International Journal of Heat and Mass Transfer 54 (2011) 3566–3574

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

The development of active vortex generators from shape memory alloys for the convective cooling of heated surfaces

M.S. Aris [a,*], I. Owen [b], C.J. Sutcliffe [b]

[a] Department of Mechanical Engineering, Universiti Teknologi Petronas, Bandar Sri Iskandar, 31750 Perak, Malaysia
[b] Department of Mechanical Engineering, University of Liverpool, Brownlow Hill, L69 3GH Liverpool, United Kingdom

ARTICLE INFO

Article history:
Received 2 April 2010
Received in revised form 16 March 2011
Available online 12 April 2011

Keywords:
Heat transfer enhancement
Shape memory alloys
Active vortex generators
Selective laser melting

ABSTRACT

A study of the convective heat transfer enhancement of heated surfaces through the use of active delta wing vortex generators is reported in this paper. The surface-mounted vortex generators (VGs) change their shape to intrude further into the flow at high temperatures to enhance heat transfer, while maintaining a low profile at low temperatures to minimise flow pressure losses. The VGs are made from shape memory alloys and manufactured in a selective laser melting process. Experiments have been carried out in a rectangular duct supplied with laminar-transition air flow. In the test section, a single, and a pair of active delta wing VGs were placed near the leading edge of a heated plate and tested separately for their heat transfer enhancement effects using infrared thermography. The pressure difference across the test section was also measured to determine the pressure drop penalty associated with the obstruction caused by the vortex generators in their active positions. Promising shape memory response was obtained from the active VG samples when their surface temperatures were varied from 20 °C to 65 °C. The vortex generators responded by increasing their angles of attack from 10° to 38° and as the designs were two-way trained, they regained their initial position and shape at a lower temperature. At their activated positions, maximum heat transfer improvements of up to 90% and 80% were achieved by the single and double wings respectively along the downstream direction. The flow pressure losses across the test section, when the wings were activated, increased between 7% and 63% of the losses at their de-activated positions, for the single and double VG respectively.

1. Introduction

The enhancement of heat transfer on heated surfaces is important in many engineering applications as it results in the use of less space and material, and allows for higher thermal loads. The key driver into this research has been the advancement in the miniaturization and design complexities of microelectronic devices in telecommunication and computing equipment. The increasing power dissipation densities of microelectronic devices are constantly monitored by the International Technology Roadmap (ITR) group which consists of globally renowned semiconductor manufacturers and research institutions. In the 2008 ITR report [1], the power densities of microelectronic devices (assembled packages) were predicted to increase by 50% in the year 2015. This implies an increase in surface temperatures and renewed thermal management challenges for semiconductor manufacturers. It is therefore important that research into heat transfer enhancement continues to receive the attention it needs to meet both the current and future demands.

Among the commonly studied heat transfer enhancement designs for heated surfaces is the so-called "vortex generator" (VG); a small surface protrusion that disturbs boundary layer flows. The earliest investigation into the use of VGs as a heat transfer enhancer was carried out by Edwards and Alker [2]. They compared surface mounted cubes and winglet designs and found that the winglets generated longitudinal vortices which had promising enhancement capabilities.

As a longitudinal VG, the delta wing generates vortices which mix the cooler free stream fluid with the warmer air just above the heated surface, as shown in Fig. 1. Persisting vortices in the flow direction extends the cooling effect on the heated plate several wing chord lengths downstream of the VG. Among the important factors which influences the enhancement capability of a delta wing VG is its geometrical features, i.e. angle of attack and aspect ratio. Fig. 2 illustrates several surface protrusion designs, including the delta wing, with definitions of their geometrical features.

Early investigations into the enhancement effects of increasing the angle of attack, α, were carried out by Fiebig [4] for delta wings placed on a fin surface, in a heated rectangular channel. The test section was supplied with developing laminar air flow for Reynolds numbers, Re_H, based on the channel height, between 1360 and

* Corresponding author.
E-mail address: mshiraz_aris@petronas.com.my (M.S. Aris).

0017-9310/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ijheatmasstransfer.2011.03.030

Nomenclature

A	area (mm^2)
B	heated plate width (mm)
b	wing width (mm)
c	wing chord length (mm)
f	apparent friction factor
h	heat transfer coefficient, (W/m^2 K)
h	VG height (mm)
k	thermal conductivity (W/m K)
L	length (mm)
$\dot{m}$	mass flow rate (kg/s)
Nu	Nusselt number, $Nu = hH/k$
Re	Reynolds number, $\rho VH/\mu$
s	VG spacing (mm)
T	temperature (°C)
V	velocity (m/s)
x, y	streamwise coordinate (mm)

Greek symbols

α	wing angle of attack (°)
Λ	wing aspect ratio, $\Lambda = 2b/c$
μ	fluid dynamic viscosity (Pa s)

Subscripts

avg	average
bm	bulk mean
f	fluid
H	channel height
o	de-activated position
s	surface

