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GEOMETRICAL OPTIMIZATION OF LOUVER-FIN ARRAYS BY USING CONSTRUCTAL LAW AT LOW REYNOLDS NUMBER REGIME

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Abstract. With recent advancements in the computing technology, electronic devices have become smaller and more powerful, which leads to generation of more and more heat. This can be an important challenge when thousands of transistors work at high frequency, and the temperature reaches a critical value where typical cooling techniques are not sufficient. Louver fins are regarded as one of the best extended surfaces that can be employed for enhancing heat transfer without considerably increasing the pressure drop. In this paper, Constructal theory has been used to optimize louver fin arrays. The selected domain has three degrees of freedom; the louver angle ratio, the louver pitch ratio, and the inlet louver length to outlet louver length ratio. The results show that the Constructal variables are insensitive to changes in Reynolds number. The flow structure in the low Reynolds number regime is a function of the louver angle ratio, the louver pitch ratio and the Reynolds number, but above a critical Reynolds number it depends on the louver pitch ratio value alone. The results showed that the Constructal law can increase the total heat transfer rate more than 6% compared with a typical geometry.

***Key words*:** Constructal theory, Louvered-fins, Louver angle, Louver pitch ratio, Optimal design.

1. INTRODUCTION

Since the birth of electronic technology, the heat flux generation from electronic devices has increased dramatically, and it seems this trend will continue. According to the International Technology Roadmap for Semiconductors, the allowable maximum junction temperature must be less than 85^{o}C for a reliable operation. Therefore, various types of cooling systems and techniques have been developed in recent years. Passive cooling technologies, like the microchannel sink with a liquid as the working fluid, fin surfaces, and jet impingement are some of the solutions to provide high heat flux dissipation. Louvered fins are popular for removing heat because they can increase the total heat transfer rate at a reasonable increase of pressure drop. However, maintaining the junction temperature lower than a safe value is a challenging problem at the low Reynolds numbers. One of the most recent technologies to overcome this problem is constructal design, which is now a growing field in thermal science.

Constructal Theory and constructal Law are terms that are appearing more and more frequently in the scientific world. Mainly this is because an increasing number of people are using the constructal paradigm to optimize the performance of Thermofluid flow systems by generating geometry and flow structure. Adrian Bejan originates of the constructal law, in 1996. He tells that the idea came to him when he was trying to figure out the problem of minimizing the thermal resistance between an entire heat generating volume and one point. The constructal law states that for every finite-size system to persist in time, it must search for a configuration that provides easier access to the current that flow throw it. A basic result of the constructal law is that a system's shape and internal flow configuration do not develop by chance, but are obtained from the permanent struggle for better performance and therefore have to be evolved in time. From a geometric point of view, natural systems are far from being perfect, because geometric perfection means symmetry. However, in the real (physical) world the higher the internal symmetry the closer to equilibrium is. In animate systems, it is possible to find the perfect geometric configuration, because they are physically and geometrically asymmetries.

A major field of applied search for constructal design architectures is the development of compact architectures for increasing the heat transfer rate. This activity began with the discovery of optimal spacing for channels with natural [1] and forced [2] convection, and the development of T-shaped assemblies for cooling [3]. In the heat transfer framework, the study of cavities and fin arrays has deserved close attention, mainly because of its adequate representation of several engineering problems, such as heat exchangers, microelectronics, and thermal energy storage systems [4–6].

Concerning the employment of constructal law for an arrangement of fins, Bejan and Almogbel [7] conducted a study on geometric optimization of a T-shaped fin with the purpose to maximize the total heat transfer rate. Then, other geometries were investigated, such as Y-shaped [8], T-Y shaped [9], I-Y shaped [10], and X-shaped [11].

Feng *et al*. [12] used the constructal theory for optimization of a solidification heat transfer process of a slab under continuous casting with a complex function as the optimization objective. The complex function was composed of the function of the heat loss rate and surface temperature gradient of the slab. The results showed that the functions of the heat loss rate and the surface temperature gradient after optimization were decreased by 35.04% and 21.4%, respectively. Therefore, the scheme of the optimal construction of the water distribution could reduce the heat loss rate and surface temperature gradient of the slab simultaneously.

Rubbe and Sciubba [13] and Kuddusi and Denton [14] optimized a slab by using the constructal law. Lorenzini and Biserni [15] tried to develop the application of the constructal theory to other fields like biology, geophysics, social dynamics and economics. They concluded that this theory can remove the distinction between physics and engineering. Afterwards, Lorente and co-authors [16], based on the concept of the constructal law, explained why swimmers must spread their fingers and toes. Bejan and Lorente [17] studied about the evolution of the biosphere from prehistory to today. They stated that animal flow has been spreading vertically in space and towards higher speeds, longer ranges and better vision. Then these authors focused on Constructal thermodynamics where it could place the concepts of life, design and evolution in physics [18]. This new vision to design can open the doors to new advances especially in areas where design evolution is key to performance.

