THE APPLICATION OF SHAPE MEMORY ALLOY AS LONGITUDINAL VORTEX GENERATORS FOR ENHANCED CONVECTIVE HEAT TRANSFER

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ABSTRACT

This paper is concerned with the convective heat transfer enhancement of heated surfaces through the use of delta wing and wavy channels as longitudinal vortex generators. A preliminary proof-of-concept investigation has been carried out into the use of active vortex generators manufactured from Shape Memory Alloys (SMAs) which are activated at specified temperatures. The delta wing vortex generators 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. Similarly, the wavy channels enhance heat transfer by forming a close to sinusoidal wavy shape when activated at high temperatures and turn into straight channel passages when it is deactivated at lower temperatures. As with the delta wings, a lower flow pressure loss is achieved when the channels are deactivated. One set of vortex generators was made from pre-alloyed powders of SMA material in a rapid prototyping process known as Selective Laser Melting (SLM). Another set of devices were made from commercially available flat annealed thin SMA sheets for comparison. Promising results were obtained for both the vortex generator designs when their temperatures were varied from 20^{o} to 85^{o}C. The delta wing vortex generator responded by increasing its angle of attack from 20^{o} to 35^{o} while the wavy channel elements acquired a waviness aspect ratio of 0.2. As the designs were two-way trained, they regain their initial position and shape at a lower temperature. The surface temperature of the heated plate on which the active devices were positioned were seen to reduce locally from 120^{o}C to 40^{o}C, indicating heat transfer enhancement due to the generated longitudinal vortices.

INTRODUCTION

Longitudinal vortex generators (LVG) embedded in shear flows have a significant influence on the enhancement of forced convection cooling of heated surfaces. They involve the generation of secondary flows which promotes mixing of the boundary layer with free stream fluids. The application of LVGs is mostly found on the air side of heat transfer surfaces in laminar, low Reynolds number flows. Various LVG designs are also applicable for enhancing heat transfer in microelectronic and telecommunication systems. Some examples of these designs and the parameters which are used to define their geometry are shown in Figures 1(a) and 1(b). Amongst these designs, the delta wing and wavy channels were found to be the most promising and were further explored in this paper.

The earliest study relating LVGs to heat transfer enhancement was carried out by Edwards and Alker (1974). Subsequent research, quantitatively and qualitatively discussing the effects of delta wings and winglets as LVGs were carried out by Torii et al. (1991) and Fiebig (1995). They clarified that the main mechanisms for heat transfer enhancement in laminar flow were boundary layer thinning and mixing with free stream fluid. They also reported on the effects of varying angles of attack, α and aspect ratio, Λ of the LVGs. Results from these investigations now serve as a guideline in the optimization of delta wing and winglet designs.

In an investigation carried out by Fiebig (1991), the performance of the delta wing was found to be superior to the rectangular wing/winglet and delta winglet geometries shown in figure 1(a). At $\alpha = 30^o$, Re = 1815 and $\Lambda = 1.25$, the delta wing recorded a local heat transfer coefficient enhancement of 300% and its overall heat transfer enhancement, based on the heat transfer area ratio A_{ht}, was found to be significantly higher than the other LVG designs. Research comparing the performance of other LVG designs were also reported in a review paper by Jacobi and Shah (1995) and Brockmeier et al. (1993). Apart from studying the delta wing heat transfer enhancement at different α and Λ, a comparison based on the heat transfer area ratio with other common surface enhancement designs which did not produce longitudinal vortices were carried out. It was found from their investigations that the delta wings offered better heat transfer enhancements compared to the other LVG and non LVG designs.

More recent studies on delta wings as heat transfer enhancers were carried out by Gentry (1998) and Gentry and Jacobi (1997, 2002). Their studies experimentally determined the strength of the vortices and their effects on heat transfer for a delta wing located at the leading edge of a heated plate. The values of α and Λ were varied from 10^o to 55^o and 0.5 to 2.0 respectively. Flow over the test section was laminar and the Reynolds number based on the delta wing chord length used in their experiment was varied from 600 to 1000. The authors concluded that for a fixed aspect ratio of 1.0, the optimum α for a delta wing was 40^o, for Reynolds numbers between 600-800. For Reynolds numbers above 1000, a lower angle of attack of 25^o was recommended. They also found that increasing the angles of attack further resulted in a "vortex breakdown" phenomenon which had a negative effect on heat transfer enhancement. Based on this optimized condition, the average heat transfer enhancements that the delta wing was capable of achieving was between 50 – 60%. They also cautioned that as the delta wing α was increased from 25^o to 40^o, the flow pressure loss increased from 20-200% respectively.

