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Optimal Design of an I.C. Engine Cylinder Fin Arrays Using a Binary Coded Genetic Algorithms

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ABSTRACT: *Optimization is a technique through which better results are obtained under certain circumstances. In the present study maximization of heat transfer through fin arrays of an internal combustion engine cylinder have been investigated, under one dimensional, steady state condition with conduction and free convection modes. Traditional methods have been used, in the past, to solve such problems. In this present study, a non-traditional optimization technique, namely, binary coded Genetic Algorithm is used to obtain maximum heat transfer and their and their corresponding optimum dimensions of rectangular and triangular profile fin arrays.*
This study also includes the effect of spacing between fins on various parameters like total surface area, heat transfer coefficient and total heat transfer .The aspect rations of a single fin and their corresponding array of these two profiles were also determined. Finally the heat transfer through both arrays was compared on their weight basis. Results show the advantage of triangular profile fin array.

Keywords: *Aspect Ratio, Genetic Algorithms, Heat Transfer, Heat Transfer per unit Mass, Objective function, Optimization, Rectangular Fin Array, Triangular Fin Array.*

1. INTRODUCTON

Fins are extended surfaces often used to enhance the rate of heat transfer from the cylinder surface. Fins are generally used on the surface which has very low heat transfer coefficient. Straight fins are one of the most common choices for enhancing better heat transfer from the flat surfaces. The rate of heat flow per unit basis surface increase in direct proportion to the added heat conducting surface. The arrangement of fins and their geometry in an array are the most important criteria, to dissipate heat from the cylinder surface.

Optimization is a method of obtained the best results under the given circumstances. It plays an important role in the design of energy transfer components. While designing fins and their arrays, optimization helps to reduce the material cost and weight. The present study, aimed at maximizing heat transfer with a given mass, by applying optimization technique called Genetic Algorithm. For engine cylinder, the combustible gas temperature is taken as 698 K and the environment is at 298 K.

2. NOMENCLATURE

b	=	Thickness of the fin [mm]
C	=	Violation coefficient
F	=	Fitness Value
Gr	=	Grashoff's number
h	=	Heat Transfer Coefficient [W/m^2-K]
H	=	Width of the Fin [mm]
K_a	=	Thermal conductivity of air [W/m-K]
K_f	=	Thermal conductivity of fin [W/m-K]
Mf	=	Mass of fin [Kg]
Nu	=	Nusselt Number
N_p	=	Population Size
Pr	=	Prandtl number
Q_{a1}	=	Total Heat Transfer through Rectangular fin array [W]
Q_{fa1}	=	Heat Transfer trough fins in Rectangular fin array [W]
Q_{sa1}	=	Heat Transfer through spacing in rectangular array [W]
Q_{a2}	=	Total Heat Transfer through Triangular fin array [W]
Q_{fa2}	=	Heat Transfer trough fins in Triangular fin array [W]
Q_{sa2}	=	Heat transfer through spacing in Triangular array [W]
Q_m	=	Heat Transfer per unit mass of Rectangular fin array [W/Kg]
$(Q_{a1})_m$	=	Maximum heat transfer through Rectangular fin array [W]
R	=	Penalty Parameter
s	=	Spacing between the fins [mm]
T_a	=	Ambient Temperature [K]
T_0	=	Base Temperature [K]
W	=	Width of the base plate [mm]

2.1. Greek Symbols:

ρ	=	Density of the fin material [Kg/m^3]
θ_0	=	Temperature difference at the base [K]
λ	=	Length of the fin [mm]
$\varphi(x)$	=	Modified objective function.

3. MATHEMATICAL FORMULATION

In actual practice, the bore is a cylindrical one, with cross-section as circular and the surface temperature varies along the stroke. But in the present investigation, the surface of the cylinder is assumed as a flat, with constant, uniform temperature and the fins are straight. This study is carried out under one-dimensional steady state conduction and convection heat transfer. This problem may be stated mathematically, based on the following assumptions:

1. The principal heat transfer is along the x-direction
2. Thermal conductivity of the fin material is to be constant and steady state conditions will prevail.
3. Temperature gradient at the tip of the fin is assumed as zero.

3.1. Straight Fin Array of Rectangular Profile:

The heat flow equation for a rectangular fin array as show in Fig.1 is obtained by assuming the each fin having the same base temperature T_0.

