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Effect of surface modification of a rectangular vortex generator on heat transfer rate from a surface to fluid

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ABSTRACT

Surface cooling is an essential tool in many industrial applications. Effective utilization of the wetted surface area is an important factor in the heat transfer enhancement. It may be done by optimizing the shape of the extended surfaces meant for increasing the thermal diffusion, or by improving the thermal interaction between the solid and the fluid. Creation of differential pressure using vortex generator may improve the way the thermal energy is exchanged. It may be obtained by reenergizing the boundary layer using the generated vortices. In the present work the effect of surface textures of the vortex generator on heat transfer and vortex dynamics are studied. The CFD results show that multiple and single texturing on the leading and the trailing faces of the vortex generator, respectively, can enhance the primary vortex downstream of the vortex generator. This in turn enhances the heat transfer by increasing the average Nusselt number and the skin friction coefficient of the plate. The surface temperature is also found to be reduced by the stretching of the vortex with a minimal pressure drop.

1. Introduction

With rising energy prices, various industries are focusing to provide cost-effective and energy efficient systems. Efficiency and sustainability are not only desirables, but also essential demands of upgraded systems with a squeeze on budgets and funds. It has been very important to identify ways to cut cost and to deliver high savings. One such way is the modification of intelligent design modifications in the existing systems. Such systems may improve the way the energy sources are utilized. With the developments in the fields of engineering and technology, systems are getting miniaturized. This improves the economy of a system in terms of material cost, system weight and volume, usage of energy, etc. Every system while running generates heat. It essentially demands an optimal cooling rate in order to maintain its efficiency. An over heated or cooled system always affects its performance. Therefore, with reduced size of various components of machines and equipment, the requirement of on efficient cooling system has appeared. The demand is to reduce the overall dimension of the cooling system, with improved heat transfer rate.

Surface cooling phenomenon has wide applications in many industries, viz., aerospace, metal fabrication, electronics, automobiles, etc. An effective way of surface cooling in such applications may reduce energy requirement with overall reduction in the dimensions. Use of extended surfaces like fins and vortex generators (VGs) are very much prominent in such applications. A fin increases the overall wetted surface area of heat transfer of the base system to assist the cooling process. A vortex generator induces circular flow patterns in the cooling (working) fluid domain to improve the heat transfer rate by convection. Heat transfer in such cooling system is always influenced by the overall geometric configuration, which includes the shape characteristics, material composition, surface coatings, surface temperatures, etc. However, the lower value of thermal diffusivity of any fluid becomes the biggest constraint.

A thermal system, which involves the use of a liquid or a gas to carry heat energy from solid surface, require an improvement in the design. This would in turn, enhance its thermal performance. In this context, the surface area and the surface patterns play a vital role in determining the thermal characteristics. The primary motive of any such work always involves the reduction in thermal resistance of the fluid medium. It may be done by installing (VGs) on the effective surfaces. The vortices produced by these VGs may form in various orientations with respect to the flow directions. One of the earlier works suggests the use of VGs on a flat surface to enhance heat transfer rate [1]. Patankar and Prakash [1] have found various recirculation zones produced behind the trailing edge of the VGs with the increase in pressure drop. A study reveals that the longitudinal vortices enhance the heat transfer rate with less pressure drop in comparison to the latitudinal vortices [2]. Another experimental work reveals that the heat transfer enhancement can be achieved by producing longitudinal vortices along the surface [3]. A numerical study claims a 34% increase in the surface average Nusselt

