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Use of Algorithms of Changes for Optimal Fin Geometries of the Internally Micro-fin Tubes in the Turbulent Region

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ABSTRACT

For the heat transfer enhancement, internally micro-fin tubes are widely used in commercial HVAC applications. It is commonly understood that the micro-fin enhances heat transfer but at the same time increases the pressure drop as well. In the open literature, majority of the works were focused on the development of correlations in a particular flow regime, especially in the turbulent region. Those correlations were developed based on different micro-fin geometries (fin spiral angle, fin height, and number of fins per cross-sectional area). However, the previous studies lacked information about the optimal fin geometry. It is of interest to know the optimal fin geometry because it can provide the best performance, i.e., the higher heat transfer and the lower friction loss.

A new and original optimization method, Algorithms of Changes (AOC), was successfully developed in the authors' previous publications for solving the heat exchanger design problem (1), bin packing problem (2), and the traveling salesman problem (3). It is based on the transformation operators of hexagrams in I Ching, one of the Chinese classic texts. In this study, we extended the capability of the AOC method to find out the optimal fin geometric variables (The fin spiral angle, fin height-to-diameter, and number of fins per cross-sectional area) of the micro-fin tube based on the objective function, the efficiency index. The empirical heat transfer and friction factor correlations were adopted to find out the efficiency index. For comparison purposes, the Genetic Algorithms (GA) was also used to seek out the optimal fin geometry. From the results, both numerical methods can find out the optimal solution in a short iterative process. Furthermore, the AOC and GA results outperform the efficiency index computed by the fin geometries used in the past studies. Therefore, it was proved that the AOC can be applied not only to the heat exchanger design (1) but also to the optimization of thermal systems. [**Keywords:** turbulent region; internally micro-fin tubes; fin geometries; optimization; Algorithms of Changes (AOC); Genetic Algorithms (GA).]

NOMENCLATURE

C_f	Fully developed friction factor coefficient (fanning friction factor), $(=\Delta P \cdot D_i/2 \cdot L \cdot \rho \cdot V^2)$ [dimensionless]
$C_{f,p}$	Fully developed friction factor coefficient (fanning friction factor) for plain tube, $(=\Delta P \cdot D_i/2 \cdot L \cdot \rho \cdot V^2)$ [dimensionless]
c_p	Specific heat of the test fluid evaluated at T_b [J/(kg·K)]
D_i	Inside diameter of the test section (tube) [mm]
e	Internal fin height [mm]
h	Fully developed peripheral heat transfer coefficient [W/(m^2·K)]
j	Colburn-j factor $(=St\ Pr^{0.67})$ [dimensionless]
j_p	Colburn-j factor $(=StPr^{0.67})$ for plain tube [dimensionless]
k	Thermal conductivity evaluated at T_b [W/(m·K)]
L	Length of the test section (tube) [m]
N_s	Number of starts/fins inside the cross-sectional area [dimensionless]
Nu	Local average or fully developed peripheral Nusselt number $(= h \cdot D_i /k)$ [dimensionless]
p	Axial fin pitch $[=\pi \cdot D_i /(N_s \cdot \tan \alpha)]$ [m]
Pr	Local bulk Prandtl number $(=c_p \cdot \mu_b/k)$ [dimensionless]

Re	Local bulk Reynolds number ($=\rho \cdot V \cdot D_i/\mu_b$), [dimensionless]
St	Local average or fully developed peripheral Stanton number [=Nu/ (Pr·Re)] [dimensionless]
T_b	Local bulk temperature of the test fluid [ºC]
t	fin width [mm]
V	Average velocity in the test section [m/s]

Greek Symbols

α	Spiral/helix angle [degree]
β	Included angle [degree]
η	Efficiency index [dimensionless]
ΔP	Pressure difference [Pa]
μ_b	Absolute viscosity of the test fluid evaluated at T_b [Pa·s]
ρ	Density of the test fluid evaluated at T_b [kg/m^3]

