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Influence of Holes in Vortex Generators on the Thermal Performance of Flat Plate

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ABSTRACT

Vortex generators (VGs) are used in aviation to delay boundary layer separation, which is crucial for increasing the critical angle of attack and, as a result, delaying the aircraft's entry into stall. This is because the vortex generators (VGs) increase the flow energy within the boundary layer. In this paper, the impact of punched triangular vortex generators on convective heat transfer was investigated on a flat plate. Using a wind tunnel (DUC), four pairs of triangular vortex generators were placed on a flat plate, with nine thermocouples implanted in it to measure the temperature change. Three experiments were conducted: the first with a flat plate without a VG, the second VG without holes, and the last VG with holes. The results showed that the presence of the holes had a positive effect on improving heat transfer.

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1. INTRODUCTION

Vortex generators (VGs) are used in aerodynamics to increase the energy of the airflow inside the boundary layer, which in turn delays the separation of this layer at high angles of attack, which leads to an increase in the maximum values of the lift coefficient. [1].

Vortex generators (VGs) enhance flow mixing and increase the rate of heat and mass transfer, especially in the boundary layer where particle motion is limited. By pushing warm gas near the wall away, they increase the convection heat transfer coefficient. The spiral motion induced by the vortices also increases the velocity of air particles after passing through the VGs, thereby improving the thermal performance of the surface on which they are mounted.

Vortex generators can improve heat transfer significantly, depending on: Type and shape of (VGs), Angle of attack, Spacing and placement and Reynolds number.

The strength of the vortex generated is directly proportional to the height of the vortex generator (VG) [2]. However, increasing the VG height also increases the drag coefficient, which is undesirable from an aerodynamic perspective. Nonetheless, when the primary goal is to enhance thermal performance, VGs can be designed with a height slightly greater than the boundary layer thickness to maximize heat transfer benefits.

In [3], an experimental study was conducted using triangular-shaped vortex generators (LVGs) mounted on a flat plate. The study determined the optimal dimensions for (VG) height, angle of attack, and spacing between VG pairs to enhance performance.

There are many shapes of (VGs) used, including rectangular, triangular, parabolic, ogive and arched.

The results show that triangular vortex generators are the most suitable for controlling boundary layer separation, as they deliver maximum airflow energy from the boundary layer periphery. Therefore, this shape was chosen in implementing this research.[4].

In the scientific research conducted by Guobing Zhou several forms of VGs have been used. Reached that curved winglet type (VGs) (CRWP, CTWP and CDWP) have better heat transfer enhancement and lower flow resistance than corresponding plane winglet VGs in both laminar and turbulent flow regions. [5].

In another research [6], a computational model of different geometries of vortex generators placed on a flat plate was implemented through full-grid computational simulations using Reynolds-averaged Navier-Stokes (RANS) equations.

While vortex generators enhance heat transfer, they can also induce pressure loss. To reduce this pressure loss, a design featuring vortex generators with punched holes was proposed [7], in this study, rectangular hole vortex generators were used.

2. Experimental facility and methods.

2.1. Apparatus

The experiment was carried out using a low-speed wind tunnel manufactured at Dijlah University College, as shown in Figure (1). The wind tunnel measurements test section (320 mm × 320 mm × 400 mm). In this section, the flat plate was installed to study the effect of vortex generators on the thermal properties of the boundary layer.

Fig. 1. Experimental setup

The flat plate used in the experiment was made of duraluminium with dimensions ((300 x 400) mm. The (VGs) arrangements on the flat plate are presented in in the Figure (2).

