TAGUCHI BASED PERFORMANCE ANALYSIS OF AN OFFSET STRIP FIN HEAT SINK

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ABSTRACT

The contributions of offset strip fin heat sinks parameters to their performance are demonstrated using the Taguchi method. In this study, the rate of overall entropy generation of the heat sink is used as the performance criterion. The effect of the environmental noise on the analysis is evaluated by calculating the value of the performance criterion from two alternative models. The Taguchi method indicates the prominent contribution of the approach velocity to the overall performance of the heat sink. However, the effects of the fin height, fin spacing and swept length on the overall entropy generation rate of the heat sink are also considerable.

Keywords: Offset strip fin, Heat sink, Performance analysis, Entropy generation, Taguchi method

INTRODUCTION

Optimum design of cooling devices is an integrated part of any attempt to improve the efficiency of a thermal system. Micro-channel, circular pin-fin, and offset strip fin (OSF) heat sinks in addition to single and multiple submerged jet impingement are amongst the techniques used in heat exchanging devices. A comparison of these techniques for a particular cooling application can be found in (Jonsson and Moshfegh, 2001, Khan et al., 2006, Lee and Vafai, 1999, Ndao et al., 2009, Sahiti et al., 2007, Yang et al., 2007). These methods could be employed in various applications including electronic packaging and the design of process heat exchangers. This paper focuses on the optimum operating condition of OSFs using Taguchi method.

Different approaches are proposed for optimization of the performance of fins (Ahmadi and Razani, 1973, Bar-Cohen and Iyengar, 2002, Bejan and Morega, 1993, Chen and Meng, 2008, Chen et al., 2007, Guo et al., 2009). Bejan (Bejan, 1996, Bejan, 1982) developed a model based on the thermodynamic second-law to consider the combined effect of heat transfer and flow friction as a measure of system performance. Since then, this model has been used extensively by others (Jha and Chakraborty, 2005, Khan et al., 2006, Ndao et al., 2009, Poulikakos and Bejan, 1982). A comprehensive review of studies on thermal fluid characteristics of offset strip heat sinks can be found in (Webb and Kim, 2005).

In recent years the Taguchi method has been successfully applied as an efficient measure for determination of the optimum operating conditions of thermal systems (Bilen et al., 2001, Chiang, 2005, Yakut et al., 2005). Taguchi method is capable of revealing significant factors which affect a thermal system through a minimum number of evaluations. The Taguchi method reduces the variability around the desired working conditions. Moreover, decisions made based on this method are reproducible in a real environment. Interested readers are referred to (Kackar, 1985, Taguchi, 1987) for further information on this technique.

Herein, the main objective is to investigate the level of influence of OSF heat sink parameters on its performance using Taguchi method. The oncoming velocity, fin length, fin height, and the distance between fins are considered as decision variables each with five levels. The formulated overall entropy generation is selected as the cost function. Two alternative approaches are employed to evaluate the total entropy generation. This is to introduce a deliberate noise in the results and take into account the possible uncertainties in a real working condition.

The optimum working condition of an identical OSF heat sink was determined in the previous studies through genetic and harmony search algorithms (Jha and Chakraborty, 2005, Mehdizadeh et al., 2010).These studies have employed the model used in the present study while variables were defined such it was allowed to take any value within their specified ranges. In contrast, the Taguchi method used in this investigation suggests the optimal working condition within the specified levels of decision variables which are limited to a number of discrete values.

MODELLING OF ENTROPY GENERATION RATE

A schematic of staggered fins and their relevant parameters is depicted in Figure 1. The substrate entrance width is B , and L is the stream-wise length. The fins' base is taken to be uniformly heated at the rate of Q_b . The approach velocity is U at the initial temperature of T_∞ . The fin thickness assumed to be constant and equal to 1 mm.

