تجربی به عنوان ورودی، شبیه‌سازی ریاضی را توسعه می‌دهد. این شبیه‌سازی بر مبنای محاسبات ترمودینامیک و انتقال حرارت است و نرخ خنک کاری مبدل حرارتی را در هر لحظه با خطای کمتر از ۱٫۶۸٪ محاسبه می‌کند.

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