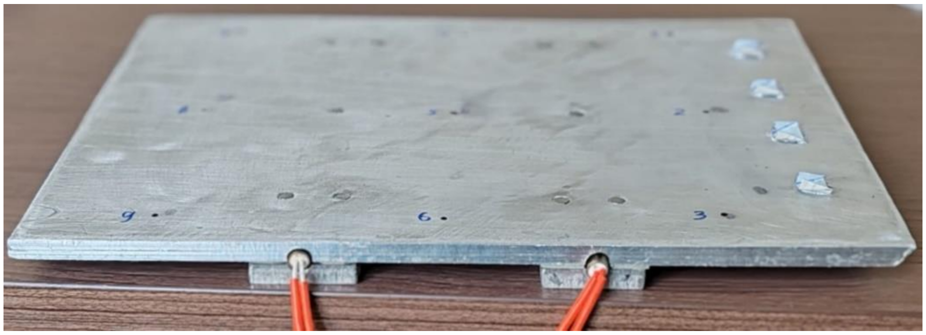


Fig. 2. Vortex arrays in the flat plate

Nine sensors are installed to measure the temperature (fig 3). These sensors are distributed across the plate surface to ensure that temperature changes are captured in most areas. The plate, without any additional modifications, was horizontally mounted in the test section of a wind tunnel manufactured at Dijlah University College Plate heating is achieved using four electric heaters, with two installed on each side.

Figure 3 presents the arrangement of the (VGs) on the flat plate.

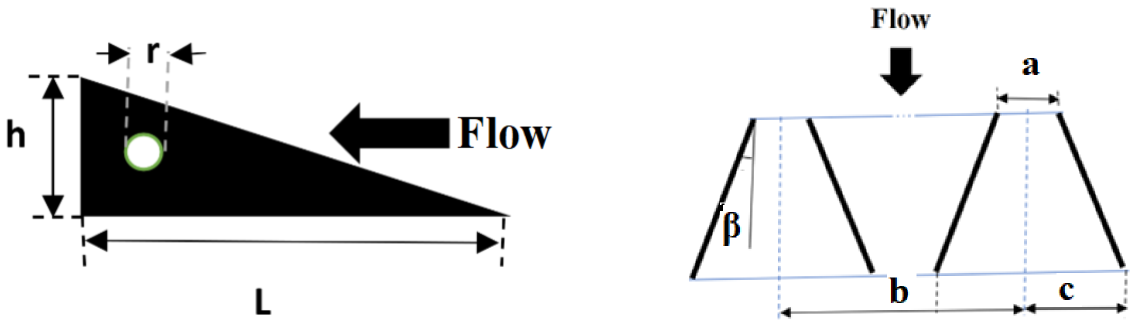
2.2. The Vortex Generators

In previous studies and research, the triangular shape of vortex generators was identified as one of the most suitable shapes to improve the thermal performance of the flat plate.

Three experiments were conducted, and the results allow for a comparison of the thermal performance between: a flat panel without vortex generators (VGs), a flat panel with plane VGs, and a flat panel with (VGs) incorporating a single hole.

The introduction of punched holes significantly reduces flow resistance in all cases. Moreover, an increase in hole diameter results in a further decrease in flow resistance. These punched holes enhance the thermohydraulic performance of vortex generators (VGs); however, the optimal hole diameter must be appropriately matched to the face area of the VG to maximize performance. Additionally, the position of the holes has only a slight influence on the flow resistance of the VGs. [8].

Figure (4 a) shows the location and measurements of the hole and the (VG). The arrangement and location of the generators on the flat panel is shown in (Figure 4 b)



(a) **(b)**

Figure (4) Transversal section of computational domain to show vortex generators.

The following dimensions and parameters were used in the study:

a = 10 mm, b = 26 mm, C = 75 mm, L= 15 mm, h = 5 mm, β = 16^0, r = 2 mm,

T_{atm} = 260, V = 8 m/s.

3. Theoretical work.

For convection heat transfer, the Newton. law of cooling is applied.

$$Q = hA(T_s - T_\infty) \quad (1)$$

Q: amount of Convection heat transfer, (Watt)

h: Convection heat transfer coefficient (W/m²K)

A: Surface area of the plate, (m²).

Ts: Is surface temperature, ^{0}C

T_∞: Surrounding air temperature, ^{0}C.

The theoretical Nusselt number is estimated by using the equation

$$Nu = Pr^{1/3}/ (0.037\ R^{0.}C - 871) \quad (2)$$

For laminar-turbulent flow over flat plate. In two steps convection heat Process, the procedure of adding triangle vortex generator in two steps is to add plain (VG) and second step is to replace it by Perforated Vortex generator.

