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ACHIEVING HEAT FLUX UNIFORMITY OVER A HEATED FLAT PLATE SUBJECTED TO PARALLEL FLOW USING AN OPTIMAL ARRANGEMENT ARRAY OF TURBULATORS

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ABSTRACT

In this study, uniform heat flux distribution over part of an isothermal flat plate is achieved by using optimal arrangements of circular-shaped or wedge-shaped turbulators, positioned in a cross-flow arrangement. Coordinates of these turbulators in the two-dimensional space constitute six geometric design variables. The Reynolds number is the other independent design variable. The objective is to achieve a predetermined uniform heat flux or convective heat transfer coefficient (i.e., Nusselt number) along the plate. The root-mean-square deviation of the heat flux from the "design" uniform distribution at discrete locations is taken as the objective function in the optimization process, which is minimized by the pattern search method. Optimization process is subject to some geometric constraints. For three different desired design heat flux distributions, an optimal combination of design variables as well as the required inlet velocity have been found. In all these cases, circular shaped turbulators show superior performance, although for low values of design heat flux, the contrast between circular shaped and wedge shaped turbulators is more profound.

KEYWORDS: Heat flux uniformity, Optimization, Turbulator, Flat plate, Pattern search method, Computational fluid dynamics

1. INTRODUCTION

Creating a uniform distribution of heat flux is a pressing issue in many different industries [1-6]. Forouzanmehr et al. made use of optimal arrangements of slot jets to generate uniform distributions of heat flux over flat plates [7]. They employed Conjugate Gradients Method to find the optimal arrangements. Bijarchi and Kowsary used a coaxial impinging jet to obtain uniform heat flux over an isothermal heated surface [8].

In this research, optimal arrangements of three circular-shaped or wedge-shaped turbulators are used to uniformize the heat flux over flat plates. The pattern search method is employed to find these optimal arrangements. For each set of design variables, the resulting heat flux distribution is calculated by standard methods of computational fluid dynamics.

2. PROBLEM FORMULATION

The two-dimensional computational domain consists of an isothermal wall kept at constant temperature of 200^oC at the bottom, inlet boundary condition at the upstream, and two outflow boundary conditions at the top and downstream. The length of the flat plate is 1m. Air enters the domain at 20^oC. Wedge-shaped turbulators are isosceles right triangles with side length of 6cm. The diameter of circular turbulators are also 6cm. The computational grid is made of more refined structured quadrilateral elements near the flat plate and unstructured wedge-shaped elements elsewhere. Governing equations of fluid dynamics and heat transfer (i.e. continuity, x-momentum, y-momentum, and energy) are solved for the steady-state flow of air in this two-

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*Corresponding Author: fsamadi@crimson.ua.edu dimensional domain. A grid independence study is conducted, and the numerical simulation of laminar and turbulent flow have been validated against the classic analytical solution of Blasius and the Chilton-Colburn analogy.

Due to the fact that the flat plate is isothermal, uniform heat flux distribution over an isothermal plate is analogues to uniform local heat transfer coefficient (h_x), as given by

$$q_x = h_x(T_w - T_b). \tag{1}$$

In this study, the dimensionless local Nusselt number defined as

$$Nu_x = \frac{h_x L}{k} \tag{2}$$

is used to define the objective function. Using this alternative definition, the objective function is defined as the root-mean-square deviation of the local Nusselt number from the desired uniform distribution (Nu_d) in 10 evenly spaced nodes. That is,

$$E_{rms} = \sqrt{\frac{1}{10}\sum_{i=1}^{10}\left(\frac{Nu_d - Nu_i}{Nu_d} \times 100\right)^2} \tag{3}$$

Spatial positions of the turbulators and the inlet velocity of air are seven design variables of the optimization problem. The objective function is minimized using the pattern search method, while subjected to several necessary geometrical constraints.

3. RESULTS

Optimal arrangements of the turbulators for three different desired uniform Nusselt numbers of 100, 500, and 1000 are provided in Fig. 1, and the resulting local Nusselt numbers are plotted in Fig. 2-4. Values of all six sets of design variables at their respective optimal points are tabulated in Table 1. The length of the plate is one meter, so the x and y values could be considered as dimensionless, if normalized by the length of the plate (i.e., 1000 mm).