Compared with the delta wing, not many publications are available on the heat transfer enhancement capabilities of the wavy channel. Only in recent investigations carried out by Nishimura et al. (1986, 1987), Vyas (2005) and Gschwind, et al. (1995), were the flow conditions in the wavy passages extensively studied. The authors reported from their experimental measurements that the longitudinal vortices originated from the trough regions of the channels and extended to the entire streamwise length of the channels. The parameters which were crucial in determining the vortex strength, apart from the flow Reynolds number were the waviness aspect ratio, γ and the wavy element spacing ratio, ε. Based on his experimental measurements, Vyas (2005) recommended the flow conditions and geometrical parameters for a full streamwise longitudinal vortex coverage to be, $135 < Re < 700$, $1 < \varepsilon < 1.5$, $0.2 < \gamma < 0.5$.

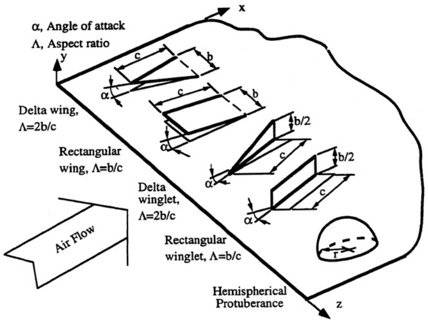


Figure 1(a): Common Surface Protrusions and their Associated Geometrical Definitions (Jacobi and Shah, 1995)

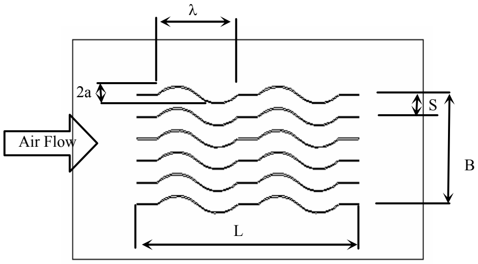


Figure 1(b): Wavy Flow Control Elements (Top View) and their Associated Geometrical Definitions

The heat transfer enhancement features of delta wings and wavy element LGV do however have a significant disadvantage. Even though higher heat transfer enhancement is observed at high angles of attack for the delta wing, increasing this angle results in greater flow pressure losses as reported by Brockmeier et al. (1993) and, Gentry and Jacobi (1997, 2002). Vyas (2005) also reported high flow pressure losses associated with a high waviness aspect ratio for the wavy channels. These characteristics of the LVGs have made them less attractive as heat transfer enhancers as opposed to the non-LVG designs such as louvered and offset-fin strips, found on heat exchanger surfaces.

To make the LVGs more attractive as heat transfer enhancers, a self activating vortex generator design is needed. This active feature must allow the delta wing vortex generator to be activated to a high angle of attack when cooling is required by the heated surface and otherwise return to a low angle of attack position. In the wavy channels, the wavy elements need to form a wavy passage when activated for cooling and resume as straight elements when cooling is not required.

The mechanism involved in activating and deactivating the vortex generators is found in the shape memory alloy (SMA) material used in their manufacture. A diffussionless solid phase transformation of the SMA allows it to deform to a specified shape at a high temperature and return to its pre-deformed shape at low temperatures. As the activation and deactivation process is carried out without any requirements for external sources, this would make the design superior to the earlier active LVGs proposed by Jacobi and Shah (1995).

To build the vortex generator at a specific angle of attack in its pre-deformed position, a rapid manufacturing technique, Selective Laser Melting (SLM) has been used in the present study. This process melts the powdered shape memory alloy material by layers to eventually form the desired shape.

The research reported in the present paper is a proof-of-concept investigation into attempts to use SMAs to improve the performance of forced convection air-cooled heated surfaces. This was carried out by introducing active flow mixing from delta wing and wavy vortex generators. The intention was to activate the delta wings to a high angle of attack and the wavy elements into a sinusoidal like shape to enhance heat transfer from the surface of a heated plate when it reached a predetermined temperature; and for them to return to a low pressure-loss position and shape when the surface had cooled.