INTRODUCTION

Single-phase liquid flow in internally enhanced tubes is becoming more important in commercial HVAC applications, where enhanced tube bundles are used in flooded evaporators and shell-side condensers to increase heat transfer. This enables water chillers to reach high efficiency, which helps mitigate global warming concerns of HVAC systems. One kind of internally enhanced tube is the spirally micro-fin tube. For the single-phase flow, the heat transfer enhancement in the turbulent region was more obvious than that in the laminar region. Jensen and Vlakancic (4) defined the micro-fin tube to have a height less than $0.03D_i$ (i.e. $2e/D_i<0.06$), where D_i is the inside tube diameter and e is the fin height. Basically, such kind of tube is widely used in high flow rate applications because the heat transfer enhancement in high flow rates (turbulent region) is more pronounced than that in the low flow rates (laminar region). Khanpara et al. (5) reported that the turbulent heat transfer in micro-fin tubes had an increase of 30 to 100% with Reynolds numbers between 5,000 and 11,000. Brognaux et al. (6) indicated that there was a 65 to 95% increase in heat transfer for the micro-fin tube over the smooth tube. However, there was also a 35 to 80% increase in the isothermal pressure drop. The work of Jensen and Vlakancic (4) indicated that the micro-fins increased heat transfer ranging from 20 to 220% in the turbulent flow region. However, there was a penalty due to the increase in the friction factor ranging from 40 to 140%. Webb et al. (7) calculated the "efficiency index", defined as the ratio of the heat transfer and the friction factor of enhanced tube to those variables for the plain tube, to vary from 0.9 to 1.2 for the seven different micro-fin tubes with Reynolds numbers between 20,000 and 60,000. They also developed the linear multiple regression correlations to predict the heat transfer coefficients and friction factors as a function of the enhancement dimensions. Zdaniuk et al. (8) also studied the heat transfer coefficients and friction factors experimentally for eight helically micro-tubes and one smooth tube using liquid water with Reynolds numbers ranging from 12,000 to 60,000. Power-law correlations for Fanning friction and Colburn j-factors were developed using a least-squares regression. The performance of the correlations was evaluated with data of other researchers (4, 7) with average prediction errors between 30% and 40%.

Since the heat transfer enhancement of micro-fin tube was significant in the turbulent region, in the open literature, majority of the works were focused on the development of correlations for heat transfer coefficient and the friction factor in the turbulent region. Those correlations were usually developed with involvement of the fin geometric variables (fin spiral angle, fin height-to-diameter ratio, and number of starts per cross-sectional area). However, the studies in the open literature lacked information about the optimal fin geometry or spirally micro-fin tubes. In fact, application of the optimal fin geometry tube to the heat exchanging system can help not only to increase the heat transfer performance but also to achieve a lower friction penalty.

In recent studies, several researchers, reviewed in (9), applied the Genetic Algorithm (GA) (10) for optimizing the fin shapes for increase of heat transfer performance (11-16). In between, Fabbri (15) applied the GA method for optimizing the geometry of internally finned tubes under the laminar flow condition. Based on the finite element (or numerical) model, the optimal polynomial lateral profile for the longitudinal fins was obtained. For the current fin geometry optimization problem, the GA method will be used as a reference to check the results obtained by the proposed new optimization method described next.

Recently, a new and original optimization method, Algorithms of Changes (AOC), was developed by the authors and applied successfully to the heat exchanger design problem (1), the bin packing problem (2), and the traveling salesman problem (3) The AOC method was developed on the basis of the traditional Chinese book, I Ching. The book of changes (I Ching) was a collection of statements about divination with 64 hexagrams. There were generally three processes of divining with I Ching: (i) obtain a hexagram; (ii) read or understand the obtained hexagram, there are several methods (operators) of obtaining more information from a hexagram (e.g. to see the wrong, synthesis or mutual ancient divination symbol of the original one), and (iii) get the corresponding inscriptions of the hexagrams through the book I Ching. In China, people used the inscriptions as an aid of making decision or predicting future. In this study, the authors proposed that the 64 hexagrams can be generalized to the set of binary string with length L such that the points in the domain of the optimizing function can be encoded to the generalized hexagrams, thus the corresponding operators (methods of obtaining more information from a hexagram) is also generalized. In computation, random search is used to obtain the hexagram in the first process. The inscriptions of hexagrams is changed to the optimizing function values such that comparison can be made in each iteration. Through the generalized I Ching process, the optimal solution can be given.

In this study, the objective is to propose the AOC method for finding the optimal geometric variables of micro-fin tubes in the turbulent region. Since there was no information about the optimal fin geometry of spirally micro-fin tube in the open literature, therefore, the GA method will be used as a reference. In comparison with GA, the AOC method will be evaluated to see if it is applicable for the optimization problem of micro-tube fin geometry.

