A Particle Image Velocimetry Study of Flow Structure in an Offset-Strip Array with Delta-Wing Vortex Generators

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to Enhance Air-Side Heat Transfer
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Abstract

The potential for heat transfer enhancement from the combination of spanwise and streamwise vorticity has been investigated using a vortex-enhanced interrupted fin (VEIF) array. The VEIF consists of a fin with two delta-wing vortex generators (VGs) located symmetrically about the fin’s spanwise centerline. The VEIF was placed in an offset-strip fin array, and the array was thus called the Two-VG array. Spanwise vortices were created by the offset-strip array, and streamwise vortices were introduced to the flow by the VGs. The Two-VG array and a baseline offset-strip array were examined over the Reynolds number range $1025 \leq \text{Re} \leq 2450$. The flow structure through the array was investigated using dye-in-water flow visualization and particle image velocimetry (PIV), and the results were compared to naphthalene sublimation heat transfer data obtained in a separate study.

The Two-VG array showed heat transfer enhancement at $\text{Re} \leq 1025$. At these Reynolds numbers, spanwise vortices are not dominant in the offset-strip array. The introduction of streamwise vortices by the VGs enhances the heat transfer behavior of the baseline array by increasing the mixing of freestream fluid with the boundary layer fluid of the fins. Shear layer instabilities in the wake of the baseline array occur at $\text{Re} = 1230$. The onset of these oscillations at $\text{Re} = 1230$ corresponds to a decrease in heat transfer near the exit of the Two-VG array, where no oscillations or instabilities occur.

Spanwise vortex shedding begins at the back of the array as the Reynolds number increases past $1550$ in the baseline array, and past $1610$ in the Two-VG array. As the Reynolds number is increased through $\text{Re} = 1780$, the heat transfer decrement persists, and moves upstream through the array. The onset of spanwise vortex shedding similarly moves upstream with increasing Reynolds number. The heat transfer behavior of the Two-VG array within the Reynolds number range $1230 \leq \text{Re} \leq 1780$ suggests that the interaction of spanwise and streamwise vorticity is destructive. An increase in Reynolds number to $\text{Re} = 2450$, however, showed improved heat transfer behavior, and, thus, a beneficial interaction of spanwise and streamwise vorticity. Spanwise vortex shedding occurred throughout the baseline and Two-VG arrays at $\text{Re} = 2450$. Spanwise flow unsteadiness in the Two-VG array began at fin 3 for $\text{Re} = 2450$. At the lower Reynolds numbers investigated, flow unsteadiness did not begin before fin 6.
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Nomenclature

**English Symbols**

A<sub>core</sub> minimum free-flow area of the test array
A<sub>Total</sub> total surface area of the test array
A<sub>F</sub> fin surface area
A<sub>VG</sub> vortex generator surface area
b vortex generator base dimension or plate spacing
c vortex generator chord length
d<sub>r</sub> particle image diameter
d<sub>p</sub> true particle diameter
D<sub>h</sub> hydraulic diameter
f friction factor
f<sub>o</sub> baseline friction factor
f<sup>*</sup> lens f-number
H channel height
I image intensity field
j Colburn factor
L fin length
L<sub>core</sub> length of the test array
M magnification
Nu Nusselt number
Nu<sub>b</sub> baseline Nusselt number
R<sub>II</sub> spatial cross-correlation function
Re Reynolds number
Re<sub>C</sub> Reynolds number based on chord length
Re<sub>D</sub> Reynolds number based on hydraulic diameter
Re<sub>L</sub> Reynolds number based on fin length
Re<sub>t</sub> Reynolds number based on fin thickness
S fin spacing
St Strouhal number
t time or fin thickness
T<sub>bx</sub> bulk temperature at position x
T<sub>i</sub> bulk inlet temperature
T<sub>w</sub> plate temperature
U streamwise velocity
U<sub>core</sub> core (maximum) velocity
V transverse velocity normal to fin surface
\| V \| velocity magnitude
W spanwise velocity
X streamwise coordinate or horizontal coordinate for image evaluation
X<sub>o</sub> X dimension of spot window
X<sup>*</sup> non-dimensional fin location, X<sup>*</sup> = X/L
Y transverse coordinate normal to fin surface or vertical coordinate for image evaluation
Y₀ Y dimension of spot window
Z spanwise coordinate