In order to demonstrate their application, convective heat transfer tests were carried out using a flat heated surface with the vortex generators positioned over it. Computational Fluid Dynamics (CFD) software, FLUENT, was used to evaluate the designs before an appropriate design was selected to be built and subsequently tested.

EXPERIMENTAL STUDY

Materials

The choice of shape memory alloy materials explored for this research were TiNi and CuNiAl. TiNi was selected based upon its previously reported application as a variable roughness heat enhancement device in pipes by Champagne and Bergles (2001). This alloy has also been used in various engineering, medical and orthodontic applications as reported by Otsuka and Wayman (1998). Two-way strain rates of 6% are common and reported to be the highest amongst shape memory alloys. The material, however, has some disadvantages. It is reported to have a low thermal conductivity, between 8-10 W/m^{2}K and if it is to be used for heat transfer applications, it could contribute as a thermal resistance. The other challenge in the use of TiNi is its high cost. As an alternative, CuNiAl, which is cheaper, and reported by Srinivasan (2001) to have shape memory alloy properties and higher thermal conductivity, was also selected for this research.

Design and Manufacture

Two manufacturing processes have been used in the development of the delta wing and wavy vortex generators. The first method involved a flat annealing process in which thin sheets of TiNi alloys were formed and later cut into shapes of delta wing and wavy vortex generators. The thin sheets have a uniform thickness of 108 μm and were procured from Memory-Metalle GmbH.

Considering first the delta wing vortex generator, its base was mounted on a heated plate while the tip was allowed to have angular movements of between 0^o to 45^o. The wing angular positions refer to its angles of attack in the direction of the air flow. The wavy elements were mounted on a heated plate at their fixed sections. The linear movements of its wavy sections controlled the generation of longitudinal vortices. In its fully activated shape, the wavy elements had a waviness aspect ratio, γ of 0.2. Air passing through the channels of this shape generated longitudinal vortices at the trough sections which then advanced through the entire streamwise length of the heated plate. An illustration of the activated and deactivated positions and shapes of the delta wings and wavy elements are shown in Figure 2.

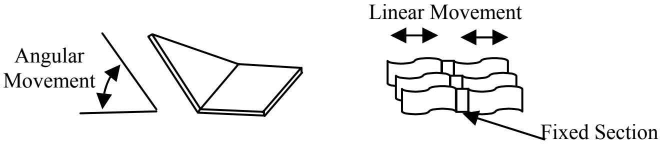
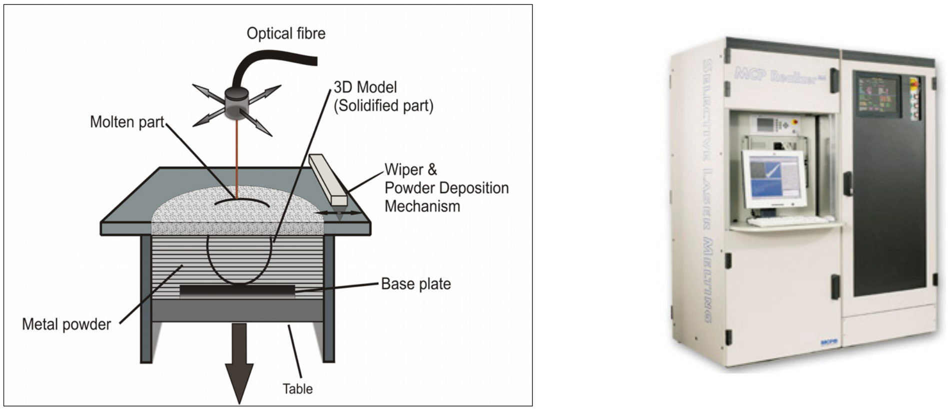


Figure 2: Delta Wing and Wavy Elements

The dimensions for the thin film delta wings based on the work of Liou et al. (2000), has a chord length, c of 12.7 mm and an aspect ratio, Λ of 2. As for the wavy channels, their dimensions were based on a research reported by Vyas (2005).

The second manufacturing method, which was only applied to the delta wing, involved melting powders of pre-alloyed TiNi and CuNiAl in a manufacturing process known as Selective Laser Melting (SLM). The features built in this process were delta wing vortex generators of 75 μm thickness for TiNi and 106 μm for CuNiAl. The SLM process has the capability of producing small scale 3D features, which is its advantage over other available rapid manufacturing methods. In this process, a succession of individual part cross sections, predetermined with computer assisted design, are created from powdered materials by melting them with a Ytterbium Fibre Laser. A layer of build powder is pre-deposited onto a surface and spread uniformly by a wiper blade, the laser then “writes” the layer pattern in the powder bed melting the material and fusing it to the previously formed build structure. Figure 3 illustrates the SLM process and the MCP Realizer 200 machine used in this work.