EVALUATION OF THE OPTIMAL FIN GEOMETRY WITH USING GA

Figure 1 shows the internal geometry of the spirally micro-fin tube. The axial fin is extruded along the tube by a spiral angle. In Figure 2, it is clearly shown that the fin geometric variables include fin height (e), the fin pitch (p), the spiral angle (α), the number of starts per cross-sectional area (N_s), and fin width (t), etc. In general, the spiral angle, fin height, and number of starts were used in the correlations for heat transfer coefficient and friction factor.

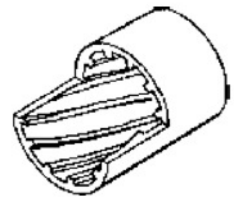

Figure 1 A spirally micro-fin tube (adopted from Zdaniuk et al. (8))

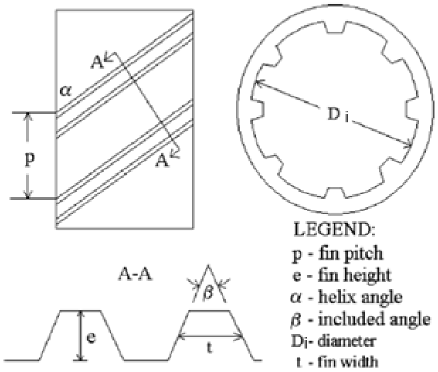

Figure 2 Geometric variables of the spiral fins (adopted from Zdaniuk et al. (8))

For the heat transfer coefficient and friction factor in the turbulent region, the correlations developed by (7, 8) were more simple and comprehensive because the fin geometric variables were correlated in the power law form. Those correlations were developed based on several internally micro-fin tubes with various fin geometries. In those studies, water was used as the test fluid and the heat transfer and friction factor data were collected under the uniform wall cooling flux boundary condition. Moreover, the inner diameter (or fin based diameter) of the plain and micro-tubes used in (7, 8) was around 15.5mm.

The heat transfer and friction factor correlations for the micro-fin tubes developed by Webb et al. (7) are given as:

$$j = 0.00933\, Re^{-0.181} N_s^{0.285} (e/D_i)^{0.323} \alpha^{0.505} \quad (1)$$

$$C_f = 0.108\, Re^{-0.283} N_s^{0.221} (e/D_i)^{0.785} \alpha^{0.78} \quad (2)$$

where the ranges of variables are $20{,}000 \le Re \le 60{,}000$, $10 \le N_s \le 45$, $0.0210 \le e/D_i \le 0.0356$, $25 \le \alpha \le 45$.

The heat transfer and friction factor correlations for the micro-fin tubes developed by Zdaniuk et al. (8) are in the form of:

$$j = 0.029\, Re^{-0.347} Ns^{0.253} (e/D_i)^{0.0877} \alpha^{0.362} \quad (3)$$

$$C_f = 0.128\, Re^{-0.305} Ns^{0.235} (e/D_i)^{0.319} \alpha^{0.397} \quad (4)$$

where the ranges of variables are $12{,}000 \le Re \le 60{,}000$, $10 \le N_s \le 45$, $0.0199 \le e/D_i \le 0.0327$, $25 \le \alpha \le 48$. From the Equations (1) to (4)**,** both j and C_f increase with increasing N_s, e/D_i, and α.

In Webb et al.'s study (7), the efficiency index,

$$\eta = (j / j_p) / (C_f / C_{f,p}) \quad (5)$$

was defined in order to evaluate the overall performance (heat transfer enhancement and pressure drop penalty) of micro-fin tubes. Referring to (8), the Dittus and Boelter (17) correlation ($Nu_p = 0.027\ Re^{0.8}\ Pr^{0.4}$ or $j_p = 0.027\ Re^{-0.2}\ Pr^{0.067}$) and the Blasius (18) equation ($C_{f,p} = 0.0791\ Re^{-0.25}$) can be treated as the plain tube equations to be used in Equation (5).

In the studies (7, 8), the optimal fin geometry with the best efficiency index was not identified. If we just used the trial method for finding the optimized geometric variables, it would be time-consuming and would not guarantee an optimal solution. Therefore, referring to (15), the GA method was an effective way to evaluate the optimal fin geometry. In this study, for the GA optimization process, the fin spiral angle, fin height-to-diameter ratio, and number of starts per cross-sectional area were arranged as the optimized variables. The efficiency index, Equation (5), was treated as the objective function.