**Greek Symbols**

α flow passage aspect ratio, \( \alpha = (b – t)/(S – t) \)
β vortex generator angle of attack
Δ variable change
ε effectiveness parameter, \( \varepsilon = (T_{bx} – T_i)/(T_w – T_i) \)
λ wavelength of light
Λ vortex generator aspect ratio, \( \Lambda = 2b/c \)
ω vorticity

**Abbreviations**

CCD charge coupled device
CHC choice code
HP high-pressure
LP low-pressure
Nd:YAG neodymium-yttrium-aluminum-garnet
PIV particle image velocimetry
RMS root mean square
SNR signal-to-noise ratio
VEIF vortex-enhanced interrupted fin
VG vortex generator
Chapter 1: Introduction

1.1 Motivation
Air-side heat transfer enhancement has been a subject of great interest in recent years due to its significant impact on heat exchanger performance. Heat exchanger performance is crucial to many heating, ventilation, air-conditioning, and refrigeration (HVAC/R) applications because of increased environmental and economic concerns. Air-side thermal resistance is dependent on fin area, surface efficiency, and the heat transfer coefficient. Although increasing the fin area enhances heat transfer by reducing the air-side thermal resistance, it also increases heat exchanger size, and therefore cost. Thus, enhancing the heat transfer coefficient or the surface efficiency are more desirable goals.

Several techniques for enhancing the heat transfer coefficient exist and are easy to implement. For this reason, the heat transfer coefficient is often the parameter chosen for enhancement. Two popular techniques for heat transfer coefficient enhancement are the use of highly interrupted fins, and the use of flow manipulators known as vortex generators (VGs). Interrupted fins create periodic spanwise shedding and boundary layer restarting, each of which have been documented to increase the heat transfer coefficient significantly [1-5]. Vortex generators add streamwise vorticity to the flow field. Local heat transfer enhancements of up to 150%, and average enhancements of 20% to 50%, have been measured [6-8].

The potential for additional enhancements from the combination of these techniques is suggested by detailed experiments on vorticity in shear layers [9, 10]. Within these shear layers, counter-rotating streamwise vortex pairs exist in the braid region between the dominant spanwise Brown-Roshko rollers. The locations where the streamwise vortices wrap around the spanwise vortices are regions of very high mixing of freestream fluid within the shear layer. To the author’s knowledge, no literature exists on the effect of similar spanwise/streamwise structures on heat transfer. In addition, no guidelines exist for the placement of vortex generators within interrupted geometries with respect to heat transfer enhancement and pressure loss penalties. The purpose of this research is to contribute a fundamental understanding of the enhancement capability of combined spanwise and streamwise vorticity to HVAC/R applications. To reduce the extensive parameter space involved with this problem, this research will only investigate the simple case of an offset-strip fin array and delta-wing vortex generators.

1.2 Literature Review
The literature review has been divided into two sections. The study of interrupted fin geometries is by no means a new area. Louvered, convex-louvered, and offset-strip geometries are a few of the concepts that have been investigated. The first section of this literature review will focus on the offset-strip geometry, as it is the geometry of interest in this research. The study of vortex generators in channel flow and flat-plate flow is another area of extensive literature. Several types of vortex generators exist, but wing-style vortex generators will be the focus of the second section of this review.
1.2.1 Offset-Strip Fins

Interrupted fin geometries have been investigated with the purpose of developing heat transfer and pressure drop correlations, as well as for flow structure. London and Shah [11] were among the first to develop correlations for offset-strip fins. In 1968 they studied the basic heat transfer and pressure drop for eight offset-strip arrays with $100 \leq \text{Re}_D \leq 5000$, where $D$ represents the hydraulic diameter, and the characteristic velocity was the core velocity through the array. The array shown in Figure 1.1 is representative of the geometries investigated by London and Shah. The fin rows were offset by approximately 50 percent of the channel width ($S$). Graphs for the Colburn and friction factors, $j$ and $f$, were developed for the eight geometries as a function of $\text{Re}_D$. From the heat transfer versus pressure drop data, an offset spacing ($\text{fin length}/D_h$) below 1.796, a flow passage aspect ratio above 4.72, and small fin thickness were found to be advantageous for heat transfer performance. The aspect ratio was defined as:

$$\alpha = \frac{(b - t)}{(S - t)} \quad (1.1)$$

for which $b$ is the fin dimension into the page in Figure 1.1, $t$ is the fin thickness, and $S$ is the fin pitch (Figure 1.1).