The total heat transfer from the base plate by conduction and free convection through an array is

$Q_{a1} = Q_{fins} + Q_{spacing} = Q_{fa1} + Q_{sa1}$

$$Q_{a1} = \left(\frac{W}{s+b}\right) H\theta_0 \left[\sqrt{2hk_f b}\ \tanh\left[\frac{2h\lambda}{k_f b}\right] + hs\right] \text{---- (1)}$$

The constraints are expressed in normalized form as follows

$$\left(\frac{W}{s+b}\right)\left[\rho\lambda bH - m_f\right] \le 0 \text{---------------------------- (2)}$$

$$8b - \lambda \le 0 \text{ --- (3)}$$

$$\lambda - 10b \le 0 \text{ --- (4)}$$

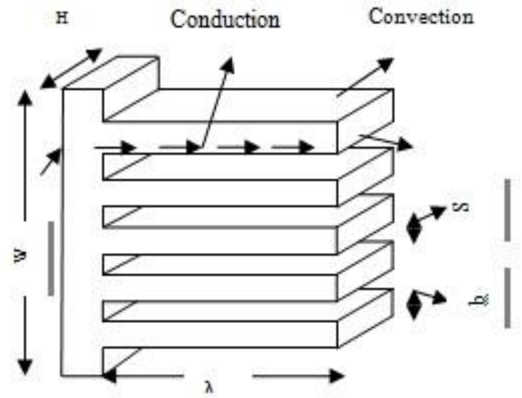

Fig.1 Geometry of Rectangular Fin Array

3.2. Straight Fin Array of Triangular Profile:

The heat flow equation for a triangular fin array as show in Fig.2 is obtained by assuming the each fin having the same base temperature T_0.

The total heat transfer from the base plate by conduction and free convection through an array is

$$Q_{a1} = \left(\frac{W}{s+b}\right) H\theta_0 \left[\sqrt{2hk_f b}\ \frac{I_1\left(2\sqrt{\frac{2h\lambda}{k_f b}}\right)}{I_0\left(2\sqrt{\frac{2h\lambda}{k_f b}}\right)} + \text{hs}\right] \text{----- (5)}$$

The constraints are expressed in normalized form as follows

$$\left(\frac{W}{s+b}\right)\left[\frac{1}{2}\rho\lambda bH - m_f\right] \le 0 \text{-------------------------- (6)}$$

$$8b - \lambda \le 0 \text{ --- (7)}$$

$$\lambda - 10b \le 0 \text{ --- (8)}$$

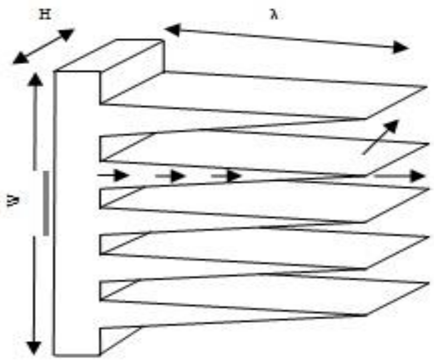

Fig.2 Geometry of Triangular Fin Array

3.3. Effect of fin spacing on heat transfer coefficient (h):

At a given temperature difference and the width of the fin, the heat transfer coefficient is varies with spacing, length and its thickness. The heat transfer coefficient can be calculated by using Nusselt number.

$$h = \left[\frac{(Nu)k_a}{\left(\frac{H}{2}\right)}\right] \text{------------------------------------- (9)}$$

Nusselt number (Nu) is taken as,

If $$10^6 < \left[Gr.Pr.\frac{s.W}{(s+b)\lambda}\right] < 2.5\ X\ 10^7$$

$$Nu = 5.22\ X\ 10^{-3}\left[Gr.Pr.\frac{s.W}{(s+b)\lambda}\right]^{0.57}\left[\frac{2\lambda}{H}\right]^{0.656}\left[\frac{2s}{H}\right]^{0.412}$$

If $$\left[Gr.Pr.\frac{s.W}{(s+b)\lambda}\right] \ge 2.5\ X\ 10^7$$

$$Nu = 2.787\ X\ 10^{-3}\left[Gr.Pr.\frac{s.W}{(s+b)\lambda}\right]^{0.745}\left[\frac{2\lambda}{H}\right]^{0.656}\left[\frac{2s}{H}\right]^{0.412}$$

4. OPTIMIZATION TECHNIQUE

Introduction: Classical search and optimization techniques demonstrate a number of difficulties when faced with complex problems. Over the few years, a number of search and optimization techniques, different in principle from classical methods, are getting increasingly more attention. These methods mimic a particular natural phenomenon to solve an optimization problem. Genetic Algorithm and simulated annealing are a few of these techniques. The major reason for GA's popularity in various search and optimization problems is its global perspective, widespread applicability and inherent parallelism.