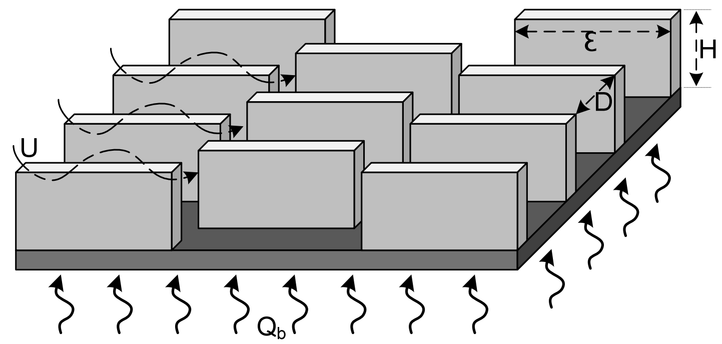

Figure 1.Schematic of the OSF heat sink

The following assumptions are considered in exergy base analysis of the problem,

- Sufficiently high ratio of ε / δ to assume one dimensional heat transfer from fins
- Distinctive boundary layers on each fin
- Adiabatic fin tips
- Laminar forced convection as the main mechanism of heat transfer due to the small swept length ε .

First approach

Jha and Chakraborty (Jha and Chakraborty, 2005) developed a fitness function based on the rate of entropy generation as a measure of OSF heat sinks performance. In their work, the entropy generation of the i^{th} row is defined as follows:

$$\dot{S}_{gen(i)} = \left(\frac{q_b \left(T_{a(i)} - T_{b(i)} \right)}{T_{a(i)} T_{b(i)}} \right) + \left(\frac{N_c f_D U}{T_{a(i)}} \right) \tag{1}$$

The overall entropy generation of the OSF is the sum of entropy generation from all individual rows defined as follows:

$$\dot{S}_{gen} = \sum_{i=1}^{N_r} \dot{S}_{gen(i)} \tag{2}$$

Details of the above formulation and definition of individual terms are presented in (Jha and Chakraborty, 2005, Mehdizadeh et al., 2010).

Second approach

In addition to equation (2), the following approach is developed to provide alternative results for the same problem. The outcome of these two models will not be exactly the same as a result of different sources that are used in calculating their variables. The heat sink efficiency is also included in the second formulation of the total entropy generation rate. The overall entropy generation of the OSF heat sink can be written as,

$$\dot{S}_{gen} = \frac{Q^2 R_{tot}}{T_a T_b} + \frac{F_D U}{T_a} \tag{3}$$

The total thermal resistance is defined as:

$$\begin{gathered} R_{tot} = R_{Cond} + R_{Conv} \\ R_{Cond} = \frac{t_b}{k_b A_b};\ R_{Conv} = \frac{1}{\eta_{HS} h A_h} \end{gathered} \tag{4}$$

η_{HS} is the heat sink efficiency and for OFS heat sinks is given by (Yang and Tao, 1998):

$$\eta_{HS} = 1 - \frac{A_{fin}}{A_h}(1 - \eta_{fin}) \tag{5}$$

The total drag force is evaluated as:

$$F_D = \Delta P . A_{fHS} \tag{6}$$

The pressure drop for OSF heat sinks is defined as (Kays and London, 1984):

$$\Delta P = \frac{\rho_f U^2}{2}\left[\left(K_c + 1 - \sigma^2\right) + f\left(\frac{4L}{D_h}\right) - \left(1 - \sigma^2 - K_e\right)\right] \quad (7)$$

The coefficients of abrupt contraction and expansion, K_c and K_e, for OSFs are adopted from (Ndao et al., 2009) as:

$$\begin{aligned} K_c &= -0.4446\sigma^2 + 0.0487\sigma + 0.7967 \\ K_e &= 0.9732\sigma^2 - 2.3668\sigma + 0.9973 \end{aligned} \quad (8)$$

The heat transfer and friction factor correlations for OSF heat sinks are presented in Table 1.