Recently, Asadi and coworkers used the constructal law for optimization of different shapes such as wavy channels in the low Reynolds number regime [19], shell-and-tube heat exchangers [20], wavy-fin channels of a compact heat exchanger with heat transfer rate maximization and pressure losses minimization [21], pin-fins [22], channel with louvered-fins with heat transfer rate maximization and pressure losses minimization [23].

Moreover, many researchers employed the constructal law for optimization of several various shapes like shell-and-tube heat exchangers conforming to TEMA standards [24], discrete heat sources flush mounted on a laminar flow cooled flat plate [25].

With these observations as a motivation, the goal of the present work is to employ the constructal law for improving the performance of a channel with louvered-fins. In 2013, Asadi and Mehrabani [26] used the entropy generation minimization (EGM) method to optimize louvered fins in a plate-fin compact heat exchanger. In the current study, the domain has three degrees of freedom, and six variables. The best configurations have been found by using the constructal law. From the Data Bank that have been provided (from geometric optimization) and with employing the Nonlinear Regression method, a correlation is developed for the total heat transfer rate versus constructal variables.

2. NUMERICAL MODEL

Figure 1a shows the mesh schematics of the louvered-fins. The configuration is two dimensional as shown in Fig. 1b with the third dimension D perpendicular to the plane of the domain. On the left side of the turnaround, L_1 is the louver pitch, and L_2 is the louver pitch on the right side. α_1 and α_2 are the louver angle on the left and right side of the turnaround louver, respectively. The inlet louver length is given by P_1, and the outlet louver length by P_2. In general, the configuration has six Constructal variables, and three degrees of freedom; the louver angle ratio, the inlet louver length to outlet louver length ratio, and the louver pitch ratio (α_1/α_2, L_1/L_2, P_1/P_2). These three degrees of freedom were also used in the study of Asadi *et al*. [23]. In that study, Asadi et al. [23] found that the louver angle effect was stronger for larger louver pitch ratios. The maximum heat transfer coefficient was dependent on the louver pitch ratio and the inlet louver length to outlet louver length ratio (P_1/P_2, L_1/L_2). For the louver pitch ratio, there was a minimum value and below this value the vortices upstream of the turnaround louver blocked the distance between louvers and so decreased the flow efficiency. The researchers compared their results with previous experimental studies presented by DeJong and Jacobi [27] and Malapure et al. [28] and showed that the channel optimized by constructal law was considerably superior compared to the standard channel in low Reynolds number regime. In the present study, the swept length is L, and it is assumed that the flow assembly is bathed by a uniform and isothermal free-stream.

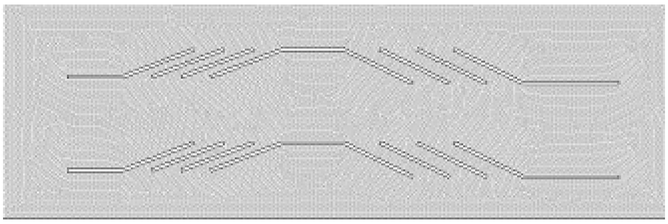

Fig. 1 – a) Mesh schematics of louvered-fins.

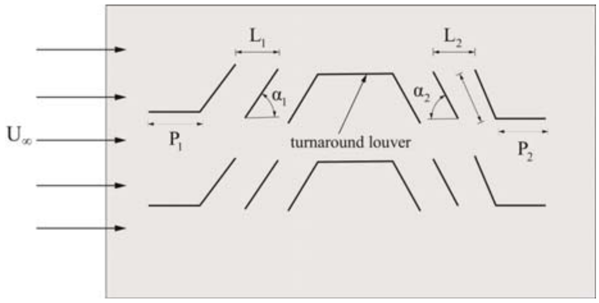

Fig. 1 – b) Two-dimensional louvered-fins.

The domain has three constraints as follows,

$$L_1 P_1 = \text{const}, \quad (1)$$

$$L_2 P_2 = \text{const}, \quad (2)$$

$$L_1 + P_1 + L_2 + P_2 = \text{const}. \quad (3)$$

The flow is considered incompressible, steady and laminar. Effects on heat transfer by radiation and natural convection are negligible and all thermo-physical properties are assumed as constant. Considering these assumptions, the continuity, momentum and energy equations are:

$$\frac{\partial \tilde{u}}{\partial \tilde{x}} + \frac{\partial \tilde{v}}{\partial \tilde{y}} = 0, \quad (4)$$

$$\text{Re}\left(\tilde{u}\frac{\partial \tilde{u}}{\partial \tilde{x}} + \tilde{v}\frac{\partial \tilde{u}}{\partial \tilde{y}}\right) = -\frac{\partial \tilde{p}}{\partial \tilde{x}} + \nabla^2 \tilde{u}, \quad (5)$$