Genetic Algorithms are computerized search and optimization algorithms based on the mechanics of natural genetics and selection. Genetic algorithms originally proposed by John Holland at the University of Michigan. The aim of his research has been to rigorously explain the adaptive process of natural system and to design artificial systems that retain the important mechanisms of validity of the techniques for function optimization. Genetic algorithms are computationally simple, but powerful in their search for improvement. Gold berg [2] describe the nature of genetic algorithm of choice by combining a Darwinian survival of the fittest procedure with a structured, but randomized, information exchange to form a canonical search procedure that is capable of addressing a broad spectrum of problems. Genetic algorithms are the search procedures based on natural genetics. Genetic algorithms differ from traditional optimization techniques in many ways. A few are listed as per [2].

- Genetic algorithm doesn't require a problem specific knowledge to carry out a search.
- Genetic algorithms work on coded design variables, which are finite length strings.
- Genetic algorithm uses a population of points at a time in contrast to the single point approach by the traditional optimization methods.
- Genetic algorithm use randomized operator, in place of the deterministic ones. The random operators improve the search process in an adaptive manner.

The four properties, separation of domain knowledge from search, working on coded design variables, population processing and randomized operators, give the genetic algorithms their relative merit.

The various genetic operators that have been identified are reproduction, crossover, mutation, dominance, inversion, intra-chromosomal duplication, deletion, translocation, segregation, speciation, migration and sharing. The present study concentrates on a simple genetic algorithm with reproduction, crossover and mutation operations only to optimize the fin and fin arrays of rectangular and triangular profiles.

The Reproduction operator emphasizes the survival of the fittest in the genetic algorithm. There are many ways of achieving effective reproduction. One simple scheme selects individual strings in the population on the proportionate basis for reproduction according to their fitness. Fitness is defined figure of merit, which is either maximized or minimized. In the effective reproduction, individuals with higher fitness values have higher probability of being selected for mating and subsequent genetic action.

Crossover is a recombination operator, which proceeds in three steps. First, the reproduction operator makes a match of two individual strings for mating. Then a cross-site is selected at random along the string length and position values are swapped between the two strings, following pair be A = (11111) and B = (00000). If the random selection of a cross-site is two, then the new strings following the crossover would be A' = (00111) and B' = (11000). This is a single site crossover. Strings A' and B' are the off spring of A and B and are then placed in the new population of the next generation.

Mutation is the random flipping of the bits or gene that is changing a 0 to 1 and vice versa. Mutation is employed to give new information and reintroduce divergence into a convergent population. This is a tool to avoid local maxima, which is a common problem in stochastic algorithms. It also prevents problem from becoming saturated with chromosome that all look alike.
The working of this simple Genetic algorithm for discrete structural optimization is explained in detail in the following section.

4.1. Working Principle of Genetic Algorithm:

This Algorithm is a population based search and optimization technique and it is an iterative procedure. Instead of working with a single solution, a GA is works with a number of solutions, which are collectively known as population. The working cycle of a GA, is expressed in the form of a flow chart is shown in Fig.4.

The operation of a GA begins with a population of initial solution chosen at random. Thereafter, the fitness value of objective function of each solution is computed. The population is then operated by three operators, namely reproduction, crossover and mutation to create a second population. This new population is further evaluated and tested for termination. First iteration of these operations is known as generation in GA.

4.1.1. Example: Straight Fin Array of Rectangular Profile

The working of genetic algorithm for design optimization of rectangular fin array is described below. The mathematical programming formulation of this problem can be written as follows: Maximize Q_{a1} subjected to $G_i(x) \leq 0$, I = 1, 2… m. Since the objective is to maximize the heat transfer through fin array of rectangular profile.

Genetic algorithms are ideally suited for un-constrained optimization problems. As the present problem is a constrained optimization one, it is necessary to transform it into an unconstrained problem to solve it using genetic algorithm. This transformation method achieves by using penalty function, which is explained in earlier section.

A violation co-efficient 'C' is computed in the following manner.
If $G_i(x) > 0$, then $c_i = G_i(x)$ or
If $G_i(x) \leq 0$, then $c_i = 0$

$$\therefore C = \sum_{i=0}^{m} C_i \text{ ------------------------------------- (10)}$$

'M' is the number of constraints.