(a) (b)

Figure 3 (a) and (b): Schematic of SLM Process and SLM Apparatus (www.mcp-group.com)

The delta wings built with the SLM process involved various stages for finding the appropriate manufacturing parameters before a build with acceptable material properties could be achieved. The CuNiAl and TiNi vortex generators reported in this paper were built by varying the key parameters of laser power and exposure time. These parameters determined the density, material strength and surface finish of the build. It was important at this stage of the work, to establish a build with good shape memory effects. Finding the optimum parameters to produce high strength builds with good surface finish were not a priority and were left for future development.

The SLM designs were focused on delta wing vortex generators due to their simplicity and ability to react as active heat transfer devices when required. Figure 4 shows SLM samples made from TiNi and CuNiAl. The operating details of this design are similar to the earlier mentioned thin film vortex generators. The delta wings built with this process were chosen based on Gentry (1998) with an angle of attack of 45^{o}, aspect ratio of 0.5 and a chord length of 12.7 mm.

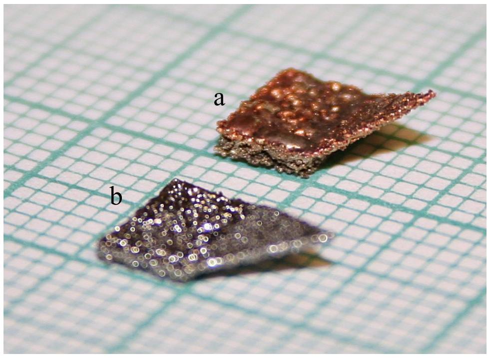


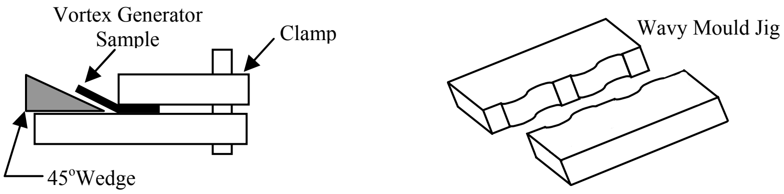
Figure 4: SLM Samples, (a) CuNiAl (b) TiNi

The dimensions selected for both the thin sheet and SLM vortex generators represented the extreme ends of the aspect ratios tested in previous research. Limitations on the SLM process were also considered in selecting the appropriate angles of attack and aspect ratios for the vortex generators.

Shape Memory Effect Training

Before a shape memory alloy can respond to temperature set-points, it has to be thermally trained. A two-way shape memory training process was used for this purpose. In this training process, the thin sheet delta wing was placed in a training jig shown in figure 5(a). The sample was heated until it reached a temperature of 85^{o}C and a wedge was used to deform the sample to a 45^{o} angle of attack. The sample was then allowed to cool to a temperature of 20^{o}C and then deformed to a flat position. The process was repeated for 10 cycles before the delta wing was allowed to respond to the high and low temperature set points without external help. The training process for the thin sheet wavy elements involved a jig shown in figure 5(b). The thin sheets were shaped into wavy channels using the wavy mould jig when their temperature reached 85^{o}C. They were then straightened after they were cooled down to 20^{o}C. Similar to the delta wings, the training process was repeated for 10 cycles.

As for the SLM built delta wing, its thermal training process was simplified as it was built to its high temperature position in the SLM process. All that was left in the training process was to deform the sample to its low temperature position at 20^{o}C and allow it to form its high temperature position by heating it up to 85^{o}C. This process was also repeated for 10 cycles.



(a) (b)

Figure 5: Training Jigs for the Delta Wing and Wavy Elements

Heat Transfer Enhancement

Experimental work was carried out to investigate the heat transfer enhancement outcome of the vortex generators. The test rig used for this experiment consisted of a heated copper base, supplying heat to an aluminum block where the samples were mounted. A schematic of the experimental set up is shown in Figure 6.