The effectiveness of using plain vortex generator equations

$$\epsilon_{VG} = \frac{Q_{enhancement(VG)}}{Q_{bare}} = \frac{\text{amount of heat transfer of aplate with VG}}{\text{amount of had transfer of abare plate}} \quad (3)$$

$$\epsilon_{VGP} = \frac{Q_{enhancement(VGP)}}{Q_{bare}} = \frac{\text{amount of heat transfer of aplate with Perforated VGP}}{\text{amount of had transfer of abare plate}} \quad (4)$$

At velocity = 2m/s

It is also noticed that at the same velocity as example v=2 m/s the values of Nusselt numbers were (50,80,160) for bare plate, plate with vg and plate with perforated VG consequently.

It is also noticed that the effect of perforated vg is larger than the non-perforated VG plate by a large difference as seen from figure

As velocity increase, the convection heat transfer coefficient (h) increases and for the same velocity, the convection heat transfer coefficient increases as changing the plate from the bare to VG plat and VGP plate

It is noted as velocity increases the effective of VG decrease and also with VGP decrease and for same velocity the $\in_{\mathrm{VGP}}$ is greater than the $\in_{\mathrm{VG}}$.

The best case is the VGP such that Q and h are maximum.

It was noted that there is a big difference between VG and VGP in favor of VGP.

For the flow of liquid or gas over a plate, Newton's low of cooling equation is used:

$$q = hA(T_s - T_\infty) \quad (5)$$

Where:

$h -$ heat transfer coefficient, W/ (m² K).

$A -$ Area of the plat.

$T_s -$ plate surface temperature.

$T_\infty -$ flow temperature.

For a laminar boundary layer

The local heat transfer coefficient can be calculated using the empirical formula for plates in turbulent or laminar regimes:

$Nu_x = 0.332 Re_x^{1/2} Pr^{1/3}$ (laminar regime)

$Nu_x = 0.0296 Re_x^{0.8} Pr^{1/3}$ (turbulent regime)

Prandtl number

$Nu_x = \frac{h_x x}{k}$ local Nusselt number

$Re_x = \frac{U_x X}{v}$ Reynolds number

$Pr = \frac{c_p \mu}{k}$ Prandtl number

4.Experimental results and discussion.

Using the equations mentioned above, the parameters (Nusselt number, convection heat transfer coefficient, convection heat transfer and Effectiveness) were calculated at different speeds (1 - 8) m/s, the results were obtained in table (1)

Table 1. Parameters values relative to air flow.

air flow speed m/s	Nusselt number Nu			convection heat transfer coefficient, h (W/m^2. K)			Amount of convection heat transfer -Q (W)			Effectiveness $\in$	
	Nu_b	Nu_{VG}	Nu_{VGP}	h_b	h_{VG}	h_{VGP}	Q_b	Q_{VG}	Q_{VGP}	$\in_{VG}$	$\in_{VGP}$
1	27.8	64.7	133.5	2.75	4.4	6.8	18	29.4	42.08	1.6	2.02
2	44.8	77.7	153.7	3.4	5.1	8.05	22.6	33.7	53.1	1.53	2.2
3	60.6	95.9	186.9	4.125	5.775	9.3	27.22	38.05	64.22	1.4	2.46
4	75.4	112	218.7	4.6	6.6	11.2	31.7	43.5	76.4	1.35	2.31
5	89.4	127.1	242.9	5.05	7.425	13.05	36.3	49	85.53	1.3	2.16
6	102.6	134.6	252.5	6.1	8	14.8	41.7	52.2	91.5	1.23	2.12
7	115.3	153.8	262.2	7.15	8.52	16.7	47.2	56.3	93.4	1.192	2.1
8	127.5	158.1	261.1	7.3	8.9	17.3	49.8	57.2	94.1	1.16	2.1