Now the modified objective function is written, incorporating the constraint violation as:

$$\varphi(x) = Q_{a1}(1 + RC) \text{----------------------------- (11)}$$

4.1.2. Individual string of length 30:

'R' is the penalty parameter, which is selected, depending on the influence of a violated individual in the next generation. Design variables are thickness, length and spacing between the fins and the values are taken in the range of 0 to 5, 0 to 148 and 0 to 9 mm respectively. There are three design variables can take one of the values between minimum and maximum values in the given range. A binary string of length 10 is capable of representing different values between the rages given. As there are three groups, the total length of the string becomes 30 with the substring of length 10 each shown in Fig.3. A substring (0000000000) will represent the first value that is 0 mm, and (1111111111) will represent the upper limit values 5, 148 and 9 mm for b, λ and s respectively. Any intermediate values can be represented with appropriate bit coding.

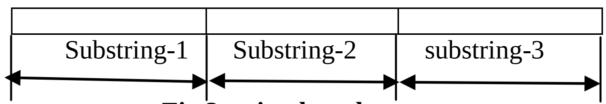

Fig.3 string length

In the present study, the twenty-first generation, shown in Table-3 & 5, all the population satisfies under the given constraint conditions. That is for all population in 21st generation the violation coefficient is zero and also the average fitness value is almost equal to the best fitness value in the population. In the present work number of generation is the criterion for termination.

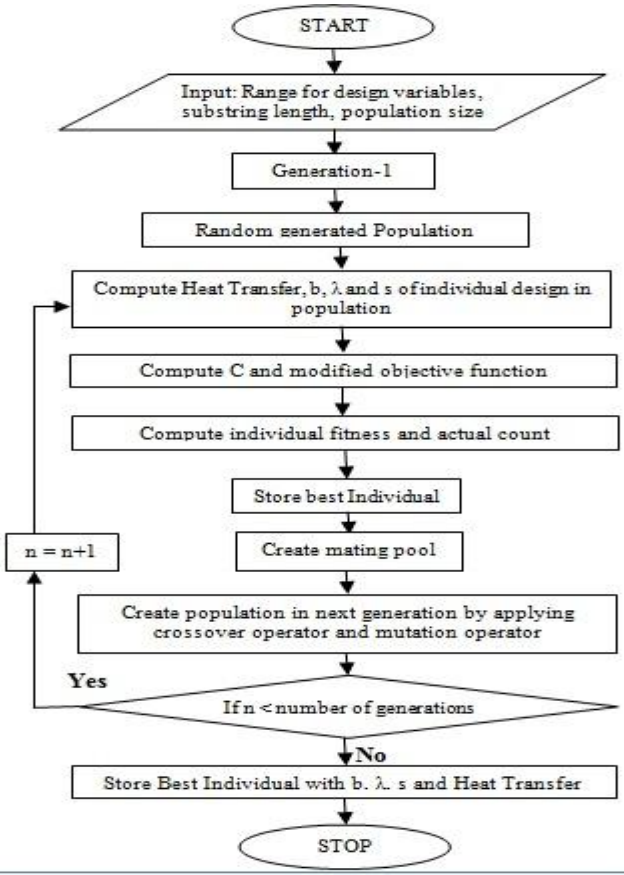

Fig.4 Flow Chart

5. RESULTS AND DISCUSSION

5.1. RESULTS:

Table-1: Comparison of Aspect (λ/b) Ratio

Fin Profile	Single fin	Fin array
Rectangular	8.896	9.94
Triangular	8.227	9.31

Table-2: Comparison of results (Base area 100x100mm²)

Optimized parameter	Rectangular Fin Array	Triangular Fin Array
Maximum Heat Transfer	158.9546W	84.43306W
Length of the Fin	46.72mm	45.37mm
Fin Thickness	4.70mm	4.87mm
Fin Spacing	7.54mm	11.71mm
Aspect Ratio (λ/b)	9.94	9.31
Heat Transfer per unit mass	327.07 W/Kg	468.08 W/Kg

Population size: 10
Number of generations: 21
Crossover Probability: 0.8
Mutation probability: 0.05

Table-3: Population of Rectangular fin array from 20th Generation

Pop. No.	Population from generation-20		
	Group-1	Group-2	Group-3
(1)	**(2)**	**(3)**	**(4)**
1	1111000010	0101000011	1101011010
2	1111000010	0101000011	1101010000
3	1111000110	0101000011	1101010010
4	1111000010	0101000011	1101000010
5	1111000010	0101000011	1101010010
6	1111000000	0101000011	1101001110
7	1111000010	0101000011	1101011010
8	1111000010	0101000011	1101011010
9	1111000010	0101000011	1101010010
10	1111000010	0101000011	1101011010