Since the ranges of variables and the coefficients and exponents of the Webb and Zdaniuk's correlations (Equations 1 to 4) were different, it was better to separate the two studies (7, 8) into two cases, CASE I for Webb et al. (7) and CASE II for Zdaniuk et al. (8). For CASE I, referring to the ranges of variables of Equations (1) and (2), the upper and lower bounds of the optimized variables were employed: $10 \le N_s \le 45$, $0.0210 \le e/D_i \le 0.0356$, $25 \le \alpha \le 45$. Furthermore, the optimized variables were evaluated in the Reynolds number ranging from 20,000 to 60,000. For CASE II, referring to the ranges of variables of Equations (3) and (4), the upper and lower bounds of the optimized variables were employed: $10 \le N_s \le 45$, $0.0199 \le e/D_i \le 0.0327$, $25 \le \alpha \le 48$. Furthermore, the optimized variables were evaluated in the Reynolds number ranging from 12,000 to 60,000.

The basic GA method with selection, mutation and crossover operators was applied for both cases. It was run in the GA Matlab toolbox (19). The GA method was applied to find the optimal N_s, e/D_i, and α. In the GA process, the population size, the length of the strings, mutation probability, generation gap and iteration were set to be 50, 21, 0.03, 0.6 and 200, respectively. To ensure the result consistency, all the GA results were examined with 20 times.

After a quick computation, the GA results (Re=60,000) obtained for CASE I are presented in Table 1. For comparison purposes, the other fin geometries used in (7) and their heat transfer enhancement (j/j_p), the pressure drop penalty ($C_f/C_{f,p}$), and the efficiency index (η) calculated by Equations (1-2, 5) are also listed in Table 1. In fact, the optimized fin geometric variables obtained by GA is the same in the overall Reynolds number range (from 20,000 to 60,000). Referring to the Figure 3, for CASE I, the highest efficiency index was obtained when Re=60,000. Therefore, the results presented in Table 1 are for the highest efficiency index in the overall Reynolds number range.

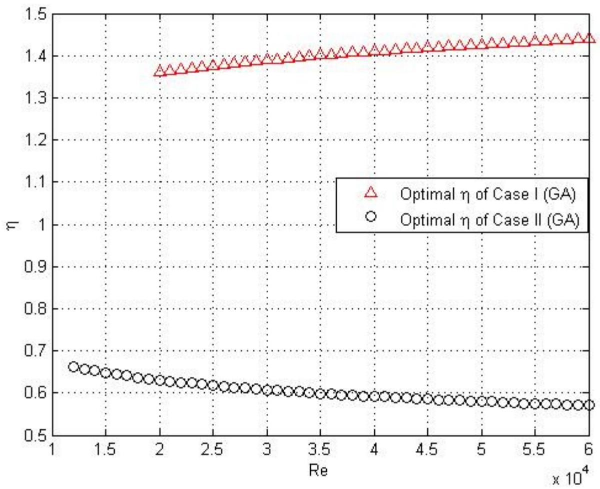

Figure 3 Comparisons of the optimal efficiency index η with using the GA and AOC methods along the entire Reynolds number range.

Table 1 shows the optimal fin geometries (N_s = 45, e/D_i = 0.021, α = 25) and the efficiency index (η = 1.41) computed by the GA method. The efficiency index of GA is obviously larger than the index of all the other fin geometries used in the study of Webb et al. (7). Although there is 184% increase in heat transfer for the optimal fin geometry over the plain tube, the friction penalty is much less (131% increase) when compared with the other fin geometries.

Table 1 Efficiency index of all the fin geometries used in Webb et al's study (7) and the GA results

CASE I (Re = 60,000)						
	e/D_i	N_s	α	j/j_p	$C_f/C_{f,p}$	η
Tubes #1 - #7 used in (7)	0.0210	45	45	2.48	2.07	1.19
	0.0256	30	45	2.35	2.21	1.06
	0.0277	10	45	1.76	1.84	0.96
	0.0300	40	35	2.36	2.19	1.08
	0.0317	25	35	2.11	2.07	1.02
	0.0342	25	25	1.82	1.69	1.08
	0.0356	18	25	1.68	1.62	1.04
GA results	0.0210	45	25	1.84	1.31	1.41

Table 2 represents the GA results for CASE II (Re= 12,000). For comparison purposes, the other fin geometries used in (8) and their heat transfer enhancement (j/j_p), the pressure drop penalty ($C_f/C_{f,p}$), and the efficiency index (η) calculated by Equations (1-2, 5) are also listed in Table 2. In fact, the optimized fin geometric variables obtained by GA is the same in the overall Reynolds number range (from 12,000 to 60,000). Referring to the Figure 3, for CASE II, the highest efficiency index was obtained when Re=12,000. Therefore, the results presented in Table 2 are for the highest efficiency index in the overall Reynolds number range.