Table 1. Heat transfer and friction factors for OSF (Manglik and Bergles, 1995)

Nusselt number correlation	$Nu_{D_h} = jRe_{D_h}Pr^{1/3}$ $j = 0.6522Re_{D_h}^{-0.5403}\left(\frac{\beta-\gamma}{\alpha}\right)^{-0.1541}\gamma^{0.1499}\left(\frac{\gamma}{\beta-\gamma}\right)^{-0.0678}$ $\times\left[1 + 5.269e-5Re_{D_h}^{1.34}\left(\frac{\beta-\gamma}{\alpha}\right)^{0.504}\gamma^{0.456}\left(\frac{\gamma}{\beta-\gamma}\right)^{-1.055}\right]^{0.1}$
Friction factor	$f = 9.6243Re_{D_h}^{-0.7422}\left(\frac{\beta-\gamma}{\alpha}\right)^{-0.1856}\gamma^{0.3053}\left(\frac{\gamma}{\beta-\gamma}\right)^{-0.2659}$ $\times\left[1 + 7.669e-8Re_{D_h}^{4.429}920\gamma^{3.767}\left(\frac{\gamma}{\beta-\gamma}\right)^{0.236}\right]^{0.1}$

The OSF geometrical fractions α ,β , γ , σ are defined in Table 2. Hydraulic diameter D_h, is also presented as a function of these parameters in this table.

Table 2. Definition of the parameters used for OSF heat sinks in this study

α	β	γ	σ	D_h
H/ε	D/ε	δ/ε	$(\beta-\gamma)/\beta$	$2(\beta-\gamma)\alpha\varepsilon/\left[(\beta-\gamma)+\alpha+\alpha\gamma\right]$

T_a is the average flow temperature through the heat sink passages and is calculated as:

$$T_a = \frac{Q + F_D U}{2(\dot{m}_a C_{P,a})} + T_\infty \quad (9)$$

And for the average substrate temperature T_b, the expression is:

$$T_b = \frac{Q}{hA_h} + T_a \quad (10)$$

TAGUCHI METHOD IMPLEMENTATION

The values of decision variables at each level are presented in Table 3.

Table 3. Parameters and their associated values at each level in this study

Factors	Units	Levels				
		1	2	3	4	5
Approach velocity, U	(m/s)	1	2	4	8	15
Fin swept length. ε	(m)	0.01	0.0125	0.015	0.0175	0.02
Fin spacing, D	(m)	0.004	0.0055	0.007	0.0085	0.01
Fin height, H	(m)	0.01	0.02	0.03	0.04	0.05

The effect of the environmental noise on the performance of the OSF heat sink is included using the predictions of two alternative formulations for the total entropy generated. The objective is to acquire the minimum total entropy generation while including the effects of pressure drop and heat transfer simultaneously. The signal to noise (S/N) ratio is selected as the optimization criterion. This is applied as 'the smaller the better' for the total entropy generation, and is calculated using the following equation (Kackar, 1985).

$$Z_B = -10\log\left(\frac{1}{n}\sum_{i=1}^{n} Y_i^2\right) \tag{11}$$

The analysis is planned based on the orthogonal array (OA) design L_{25} in Table 4. This is an appropriate model for this condition with four parameters at 5 different levels.

Table 4. The L_{25} (5^4) orthogonal array and total entropy generation results from alternative methods