$$\text{Re}\left(\tilde{u}\frac{\partial \tilde{v}}{\partial \tilde{x}} + \tilde{v}\frac{\partial \tilde{v}}{\partial \tilde{y}}\right) = -\frac{\partial \tilde{p}}{\partial \tilde{y}} + \nabla^2 \tilde{v}, \quad (6)$$

$$\text{Re}\cdot\text{Pr}\left(\tilde{u}\frac{\partial \tilde{T}}{\partial \tilde{x}} + \tilde{v}\frac{\partial \tilde{T}}{\partial \tilde{y}}\right) = \nabla^2 \tilde{T}. \quad (7)$$

For the channel with louvered-fins, the energy equation is reduced to:

$$\nabla^2 \tilde{T} = 0, \quad (8)$$

where $\nabla^2 = \frac{\partial}{\partial x^2} + \frac{\partial}{\partial y^2}$. The hydrodynamic boundary condition is the condition of no-slip at the walls of channel, i.e. $u = v = 0$, where u and v are the components of the velocity vector ($\tilde{U}$). Equations (4) to (7) are non-dimensionalized by using the below variables:

$$(x,\ y) = \frac{(\tilde{x},\ \tilde{y})}{L}, \quad (9)$$

$$(u,\ v) = \frac{(\tilde{u},\ \tilde{v})}{U_\infty}, \quad (10)$$

$$\tilde{T} = \frac{T - T_\infty}{T_w - T_\infty}, \tag{11}$$

$$\tilde{p} = \frac{p}{\mu U_\infty / L}, \tag{12}$$

where Re and Pr, in Equations (5–7), are Reynolds and Prandtl numbers, respectively

$$\mathrm{Pr} = \frac{\mu}{\nu}, \tag{13}$$

$$\mathrm{Re} = \frac{U_\infty L}{\nu}, \tag{14}$$

T_w, T_∞, and U_∞ are wall temperature, free-stream temperature, and free-stream velocity, respectively. Furthermore, $\tilde{u}$ = 1, $\tilde{p}$ = 1 and $\frac{\partial \tilde{u}}{\partial \tilde{x}}$ = 0 prevail at the inlet of the domain; $\tilde{p}$ = 0, and $\frac{\partial \tilde{u}}{\partial \tilde{x}} = \frac{\partial \tilde{v}}{\partial \tilde{y}}$ = 0 at the exit. For the thermal boundary conditions; $\tilde{T}$ = 1 on the louvered-fin surfaces, and $\tilde{T}$ = 0 at the inlet plane of the domain. The other planes are considered as adiabatic. The geometric arrangement of main interest is that maximizing the total heat transfer rate between the louvered-fins and the surrounding fluid. The total heat transfer rate is determined as follows:

$$\tilde{q} = \frac{q / D}{k\ (T_w - T_\infty)}. \tag{15}$$

In this formula, q is integrated over the surface of the louvered-fins.

3. NUMERICAL VALIDATION

The numerical model is solved by using the commercial code FLUENT [29]. The domain is discretized using polyhedral elements. The solver is pressure based, and the velocity-pressure coupling is handled by the SIMPLE algorithm. Second order schemes are invoked to discretize the momentum and energy equations. The convergence is obtained when the residuals of mass, momentum and energy equations are less than 10^{-6}, 10^{-6} and 10^{-8}, respectively.

4. RESULTS AND DISCUSSIONS

The numerical work consisted of determining the total heat transfer rate in a large number of configurations. Figure 2 clearly shows that there is an optimal P_1/P_2 value that maximizes the heat transfer rate when the parameters of α_1/α_2 and L_1/L_2 are fixed. This optimal value is P_1/P_2 = 1.2 for the all L_1/L_2 values. It is worthwhile to mention that the performance of L_1/L_2 = 1.2 is slightly superior compared to other L_1/L_2 values. Figures 3 and 4 also show the total heat transfer rate when the louver angle ratio is 1.0 and 1.2, respectively. From these figures, it can be found that the total heat transfer rate is almost insensitive to changes in the louver angle ratio. However, it seems that it has a significant effect on the optimal L_1/L_2 value, because when α_1/α_2 = 0.8 the optimum L_1/L_2 value is 1.2, but by increasing the louver angle ratio the optimal L_1/L_2 value decreases from 1.2 to 1.0.

It can be found that for all the configurations, the optimal P_1/P_2 value is 1.2, and this shows that the length of the inlet louver must be larger than the exit louver in order to shed vortices. Overall, the optimal configuration lies in the design domain of P_1/P_2 = 1.2, 1.0 ≤ L_1/L_2 ≤ 1.2, 1.0 ≤ α_1/α_2 ≤ 1.2. Figure 5 shows the behavior of the Constructal variables as well as the total heat transfer rate for changing Reynolds number. It appears that all Constructal variables are insensitive to the Reynolds number, and only the dimensisonless heat transfer rate increases linearly with growing Re.