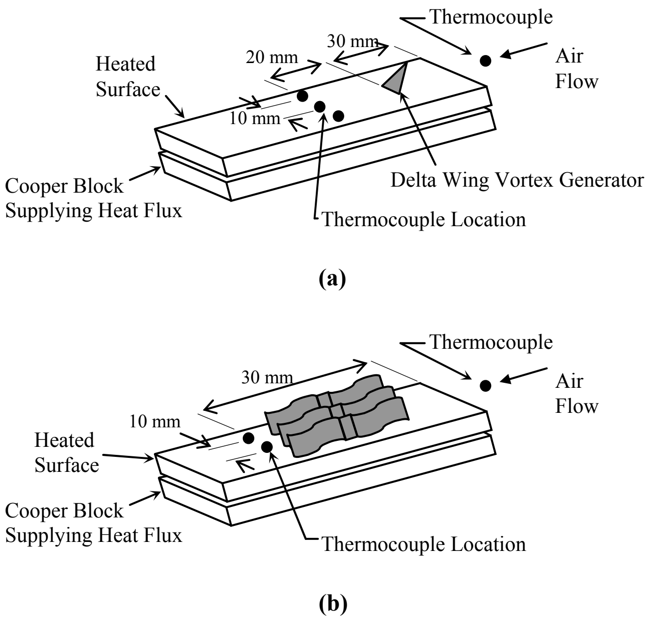


Figure 6: Test Section of the Thermal Test Rig for (a) Delta Wing Vortex Generator and (b) Wavy Channel

A constant heat flux was supplied to the test section through a heated copper block in which embedded heaters were controlled by a variable AC power supply and control unit. Air was supplied from a blower at an average velocity of 5 m/s. It was directed to the test section through a 10 mm x 50 mm rectangular cross section duct. Laminar flow over the test section was ensured by controlling the blower speed to maintain the required velocity. The Reynolds number for the delta wing experiment was determined based on the chord length of the vortex generator, as previously suggested by Gentry (1998). The surface and air temperatures were measured by thermocouples placed at the airflow inlet, on the heated plate surface at streamwise distances of 20 mm behind the sample and at a 10 mm spanwise separation. Similar flow conditions were used to test heat transfer enhancement from the wavy channels. The surface temperature for the heated surface was measured in the middle of the flow passage, 30 mm behind its leading edge. All the above data were recorded using a 20 channel Agilent Data Logger.

RESULTS AND DISCUSSIONS

Shape Memory Alloy Training

The TiNi shape memory alloy samples were two-way trained between temperatures of 20^{o}C and 85^{o}C. The CuNiAl samples, however, were much more difficult to train and had failed to respond to the training temperatures due to the brittleness of the sample. The manufactured densities of the samples were seen as a cause of failure and needs to be improved before further tests can be carried out. The following table lists the response obtained during the thermal training.

Table 1: Thermal Training Response for TiNi and CUNiAl Samples

No.	Sample	Material	T cold	T hot	Response
1	SLM Delta wing vortex generator	TiNi	20^{o}C	85^{o}C	10% strain, deformation angle between 20^o – 35^o
2	SLM Delta wing vortex generator	CuNiAl	20^{o}C	85^{o}C	Failed. Samples broke during deformation
3	Thin sheet delta wing vortex generator	TiNi	20^{o}C	85^{o}C	15% strain, deformation angle between 20^o – 45^o
4	Thin sheet wavy channels	TiNi	20^{o}C	85^{o}C	Straightened at 50^{o}C and wavy shaped to $\gamma = 0.2$ at room temperature

The vortex generator samples of the SLM builds and flat annealed thin sheets responded well to the training temperatures, consistent with a report provided in an earlier research by Clare et al. (2005). The initial vortex generator angle of attack of 45^o for the delta wing SLM samples however reduced slightly to 35^o, probably due to the numerous deformation cycles undergone during training.

As for the wavy channels, the thermal training established a straightened shape channel, resulting in lower flow pressure losses at its low temperature set-point. The channel passages then formed a sinusoidal-like wavy shape of $\gamma = 0.2$ and $\varepsilon = 1.2$ when temperatures were raised to 85^{o}C. Similar to the delta wings, the wavy elements lost some of their initial deformed shape after subsequent training cycles but its effects however were minimal.