Parameter levels				$\dot{S}_{gen,1}$	$\dot{S}_{gen,2}$		Parameter levels				$\dot{S}_{gen,1}$	$\dot{S}_{gen,2}$
U	ε	D	H				U	ε	D	H		
1	1	1	1	0.012354	0.013237		3	3	5	2	0.009258	0.0221
1	2	2	2	0.009055	0.014011		3	4	1	3	0.003751	0.007356
1	3	3	3	0.008936	0.015884		3	5	2	4	0.004755	0.009522
1	4	4	4	0.008831	0.01884		4	1	4	2	0.006369	0.014376
1	5	5	5	0.010460	0.024034		4	2	5	3	0.005541	0.016001
2	1	2	3	0.005155	0.007183		4	3	1	4	0.004466	0.015829
2	2	3	4	0.005030	0.009399		4	4	2	5	0.004630	0.014423
2	3	4	5	0.005754	0.011474		4	5	3	1	0.012241	0.022214
2	4	5	1	0.022486	0.03903		5	1	5	4	0.010927	0.041025
2	5	1	2	0.007813	0.012056		5	2	1	5	0.016278	0.100899
3	1	3	5	0.004079	0.006632		5	3	2	1	0.008172	0.025009
3	2	4	1	0.012853	0.022939							

In the Taguchi method, the optimal working condition may not be in the initial plan. In this case, the optimum performance point can be predicted using the balanced characteristic of orthogonal arrays using the following equation (Phadke et al., 1983).

$$Y_i = \mu + x_i + e_i \tag{12}$$

A confirmation run is also required to verify the predicted values against actual ones of the cost function. Equation (12) provides a point estimation to verify the result of the confirmation run. So, the confidence interval at a chosen level of error should be calculated as presented in equation (13) from (Ross, 1987).

$$\overline{Y}_i \pm \sqrt{F_{\infty;1;DF_{\text{MSE}}}\ \text{MSE}\left(\frac{1+m}{N}+\frac{1}{n_i}\right)} \tag{13}$$

The order of evaluation runs is obtained by inserting parameters into columns of OA, $L_{25}(5^4)$, chosen as the investigation plan given in Table 4.

RESULTS AND DISCUSSION

The statistical software program, MINITAB 15, was used to calculate the overall mean for the S/N ratio of the total entropy generation rate. The results can be efficiently used to investigate the effect of each parameter on the optimization criterion. The results for the mean values of S/N ratio of each parameter at their different levels are depicted in Figure 2. The performance measure of each factor is the average of its corresponding values at all cases where that factor was at a particular level.

According to Figure 2, the minimum S/N ratio belongs to the case of U_5, ε_2, D_5, and H_1. which implies the optimum working condition for the OSF heat sink based on the total rate of entropy generation. The S/N ratios in this study are presented in Table 5. The deviance and effect of each parameter on the performance of the heat sink are also listed in Table 5.