Table 2 shows the optimal fin geometric variables (N_s = 45, e/D_i = 0.00199, α = 25) and the efficiency index (η = 0.66) computed by the GA method. The efficiency index of GA is a little bit larger than the index of all the other fin geometries used in the study of Zdaniuk et al. (8). For the optimal fin geometry, there is 161% increase in heat transfer and 243% increase in friction factor over the plain tube.

Table 2 Efficiency index of all the fin geometries used in Zdaniuk et al.'s study (8) and the GA results

CASE II (Re = 12,000)						
	e/D_i	N_s	α	j/j_p	$C_f/C_{f,p}$	η
Tubes #1 to #8 used in (8)	0.0243	10	25	1.12	1.82	0.61
	0.0240	30	25	1.48	2.35	0.63
	0.0243	30	48	1.87	3.05	0.61
	0.0244	45	25	1.64	2.60	0.63
	0.0199	45	35	1.82	2.78	0.65
	0.0244	45	35	1.85	2.97	0.62
	0.0327	45	35	1.90	3.26	0.58
	0.0244	45	48	2.07	3.36	0.62
GA results	0.0199	45	25	1.61	2.43	0.66

ALGORITHMS OF CHANGES AND RESUTLS

Before solving the optimization problem, a brief introduction of the Algorithms of Changes (AOC) is shown in Figure 4.

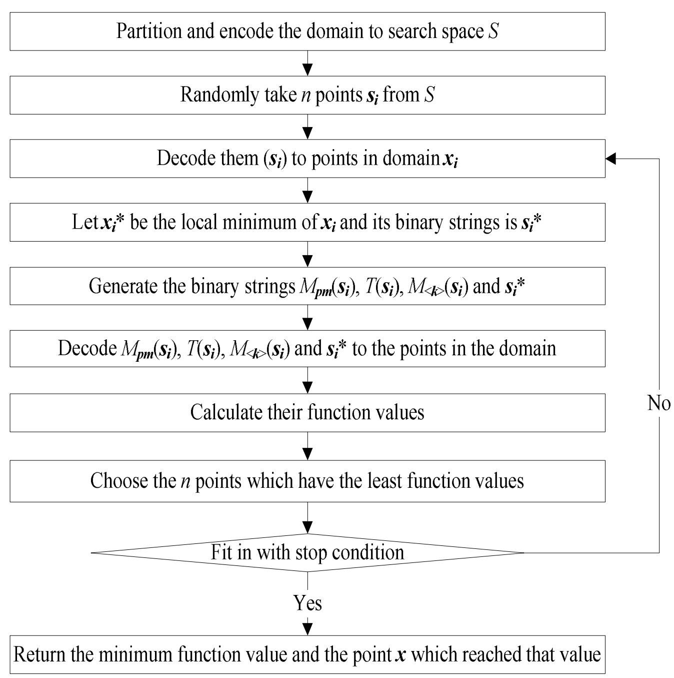

Figure 4 Flow chart of the Algorithms of Changes

The Algorithms of Changes (AOC) are described in (1). In this study, we suppose that an objective function is defined on a domain W in $\mathbf{R}^3$ and an input vector $x_i = (N_s{}^i, e/D_i{}^i, \alpha^i)$. The input vector is encoded bijective mapping to be a binary string $[N_s]_2[e/D_i]_2[\alpha]_2$ with the length $3L$ where L is a positive integer and $[\cdot]_2$ is the standard binary encoding on the corresponding intervals.