Heat Transfer Enhancement Test

Tests carried out in the thermal test rig confirmed the heat transfer enhancement effects from the TiNi delta wing and the wavy channels. During testing, the samples responded to their respective high temperature set-points as they did during thermal training. Figure 7 illustrates the delta wing (SLM) and wavy channels activation and deactivation positions during testing.

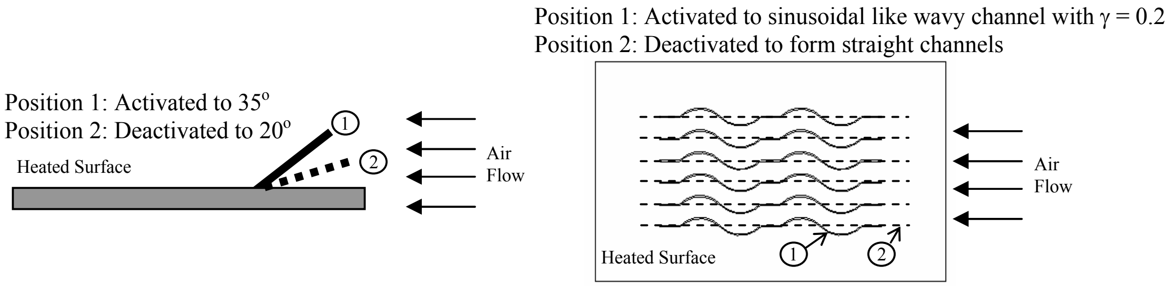


Figure 7: A Vortex Generator and Wavy Elements at their Activated and Deactivated Positions

The average spanwise surface temperatures recorded 20mm behind the SLM delta wing reduced from 120^{o}C to 100^{o}C as it moved from its deactivated to activated positions. This was due to the higher vortex strength generated at a higher angle of attack. A similar enhancement effect was observed for the thin sheet vortex generator but with a lower average spanwise surface temperature reduction from 120 to 109^{o}C. The reason for the better enhancement performance of the SLM built delta wings, was due to more rigid profile it held against the air flow as compared to the thin sheet delta wings which flapped quite often and could not maintain a consistent angle of attack. The activation time of the SLM and thin sheet vortex generators were also compared. A faster activation time of 4s for the thin sheet as compared to 120s for the SLM builds was due to a more uniform temperature distribution for the thin sheet. The manufacturing process for the thin sheet also guaranteed uniform thickness and density of the material as compared to the SLM builds.

The thin sheet wavy channels demonstrated good enhancement capabilities when they responded to the temperature set-points in the experiment. A reduction in the average spanwise surface temperature from 120^{o}C to

40^oC was taken as an indication of heat transfer enhancement of the heated surface. In its activated phase, the wavy shape of the channels enhanced heat transfer as a result of the mixing of the boundary layer with free stream fluid along the wavy passages. When deactivated, the elements were straightened and flow pressure losses were reduced over the heated surface.

CONCLUSIONS

The work reported in this paper has successfully demonstrated the concept of an active heat transfer surface through the use of shape memory alloy delta wings and wavy channel LVGs. For the first time, a single delta wing vortex generator operating between two angles of attack and wavy channels which can form straight passages have been developed. The ability of the TiNi vortex generators to shift its angle of attack from 20^o to 35^o for the delta wings and to form completely straight passages for the wavy channels not only improved heat transfer enhancement as expected, but also has the potential of addressing the problem of high pressure losses associated with the use of vortex generators.

This research was also able to confirm the capability of the SLM process in producing builds with acceptable SMA properties. They differed from the flat annealed thin sheets only in the activation response time. The response time however is expected to improve with further research, together with the subsequent improvements made to its build density.

Ongoing work on active heat transfer enhancement devices having 3D features is expected to help find specific applications in convective heat transfer enhancement.

NOMENCLATURE

A_{ht}	Heat transfer area ratio, A_{ht} = Vortex Generator Area/ Heated Plate Area
a	Wavy element amplitude, mm
B	Channel width, mm
b	wing and winglet width, mm
c	Chord length, mm
L	Channel length, mm
Re	Reynolds number, based on the mean inlet velocity and chord length
r	Hemispherical protuberance radius, mm
S	Channel spacing, mm

Greek Symbols

α	Angle of attack
ε	Wavy element spacing ratio, $\varepsilon = S/2a$
γ	Waviness aspect ratio, $\gamma = 2a/\lambda$
Λ	Aspect ratio, $\Lambda = 2b/c$
λ	Wavy element pitch

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