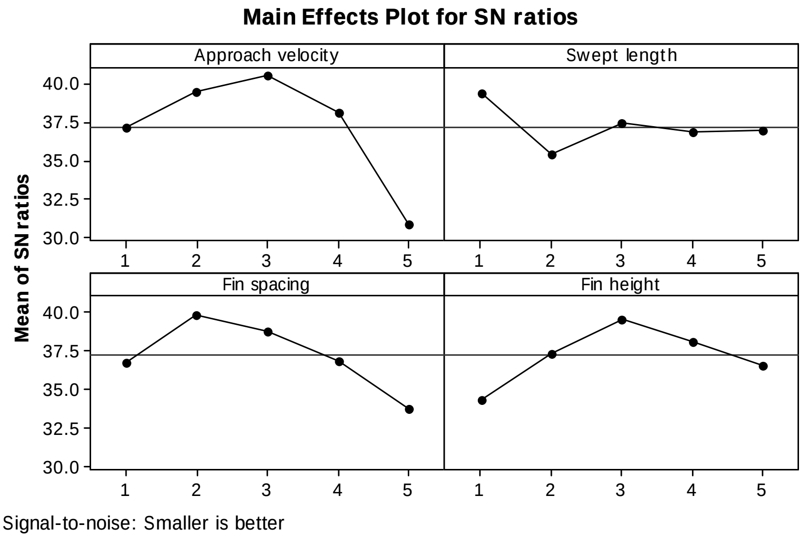

Figure 2. The mean values of S/N ratios for the parameters at different levels

The deviance is the difference between the minimum and maximum values of the mean values of the overall entropy generation for each parameter. The contribution of each parameter was calculated by dividing the deviance of each parameter over the total deviance of all parameters. As the result, it was found that approach velocity was the most influential parameter followed by fin spacing and height, respectively. Furthermore, the performance of the OSF heat sink is least sensitive to the swept length of the fins. Nonetheless, this conclusion is valid only for the parameters ranges considered in this study. For example, limiting the maximum value of the approach velocity to 8 m/s affects the sensitivity results, and in that range of velocity fin spacing will be the most prominent factor. Additionally, the mean values of the total entropy generation rate, $\overline{Y}_i$, at the different levels for each parameter are shown in Figure 3.

Table 5. Mean S/N ratios for (U_5, E_2, D_5, and H_1) and the contribution of each parameter on the OSF heat sink performance

Factors	Levels					Deviation	Contribution
	1	2	3	4	5		
U	37.10	39.44	40.47	38.11	30.88	9.59	38.70%
ε	39.33	35.38	37.47	36.86	36.96	3.95	15.94%
D	36.78	39.82	38.80	36.81	33.78	6.05	24.41%
H	34.39	37.32	39.58	38.14	36.58	5.19	20.94%

Figures 2 and 3 indicate that the minimum values of the S/N ratios do not necessarily correspond with the minimum values of the entropy generation rates. For instance, despite the minimum S/N ratio for U_5, the mean value of the total entropy generation rate is the maximum at this level. So, a more sensible decision should be made considering the results of S/N ratios together with the mean total entropy generation rates at each level for every individual parameter. Therefore, U_1, ε_4, D_4, and H_2 is a better choice with reasonably low S/N ratios and small mean total entropy generation rates. This case is not covered in the investigation plan presented in Table 4.

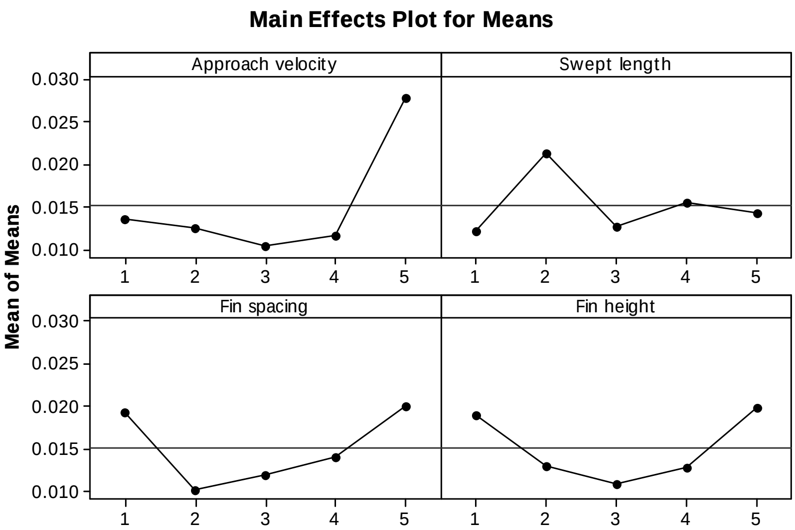

Figure 3. Mean values of overall entropy generation rate for different parameters

For the new working condition (U_1, ε_4, D_4, and H_2) the Taguchi method predicts the results presented in Table 6. The results from equations (2) and (3) are also included in this table for comparison. The Taguchi prediction is within the expected confidence interval for the value of the total entropy generation rate.