It is also important to refer that the diameter of any circle is 60 mm and the vertical sides of any equilateral triangle is also 60 mm.

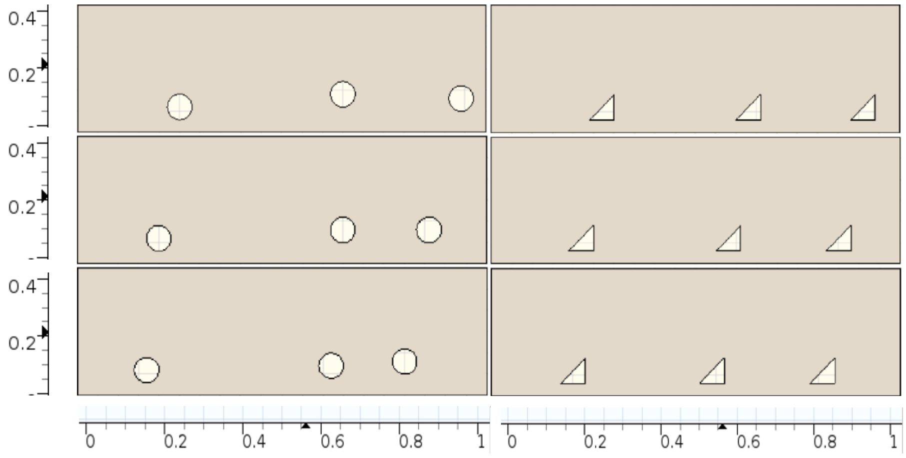

Fig. 1. Optimal arrangements of the circular and wedge-shaped turbulators for Nu=100 (top), Nu=500 (middle), and Nu=1000 (bottom). The values of coordinates are in meter.

Table 1 Optimal values of design variables and the objective function

Type	Nu_d	x_1 (mm)	x_2 (mm)	x_3 (mm)	y_1 (mm)	y_2 (mm)	y_3 (mm)	Re	E_{rms} (%)
Wedge-shaped	100	241	602	881	31	32	31	42753	50.22
Circular		252	653	943	61	91	82	38681	37.87
Wedge-shaped	500	191	552	822	32	31	32	252444	14.74
Circular		202	651	860	61	82	81	223943	13.44
Wedge-shaped	1000	171	512	784	31	31	31	529319	5.46
Circular		172	622	803	63	72	83	549677	5.31

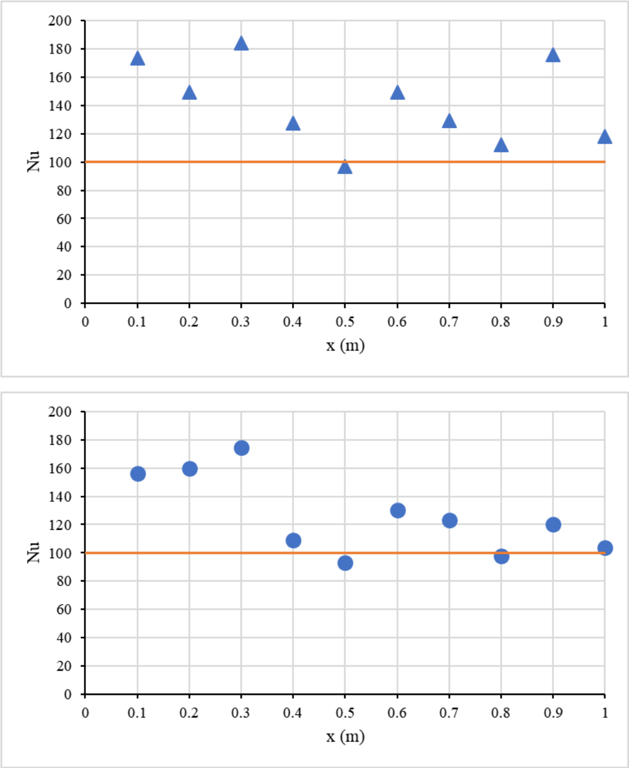

Fig. 2 Distribution of local Nusselt for the optimal arrangement of wedge-shaped (top) and circular (bottom) turbulators in the case of Nu_d=100