Then, the algorithms of AOC can be summarized as follows:

- Step1. Randomly choose q strings $(x_1, x_2, \cdots, x_q)$ from S, $M = 1$.
- Step2. Generate new strings from each old string by using mutation, turnover and mutual operators of AOC.
- Step3. Evaluate the costs of resulted strings from Step2.
- Step4. Choose the q strings which have the smallest cost.
- Step5. Compare M with maximum iteration number N, if $M = N$, go to Step6, or go back to Step2
- Step6. Output the string $x_{\min}$ with smallest cost in the last generation and $\eta(x_{\min})$

To define the operations, let $S_L = \{0,1\}^L$ be the set of binary strings with length L. The 64 hexagrams in I Ching can be represented by the set S_6. Now, the generalized I Ching operators are defined as:

Mutation Operator

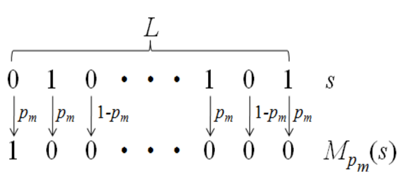

Figure 5 Mutation operator

The mutation operator $M_{p_m} : S_L \to S_L$ imitates the wrong operator. It is same as the mutation in GA. It maps $s \in S_L$ to $M_{p_m}(s) \in S_L$ by changing each bits of s from 1 to 0 or 0 to 1 according to the probability p_m, see Figure 5.

Turnover Operator

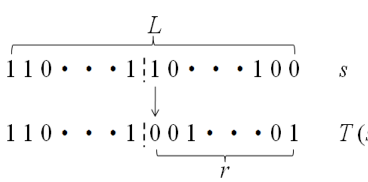

Figure 6 Turnover operator

The turnover operator $T : S_L \to S_L$ is a generalization of the synthesis operator. It maps $s \in S_L$ to $T(s) \in S_L$ by turnover the last r bits of s where r is an integer randomly chosen from 1 to L; refer to Figure 6.

Mutual Operator

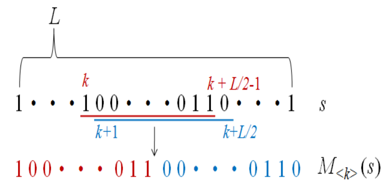

Figure 7(a) L is even

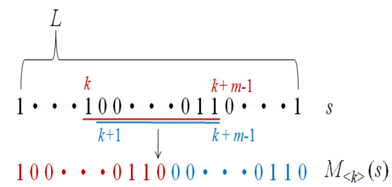

Figure 7(b) L is odd

The mutual operator $M_{<k>} : S_L \to S_L$ is a generalization of the mutual operator in I Ching. Let $s[i]$ and $M_{<k>}(s)[i]$ be the i-th bit of s and $M_{<k>}(s)$, respectively. It maps $s \in S_L$ to $M_{<k>}(s) \in S_L$ by:

$$M_{<k>}(s)[i] = \begin{cases} s[k+i-1], & 1 \le i \le k + \frac{L}{2} \\ s[k+i-\frac{L}{2}], & k + \frac{L}{2} + 1 \le i \le L \end{cases} \tag{6}$$

If L is even, where k is an integer between 1 and $\frac{L}{2}$, see Figure 7(a), and:

$$M_{<k>}(s)[i] = \begin{cases} s[k+i-1], & 1 \le i \le k + \lceil \frac{L}{2} \rceil \\ s[k+i-\lceil \frac{L}{2} \rceil], & k + \lceil \frac{L}{2} \rceil + 1 \le i \le L \end{cases} \tag{7}$$

If L is odd, where k is an integer between 1 and $\lceil \frac{L}{2} \rceil$, see Figure 7(b). Here, different k defines different mutual operators.

In this study, the population size, the length of the strings, the mutation probability p_m, the mutual parameter k, and iteration parameter m for the AOC method were set to be 50, 21, 0.01, 1 and 200, respectively. As shown in Figures 8 and 9, it was observed that the optimal efficiency index for both AOC and GA methods were stable after the 100 iterations (for CASE I) and 120 iterations (for CASE II). Referring to the Figure 10, the optimal efficiency index found by GA and AOC for both cases was nearly the same. With using the two numerical methods, the highest efficiency index for CASE I and CASE II were obtained when Re=60,000 and Re=12,000, respectively.