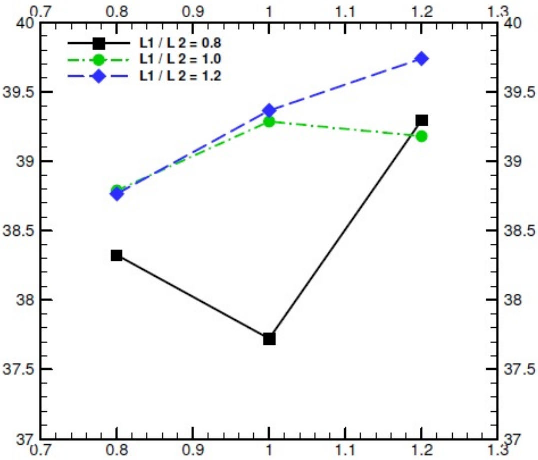

Fig. 2 – Optimization of the total heat transfer rate as function of P_1/P_2 value for several values of the louver pitch ratios when $\alpha_1/\alpha_2 = 0.8$.

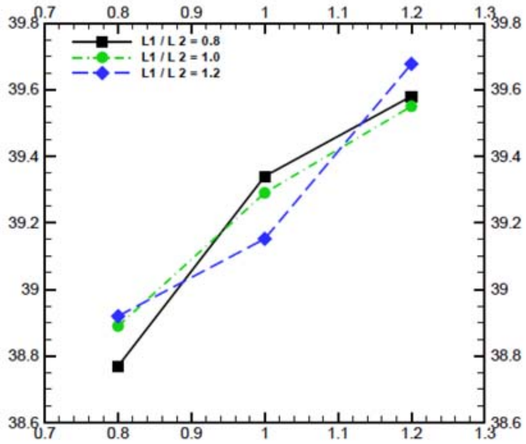

Fig. 3 – Optimization of the total heat transfer rate as function of P_1/P_2 value for several values of the louver pitch ratios when $\alpha_1/\alpha_2 = 1.0$.

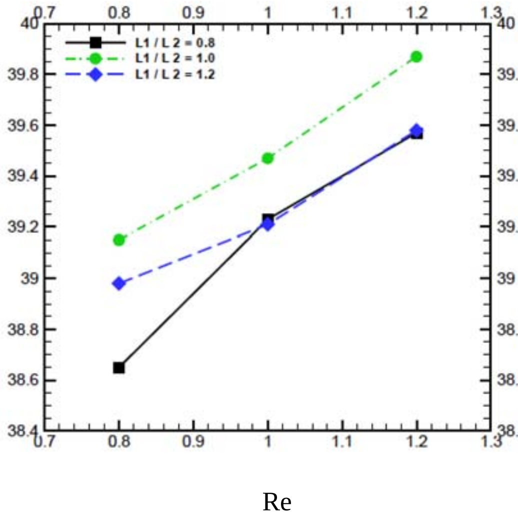

Fig. 4 – Optimization of the total heat transfer rate as function of P_1/P_2 value for several values of the louver pitch ratios when $\alpha_1/\alpha_2 = 1.2$.

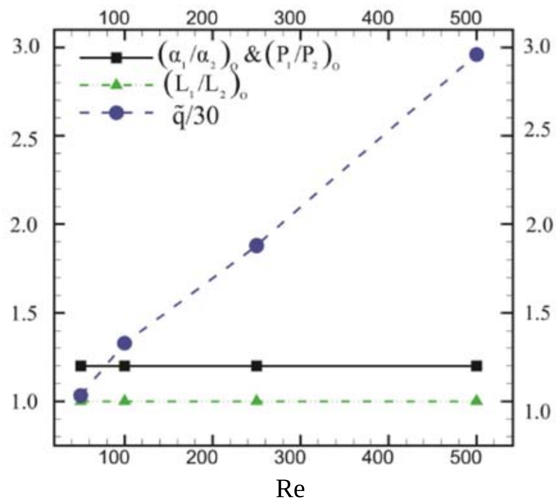

Fig. 5 – The variation of Constructal variables and heat transfer rate versus Reynolds number.

5. CONCLUSIONS

In this paper, louvered fin arrays have been optimized geometrically by using the Constructal law. The domain has three degrees of freedoms, and six variables. The results showed that the flow structure is a function of Reynolds number, the louver angle ratio, and the louver pitch ratio. It can be concluded that for the selected domain and at low Reynolds number regime, the Constructal channel is 6-8% above the typical channel from a heat transfer view.

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