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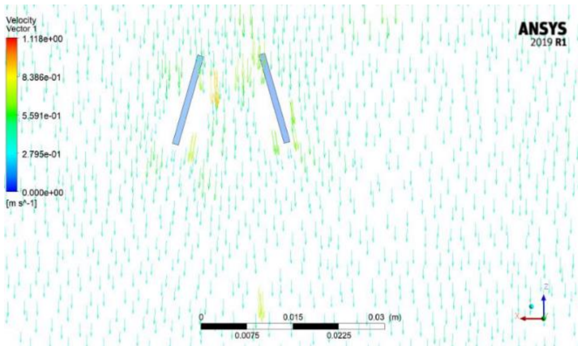
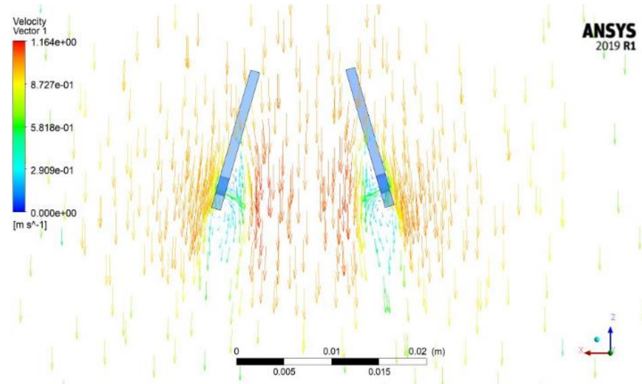
The numerical simulation is developed on ANSYS Fluent to simulate the effect of a triangular vortex generator without and with a hole on thermal and flow fields in a flat plate, as shown in Figure 5.



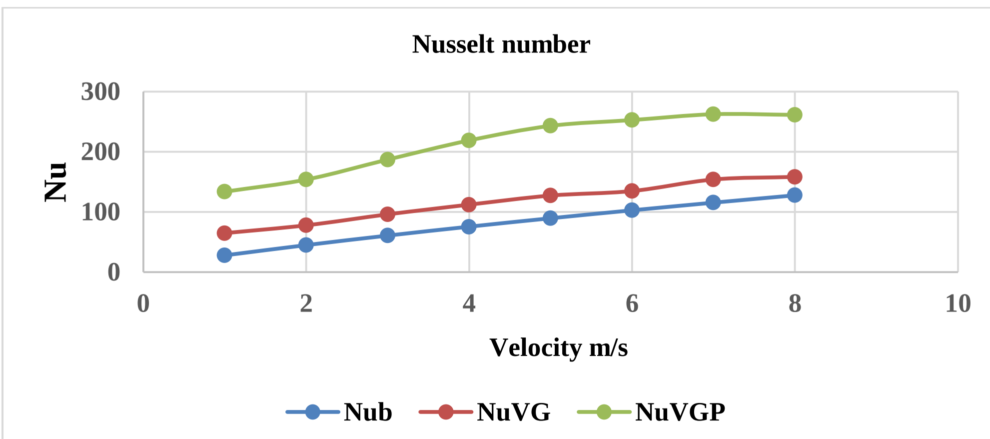
(a)



(b)

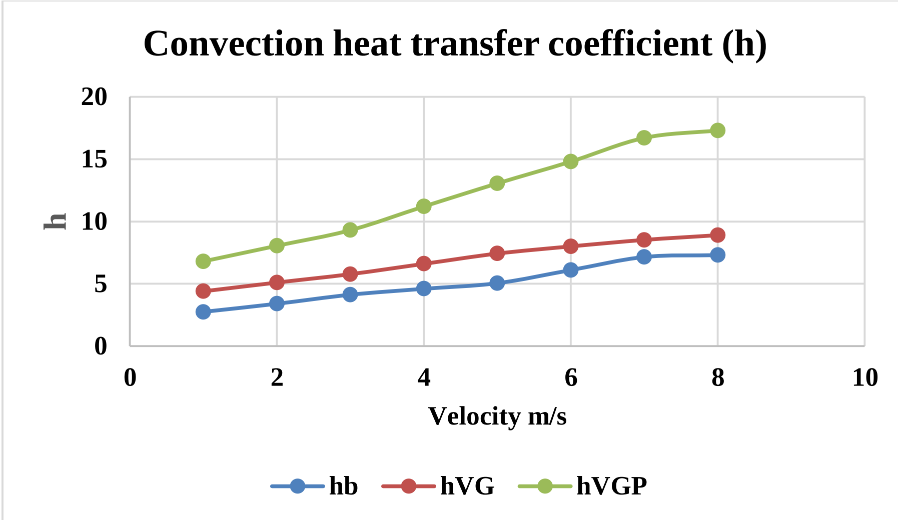
Figures 5. Isotherms for vortex generator.