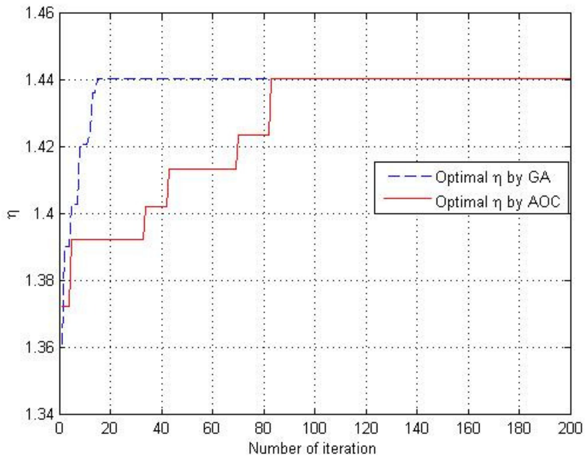

Figure 8 Performance comparisons with GA and AOC in Case I

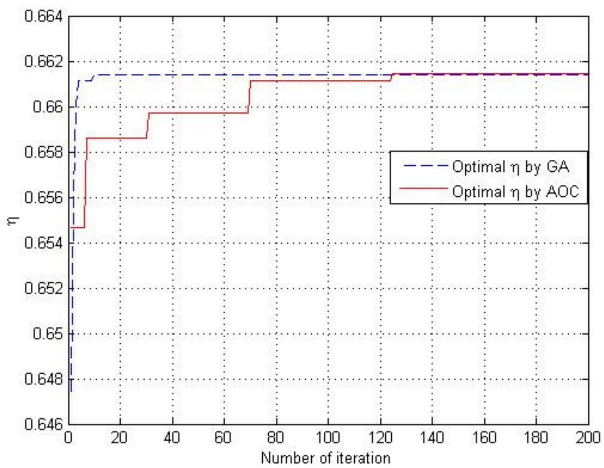

Figure 9 Performance comparisons with GA and AOC in Case II

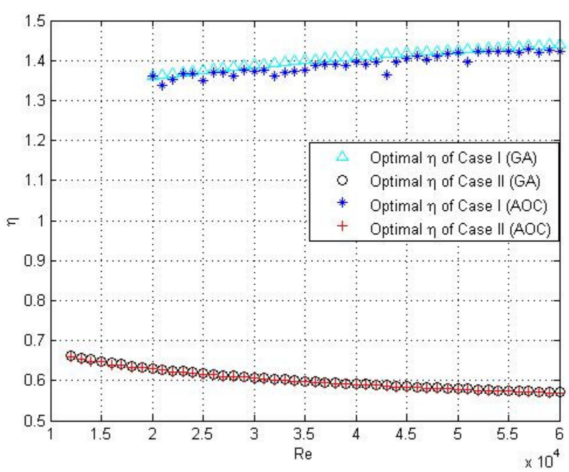

Figure 10 Comparisons of the optimal efficiency index η with using the GA and AOC methods along the entire Reynolds number range.

Finally, the optimal fin geometry found by AOC for CASE I and CASE II are summarized and compared with the results of GA and the best fin geometry used in the previous studies (7, 8) in Table 3. The optimal variables obtained from the GA and AOC were nearly identical. Compared with the best fin geometry used in (7, 8), the efficiency index of AOC is better due to the lower friction penalty. Therefore, the performance of AOC is comparable with that of the GA method and they obviously outperform the fin geometries used in the past studies. Hence, the AOC can also effectively be used for finding optimal fin geometry of micro-fin tubes.

Table 3 Best efficiency index of all the fin geometries used in the past studies (7, 8), GA, and AOC methods

CASE I (Re = 60,000)						
	e/Di	N_s	α	j/j_p	$C_f/C_{f,p}$	η
Best fin geometry used in (7)	0.0210	45	45	2.48	2.07	1.19
GA results	0.0210	45	25	1.84	1.31	1.41
AOC results	0.0210	45	26	1.88	1.35	1.39
CASE II (Re = 12,000)						
	e/Di	N_s	α	j/j_p	$C_f/C_{f,p}$	η
Best fin geometry used in (8)	0.0199	45	35	1.82	2.78	0.65
GA results	0.0199	45	25	1.61	2.43	0.66
AOC results	0.0200	45	27	1.66	2.51	0.66

CONCLUSIONS

The Algorithms of Changes (AOC) were successfully applied to the fin geometry optimization problem of micro-fin tube in this study. The AOC results outperform the fin geometries used in the past studies. Comparing with the GA method, both methods can find the optimal solution and it helps in reducing the friction factor and increasing the overall efficiency. Since it is the first time for the AOC to be used for the fin geometry problem, the AOC method is expected in the future to solve more complicated fin geometry optimization problems, such as the single-phase or two-phase flow of micro-fin tubes in the transition region.

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