Table-4: Results of Rectangular fin array at 21st Generation

b mm	λ mm	s mm	Q_{a1} Watts	C	F
(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**
4.70	46.72	7.54	158.9546	0.00	0.99272
4.70	46.72	7.46	158.7835	0.00	0.99272
4.72	46.72	7.47	158.4214	0.00	0.99270
4.70	46.72	7.33	158.5297	0.00	0.99271
4.70	46.72	7.47	158.8184	0.00	0.99272
4.69	46.72	7.44	158.9488	0.00	0.99272
4.70	46.72	7.54	158.9546	0.00	0.99272
4.70	46.72	7.54	158.9546	0.00	0.99272
4.70	46.72	7.47	158.8184	0.00	0.99272
4.70	46.72	7.54	158.9546	0.00	0.99272

Table-5: Population of Triangular fin array from 20th Generation

Pop No.	Population from generation-20		
	Group-1	**Group-2**	**Group-3**
(1)	**(2)**	**(3)**	**(4)**
1	1111100110	0101011101	0100001000
2	1111100110	0101011101	0100000010
3	1111100110	0101011101	0100000000
4	1111100110	0101011101	0100010000
5	1111100110	0101011101	0100000000
6	1111100110	0101011101	0100011100
7	1111100110	0101000110	1101011000
8	1111100110	0101011101	1101011000
9	1111100110	0101011101	0100000000
10	1111100110	0101011101	0100000000

Table-6: Results of Triangular fin array at 21st Generation

b mm	λ mm	s mm	Q_{a2} Watts	C	F
(1)	(2)	(3)	(4)	(5)	(6)
4.87	45.37	3.61	64.88708	0.00	0.98232
4.87	45.37	3.53	64.29686	0.00	0.98221
4.85	45.37	3.50	64.09313	0.00	0.98216
4.87	45.37	3.72	65.64494	0.00	0.98257
4.87	45.37	3.50	64.09546	0.00	0.98216
4.86	45.37	3.88	66.71828	0.00	0.98285
4.87	42.38	11.71	79.63562	0.00	0.98559
4.87	45.37	11.71	84.43306	0.00	0.98640
4.87	45.37	3.50	64.09546	0.00	0.98216
4.87	45.37	3.50	64.09546	0.00	0.98216

5.2. DISCUSSION:

In this Paper, the nature of thermal and physical parameters was studied for rectangular and triangular profile fin arrays. The optimum heat transfer for a given mass of fins was obtained by using genetic algorithms method. From the results

- For a given length of the fin the heat transfer through rectangular fin array is increases with spacing at first, attains a maximum value and then decreases. As the spacing increases, the heat transfer increases due to increasing the exposed base area in between the fins, beyond the optimum spacing, the heat transfer decreases with spacing due to decreasing the number of fins. Also for a given spacing the heat transfer increases with the length of the fin due to increase in surface area of the fins.
- For a given spacing the total surface area available for heat transfer through rectangular profile fin array is more than the triangular profile fin array.
- For a given length, width and spacing between the fins, the heat transfer per unit mass for rectangular fin array is less than the triangular fin array.
- For a given length of the fins the heat transfer per unit mass increases with spacing due to reduction in number of fins thereby mass of the fins and also heat transfer coefficient increases with spacing.
- Spacing between the fins for triangular fin array is more than the rectangular fin array for maximum heat transfer therefore the heat transfer coefficient for triangular fin array is higher.

6. CONCLUSIONS

In the present work, an attempt is made to optimize rectangular and triangular profile fins and their fin arrays using genetic algorithm method also compared their performance on weight and heat transfer basis. In this regard, the following conclusions are made;

1. Heat transfer through triangular fin array per unit mass is more than that of heat transfer through rectangular fin array. Therefore the triangular fins are preferred than the rectangular fins for automobiles, central processing units, aero-planes, space vehicles etc… where weight is the main criteria.
2. At wider spacing, shorter fins are more preferred than longer fins.
3. The aspect ratio for an optimized fin array is more than that of a single fin for both rectangular and triangular profiles.
4. The GA is able to find optimal solution.
5. The GA does not require gradient information of the objective function.
6. The present work limited to one dimensional steady state heat transfer

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