Figure (5b) clearly shows the secondary flow exiting the hole. The presence of a hole in the vortex generator leads to the appearance of secondary vortices. These vortices work to increase the energy within the boundary layer, which improves heat transfer locally.



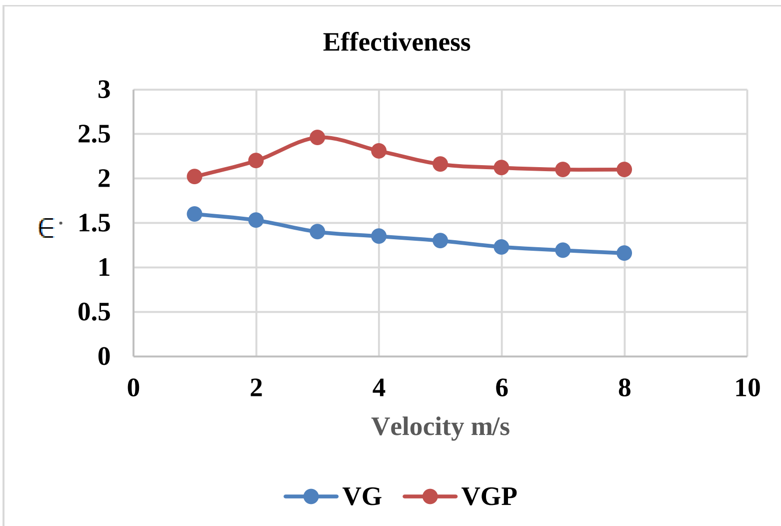
Figures 6. Nu versus velocity.

It is seen from the experiment that the Nusselt number is directly proportional to flow velocity. The bare plate has the smallest values of Nusselt number compared to the plates of vortex generators and the plate with perforated VG. The reason is that the vortex generator body (obstacles) causes more turbulence and more eddies, which increase the energy in the boundary layer and consequently increase the Nusselt number.



Figures 7. Convection heat transfer coefficient (h) versus velocity.

Also, for the convection heat transfer coefficient (h), the same effect was seen for the three plates. The best and largest value of (h) belongs to the plate of the perforated vortex generator, where the hole creates secondary eddies and vortices in addition vortices caused by the vortex generator itself.



Figures 8. Effectiveness.

It is noticed that at low velocities (1-3) m/s, the effectiveness is not affected by the small difference in velocities because there is a sufficient time of contact between the hot plate and flowing air. At high velocities of airflow, the effectiveness decreases more rapidly for the two plates since there is no sufficient time of contact between the plate and the airflow.

5. CONCLUSIONS

In order to improve heat transfer in a flat plate, the effects of vortex generators with and without holes were studied. The results were as follows:

a) There are three hot plates one is bare, the second is with (VG), and the third plate is with perforated (VG).
b) The hot plate is convicted by the cold air flow with different air velocities.
c) It was seen that the heat transfer increase consequently for the bare plate, (VG) plate and the (VGp) plate.
d) The Nusselt number and heat transfer coefficient increase with increasing air flow velocity.
e) In all cases and all velocities, the effectiveness of Nu and h of (VGp) are higher than (VG) because of holes which add more vortices and eddies that cause higher energy transfer.
f) In all cases for low velocities of airflow the contact time was higher which allow more chances to heat transfer process to be completed.
g) At higher velocity from 4m/s to 8m/s the curves of Nu and h values did not change widely with increasing of velocity because the higher velocities did not allow enough time to contact and heat transfer between the hot plate and the cold air.

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