Table 6. Taguchi predicted values for (U_1, ε_4, D_4, and H_2) and the calculated value for the decision variable

Taguchi predictions			Calculated value for $\overline{Y}$	
S/N ratio	Mean $\overline{Y}$	Standard deviation	Eq. 2	Eq. 3
36.49	0.0108	0.00106	0.015	0.029

Equation (2) has been used for parameter optimization of a heat sink utilizing the Harmony Search algorithm (Mehdizadeh et al., 2010). The optimized parameters and the total entropy generated are given in Table 7. Although the Taguchi method predictions are based on coarse discretised ranges of data, they reveal sensitivity of the process to the decision variables through only a limited number of calculations. These coarse predictions are utilized in multilevel optimization where the great number of variables makes the optimization process very hard. In such situations solving the problem through a single run, though with a great number of iterations, is far beyond reach even by heuristic approaches. Particalarly in today's state of the art evolutionary algorithms, using Taguchi result makes it possible to tune diversification and intesification rates for each variable, openning a whole new chapter in *optimizing optimization tools.*

Table 7. Harmony search optimization results based on equation (2)

Design Parameters				Q_b	Optimum $\dot{S}_{gen}$
U	ε	D	H		
2.8538	0.010002	0.00236	0.05	50	0.002011

CONCLUSION

Effects of the OSF heat sinks design parameters including approach velocity, fin swept length, fin height and fin spacing were studied using the Taguchi method. To perform the sensitivity analysis, the overall entropy generation rate was chosen as an objective. An alternative model was developed for the entropy generation rate from the OSF heat sinks. This was to include the possible environmental uncertainties on the outcomes. The results of this study demonstrated the dominant contribution of the approach velocity on the performance of the OSF heat sinks by 39%. On the other hand, the fin swept length showed the least effect on the performance by 16%. The optimum working condition of the OSF heat sink was achieved for U_1, ε_4, D_4, and H_2.

NOMENCLATURE

A	Area [m^2]	Re	Reynolds number
A_{fHS}	Heat sink frontal area [m^2]	$\dot{S}_{gen}$	Overall entropy generation rate [W/K]
C_p	Specific heat [kJ/kg/K]	t_b	Substrate thickness [m]
B	Substrate width [m]	T	Temperature [K]
D	Fin spacing [m]	U	Approach velocity [m/s]
D_h	Hydraulic diameter [m]	Y_i	Performance value of *i*th evaluation run
e_i	Random error in *i*th evaluation run	Z_B	Performance criterion (S/N ratio)
F	Total drag force [N]		
F_α	Value of *F* table	*Greek letters*	
f	Friction factor	α	Dimensionless fin height
H	Fin height [m]	β	Dimensionless fin spacing
h	Convection coefficient [W/m^2/K]	γ	Dimensionless fin thickness
i	Rows index in equations (1) & (2)	δ	Fin thickness [m]
j	Colburn *j* factor	ε	Fin swept length [m]
k_b	Base thermal conductivity [W/m/K]	μ	Overall mean performance value [W/K]
K_c	Coefficient of contraction	ρ	Air density [kg/m^3]
K_e	Coefficient of expansion	σ	Unit frontal-area ratio
L	Substrate length [m]	η	Efficiency
m	Degrees of freedom in prediction of Y_i		
$\dot{m}$	Mass flow rate [kg/s]	*Subscripts*	
MSE	Mean square error	a	Air through the heat sink

N	Number of total evaluations	b	Base (heat sink substrate)
N_c	Number of OSF heat sink columns	$Cond$	Conduction
N_r	Number of OSF heat sink rows	$Conv$	Convection
Nu	Nusselt number	D	Drag
n	Number of repetitions for numerical evaluation	f	Fluid flow
n_i	Number of repetitions in confirmation evaluation	fin	Fin
Pr	Prandtl number	gen	Generation
ΔP	Pressure drop [Pa]	h	Heat transfer
Q	Total heat transfer from the heat sink [W]	HS	Heat sink
q	Averaged heat transfer from one row [W]	tot	Total
R	Thermal resistance [K/W]	∞	Free stream

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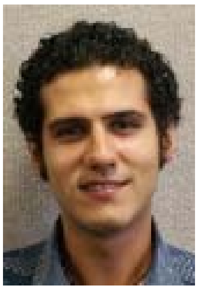

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