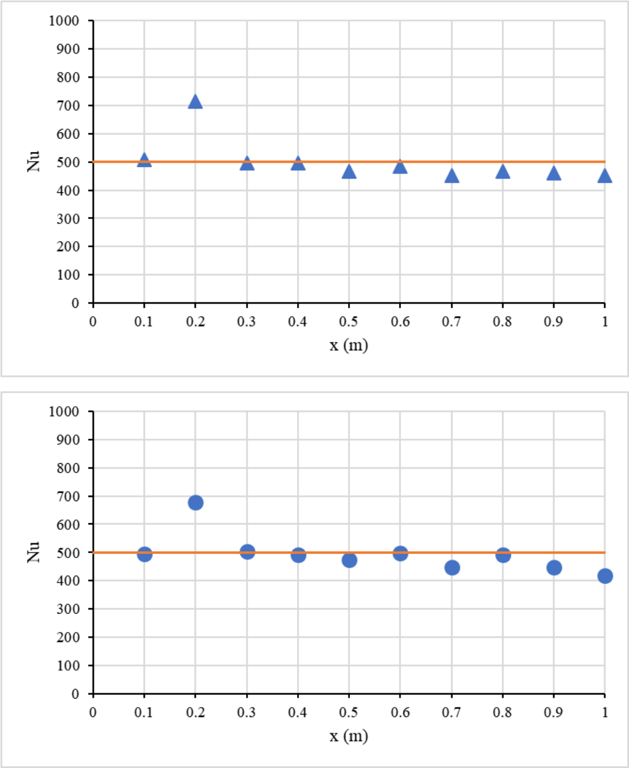

Fig. 3 Distribution of local Nusselt for the optimal arrangement of wedge-shaped (top) and circular (bottom) turbulators in the case of Nu_d=500

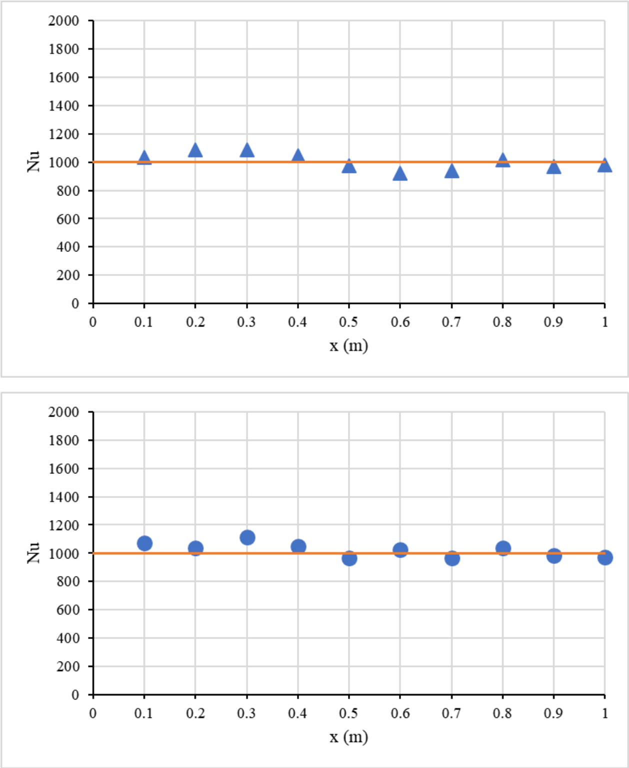

Fig. 4 Distribution of local Nusselt for the optimal arrangement of wedge-shaped (top) and circular (bottom) turbulators in the case of Nu_d=1000

6. CONCLUSIONS

Figure 1 shows that as the desired Nusselt number increases, all turbulators recede from the outlet. As it is evident from Figs 2-4 and Table 1, turbulators are far more effective in creating uniform distributions of heat flux as the desired Nusselt number increases. As expected, optimal Reynolds number increases with increasing values of the design heat flux. Moreover, optimal values of the Reynolds numbers are very close for a given value of the desired heat flux, for both turbulator geometries. In general, the circular turbulators have a superior performance than the wedge-shaped turbulators. The distinction between these two types of turbulators becomes less profound as the desired Nusselt number increases.

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