2270. By increasing α from 10° to 50°, an average heat transfer enhancement of 60% was obtained on the surface downstream of the delta wings compared to a plane surface. The negative effect of the delta wing VG is, however, the increased frictional loss and the obstruction it causes to the flow over the heated surface which contribute to pressure losses. Fiebig et al. found that by increasing the angle of attack of the delta wing, the flow pressure loss across their test section increased by as much as 15% compared to an unobstructed surface. Another important finding reported from their experiment was that the channel walls of their test section had prevented early vortex break down. This is a common vortex generation problem in unbounded test sections where VGs with high angles of attack are used. Their research provided a qualitative description of the vortex shape, intensity and location in the downstream regions of the VG which gave further insight into the use of the delta wing as a heat transfer enhancement device. In a subsequent investigation, Fiebig [5] varied the aspect ratio, Λ, of the delta wing and compared their heat transfer enhancements for a range of α at a fixed laminar flow Reynolds number. As a result of varying Λ from 0.8 to 1.5, increases in heat transfer enhancement by as much as 10% was obtained when α of between 10° and 50° were compared. Apart from increasing α and Λ, and preventing early vortex breakdown, channel walls have been found to provide positive effects on heat transfer enhancements for VGs. Fiebig [4,5] and Biswas and Chattopadhyay [6] reported that the channel walls, through increasing pressure gradients in the downstream direction, keep the longitudinal vortices stable and effective in their respective paths for a longer downstream distance, and hence provide higher overall heat transfer improvements.

Jacobi and Shah [7], in their review of experiments and numerical studies on heat transfer enhancement techniques carried out by various researchers, compared surface protrusion and extended

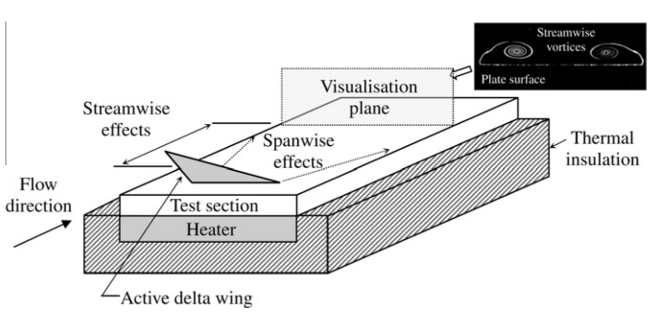

Fig. 1. Vortex formation downstream of a delta wing (adapted from Gursul [3]).

surface designs such as cubes, plate-fins, round and flat tube rows, delta and rectangular wing and winglet vortex generators. Amongst the surface protrusion devices, the delta wing and winglet geometries were the most frequently studied (see Fig. 2). In rectangular channels, the highest overall heat transfer enhancement, as high as 60% compared to a plain channel, was obtained by Fiebig [5] and Tiggelbeck et al. [8] for a single delta wing supplied with air flow in a 1300–2300 Reynolds number range. The heat transfer improvement from the single delta wing was accompanied by a 45% increase in flow pressure losses. When pairs of delta winglets were arranged in in-line and staggered arrangements, relatively higher heat transfer improvements were obtained for similar Reynolds numbers. The winglet arrangements, however, contributed to significantly higher flow pressure losses, up to 145%, compared to unobstructed channel surfaces. From their review of previous investigations, Jacobi and Shah recommended the use of high angles of attack, between 40° and 50° and aspect ratios of between 1.8 and 2 for single delta wings, particularly for use in channel flows. The increases in flow pressure losses which result from the high angles of attack of the single delta wing were reasonably low for the flow conditions explored. Further considerations, however, would be required for different flow conditions and for the use of multiple vortex generators, to prevent excessive flow pressure losses.

Gentry [9], together with Jacobi [10,11], revisited earlier research carried out on delta wing VGs and reported, in more depth, the effects of the vortices on heat transfer enhancement and flow pressure losses. Unlike other investigations, the effects of the VG location close to the leading edge of a test section were explored. They measured vortex strength for the various angles of attack and for different wing aspect ratios. This was done by two methods: (a) by direct measurement using a vane-type vortex meter and (b) using a potential-flow model and flow visualization technique. Their work supported what earlier results suggested, and managed to quantify the vortex strength at various positions downstream of the VG. They had identified from their results an α of 45° and Λ of 1.2 as suitable parameters for heat transfer enhancement from a delta wing VG. Close to the test section leading edge, it was found that the vortex strength increased, an occurrence which is believed to be due to the VG wing tips staying above the surface's developing hydrodynamic boundary layer thickness.

In turbulent flow conditions, interaction between vortices and the hydrodynamic boundary layer is expected to be significantly different from laminar flow conditions. Eibeck and Eaton [12] evaluated the mean streamwise vortices developed from a single vortex generator, on a flat surface. The enhancement of heat transfer