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number with wing type VG compared to a bare plate [4]. The VGs of paired delta winglet type with 45° angle of attack shows an enhancement of heat transfer rate by 240% [33]. The flow behaviour and heat transfer effect of longitudinal vortices produced by delta winglets in a laminar flow has been studied by Ref. [5]. The work has been performed numerically, as well as experimentally. Again, the experimental work carried out by Ref. [6] suggested that the heat transfer enhancement and the pressure drop are very much sensitive to the angle of attack offered by the VGs. Tao et al. [7] have confined their study in analysis of winglets of different sizes, locations and types that produces longitudinal vortices. It has been found that the delta winglets have an edge over the rectangular winglets [7]. Another study suggests an enhancement of average Nusselt number with the increase in angle of attack for a pair of delta winglet punched plate when compared to a plain plate with any VG [8]. Optimization of angle of attack with basic shape of winglet VG for better heat transfer enhancement has been performed by Ref. [9]. A numerical investigation has been performed for fin-and-tube heat exchanger with rectangular VG with a goal to enhance heat transfer [10]. According to Roohi et al. [11] the numerical study on five configurations of flowing channel with varying angle of attack of longitudinal vortex generator reveals an increment in average Nusselt number by 2–25%. Zhang et al. [12] studied the heat transfer performance and pressure drop for fin and-tube heat exchanger with longitudinal VGs on the fin are numerically studied. Rectangular and delta winglets are punched on the fin surface. The result shows an increment in Nusselt number by 20%. Wang and Song [13] reported that the increasing number of VG does not necessarily increase the heat transfer rate. Liu et al. [14] performed numerical study of a heat exchanger tube fitted with vortex rods. The result indicates that the presence of the vortex rods elicits a considerable heat transfer enhancement. Russeil et al. [15] performed numerical study for a delta winglet pair and compared the results with a novel design proposed with little modification on the classical delta winglet pair. Zhou and Lu [16] performed thermal and flow characteristics of plane and curved longitudinal VGs based on field synergy principle. The results show that the curved trapezoidal winglet pair provides best thermo-hydraulic performance. Islam et al. [17] numerically investigated the effects on thermal performance in a circular pipe of winglet vortex generator. The results indicate that best set of parameters for thermal performance enhancement is achieved at an angle of 30° to the incoming flow. The results showed that the novel design exhibit superior performance as compared to the delta winglet pair. The intensity of the longitudinal vortices and the heat transfer performances of longitudinal vortices are obviously affected by the interaction of the longitudinal vortices. A novel vortex generator has been proposed by Refs. [18–20] which produces a higher strength vortex as compared to rectangular winglet pair downstream of the VG. As per the experimental study carried out by Ref. [21] the use of rectangular vortex generator in a wake zone may enhance the average Nusselt number to about 9.1%. A set of combination of two longitudinal vortex generator with varying position and inclination have been studied numerically by Ref. [22]. A new VG design has been proposed by Refs. [23,24] which increases the contact area between the flowing medium and the VG. As a result, the average Nusselt number along with the friction factor are augmented. An experimental work by Ref. [25] uses perforate VGs, which further improve the convection in the flow domain. The application of VG in Nano-fluid has been performed by Ref. [26]. The authors found the effect of the position of the VG in the flow domain and concluded that an optimization of the position of the VG can provide an increment in Nusselt number by 39%. A series of new configuration of longitudinal vortex generators have been proposed and studied numerically by Ref. [27]. The results are compared based on synergy principle and it concludes that higher Nusselt number can be achieved with lower value of synergy. With a goal to obtain better heat transfer enhancement, many researchers analysed various systems with multiple vortex generators. The increased number of vortex generators need not always enhances the heat transfer rate [28]. Wang et al. [23,24] investigated the mechanism of heat transfer enhancement using longitudinal VGs in a laminar channel flow. The results show that the longitudinal vortices greatly enhance towards the contribution of the local convection. This in turn promotes the local transport of heat flux in span direction. Gentry et al. [34] has found that the intensity of the vortices always decreases with the increase in interaction with each other.

From the study of various literature, it has been observed heat transfer enhancement can be achieved by modifying the VGs, with alteration in the overall geometry. The proposed work involves the modification in the shape of the cross section of the VG using concave and convex texturing. Considerations are given to one or more number of textures in both the leading and the trailing faces of the VG. The domain consists of VG placed over a heated plate is studied computationally. In order to have an ease in comparison of various cases the volumes of the VGs across various study have been kept constant. The current work lays a foundation towards understanding of effect of surface modification on heat transfer characteristics of a system. To maintain the brevity of the manuscript only the cases of VGs with maximum two concave or convex contours are considered. In the following section the details of the geometry and the formulation are described.

2. Geometry and formulations

The heat transfer characteristics of a surface are always influenced by the connected extended surface and its configurations. The focus in this work is to study the effect of surface deformation of a rectangular VG in heat transfer rate from a plate to the fluid. The schematic diagram of the 3-D model of a VG fixed over a horizontal plate is shown in Fig. 1. A VG in a flow is placed in a way to produce distinct zones of different pressures. The pressure drop in the flow induces a circular motion to form vortices along the flow direction.

In the considered domain, a VG of size $h_v \times l \times t$ is placed over a plate of surface area W × L. The VG is oriented at an angle θ with the flow direction (Fig. 1). The present study involves thermal analysis of VG system with different shape modifications. Concave and convex shaped surfaces are considered at the leading and the trailing surfaces of the VG. A schematic diagram of all the considered cases is shown in Fig. 2.

Heat transfer in any system is mathematically represented by the energy equation. Neglecting the thermal radiation, in any fluid domain, heat transfer is mostly dominated by the convection. However, the effects of conduction cannot be neglected completely. Transfer of thermal energy in any medium is induced by the difference in the thermal potential in the system. This potential is realised in the form of difference of temperature. In order to understand the thermal behaviour and the distribution of temperature in the considered system, the energy equation is solved. In a coordinate independent form, neglecting the rate of volumetric heat generation, the energy equation [29] is given by

$$\frac{\partial T}{\partial t} + (\vec{V}\cdot\nabla)T = k\nabla^2 T \quad (1)$$

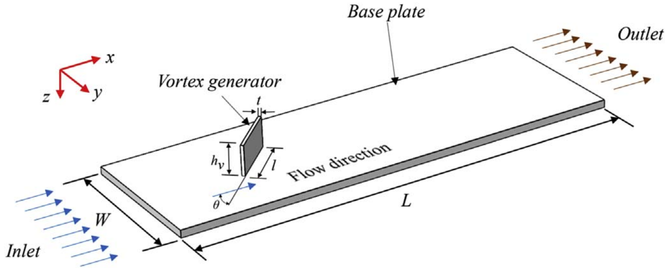

Fig. 1. Schematic diagram of the considered rectangular vortex generator fixed over a baseplate.