Weiting [12] developed empirical correlations for heat transfer and pressure drop for 22 offset-strip fin geometries using data from several sources, including London and Shah [11]. Two Reynolds number regimes were examined: $\text{Re}_D \leq 1000$ (laminar) and $\text{Re}_D \geq 2000$ (turbulent). The results of the correlations show that the flow passage aspect ratio is significant only in the laminar flow regime, while the fin thickness is only significant in the turbulent flow regime.

Mochizuki et al. [13] reported heat transfer and pressure drop correlations for 18 fin arrays including offset-strip, slotted, and plain fin arrays over a Reynolds number range of $800 \leq \text{Re}_D \leq 10,000$. Both $j$ and $f$ are enhanced by a reduction in fin length-to-plate spacing ratio at given Reynolds number for the offset array. A performance comparison based on heat transfer and pressure drop indicated that an offset array with a small fin length-to-transverse fin pitch ($S$ in Figure 1.1) ratio is superior.

Joshi and Webb [14] performed a numerical and experimental investigation of offset-strip fin arrays, developing an equation to predict the critical Reynolds number for flow transition using geometric parameters. Analytical models predicting the heat transfer coefficient and friction factor were also formulated. The numerical friction factor results deviated from experiments by approximately 9.5 percent (RMS value). Flow visualization experiments showed that, using a wake width-based Reynolds number, wake flow patterns can be correlated. Finally, empirical correlations were developed for the heat transfer coefficient and friction factor.

Manglik and Bergles [15] have developed additional correlations for offset fin arrays.

Correlations are limited to the conditions from which they are developed, and thus, a significant amount of interrupted fin research has been focused on understanding the flow structure that exists in these arrays. Sparrow performed a series of investigations of flow structure through in-line and offset-strip fin geometries. In 1977, Sparrow et al. [16] used a finite difference technique to quantify local Nusselt number and pressure drop in an offset-strip fin array in the laminar regime investigated by Weiting [12]. Assumptions,
several of which deviate from practical application, included a uniform entering flow, fins of negligible thickness, isothermal fin surfaces, steady, separation-free flow in the fin wakes, and two-dimensional flow and heat transfer with negligible spanwise variations.

Appreciably higher heat transfer rates were produced in the interrupted geometry as compared to the continuous fin case for a wide range of operating conditions when the constraints of equal heat transfer surface area and equal pumping power were imposed. The heat transfer enhancement was most significant at higher Reynolds numbers and with relatively short channel lengths. Pressure drop was found to increase with increasing Reynolds number and decreasing plate length. The authors extended their investigation beyond Weiting’s laminar range to $Re_D = 1600$ and were the first to note the existence of a periodic fully developed regime in which the average heat transfer coefficient is constant for all fins. Within the periodic fully developed regime, temperature and velocity profiles vary periodically throughout the interrupted geometry.

Sparrow and Liu [17] numerically investigated heat transfer, pressure drop, and an effectiveness parameter for in-line, offset-strip, and continuous fin geometries using a finite difference approach. Results were given for both the developing and fully developed regimes. The effectiveness was defined as $\varepsilon = (T_{bx} - T_i)/(T_w - T_i)$, where $T_{bx}$ is the bulk temperature at position $x$, $T_i$ is the bulk inlet temperature, and $T_w$ is the plate temperature. For a fixed mass flow rate and fixed heat transfer surface area, the heat transfer enhancement of the interrupted geometries was significant in both regimes. Similarly, performance curves corresponding to constant pumping power and constant surface area showed that the interrupted arrays provided higher heat transfer, compared to the continuous fin, for effectiveness values less than 0.75. Comparison of the in-line and offset-strip arrays showed that the heat transfer provided by the offset-strip array exceeded that of the in-line array for constant pumping power and constant surface area, but at the cost of higher mass flow.

Sparrow and Hajiloo [18] experimentally determined the heat transfer and pressure drop characteristics of an offset-strip fin array for $1000 \leq Re_D \leq 9000$. The naphthalene sublimation technique was used for the heat transfer measurements. Heat transfer and pressure drop measurements were made internal to the array. The heat transfer measurements indicated the existence of the periodic fully developed regime noted in earlier numerical work [16]. Within this regime, the per-fin Nusselt number remains constant for the second and all subsequent fins. At Reynolds numbers below 1200, the plate thickness showed no effect. The Nusselt number was found to increase with Reynolds number for all cases, with the magnitude of the increase greater for thicker fins. Pressure drop similarly increased with fin thickness and Reynolds number. For the thickest fins studied, the friction factor was independent of Reynolds number.

In 1982, Mochizuki and Yagi [19] studied the effect of fin arrangement on the characteristics of vortex shedding for nine offset-strip arrays with $40 \leq Re_t \leq 400$, where $Re_t$ is based on the fin thickness, $t$, and the maximum velocity through the array. Dye injection and the hydrogen bubble technique were used to visualize the flow; hot-wire anemometry was used to measure the vortex shedding frequency in an attempt to understand acoustic modes in the duct. For an array with two rows of fins, two Strouhal numbers co-exist due to the two different wakes behind the two fin rows. For arrays with between three to eight rows, multiple Strouhal numbers exist at large Reynolds numbers ($Re_t > 113$), for which vortices are shed off the fins. Only one
Strouhal number is detected at small Reynolds numbers because only the flow behind the array experiences sinusoidal oscillations.

When the offset-strip array reaches nine or more rows, the number of Strouhal numbers decreases to one, and this value is independent of both Reynolds number and the number of rows. For all arrays studied, flow visualizations showed that at low Reynolds numbers, the flow is laminar throughout the array. As Reynolds number is increased, the wakes begins to oscillate sinusoidally. Further increase of the Reynolds number finds vortex shedding starting at the back of the array, with the onset of vortex shedding moving upstream as the Reynolds number is increased.

The flow patterns seen in the arrays with nine or more rows were classified into three regimes: steady laminar, oscillating, and turbulent. The steady laminar regime existed at $Re_t < 22$, for which the flow was completely laminar throughout the array and in the wake. The oscillating regime, $44 \leq Re_t \leq 66$, is defined by sinusoidal oscillations appearing in the wake of the array, with the oscillations turning into vortex shedding within the array as Reynolds number is increased. At $Re_t > 66$, the flow transitions and becomes turbulent. The effect of array density on vortex shedding was not studied in this experiment.

Mullisen and Loehrke [20] explored the structure of flow through interrupted arrays to identify flow mechanisms important for heat transfer augmentation. The schlieren visualization and transient heating techniques were used to identify flow phenomena and determine heat transfer performance, respectively. Three fin arrays were investigated for $100 \leq Re_D \leq 10,000$: in-line, offset-strip, and a perpendicular array. The test cores were designed according to guidelines given by Weiting [12]. Steady, general unsteady, and periodic unsteady flow regimes were identified for the in-line and offset-strip arrays, while the perpendicular array did not show a periodic regime.

Average heat transfer enhancements of over 100 percent were found for the interrupted geometries. Increased mixing of the separated boundary layers caused the enhancement in the in-line array, while the offset array experienced an additional enhancement due to the disruption of boundary layer growth. Transition from steady to unsteady flow occurred at a critical Reynolds number that increased with streamwise fin spacing and fin thickness. Sudden changes in $j$ and $f$ indicated a flow regime transition for the interrupted fin arrays similar to that measured for two separated fins. The transition in the offset-strip arrays occurred at higher Reynolds numbers than for the in-line array.

Flow visualizations and simultaneous velocity and temperature measurements for $50 \leq Re_t \leq 200$ by Xi et al. [21] resulted in four major findings. Flow visualization showed the formation of discrete vortices to increase with increasing Reynolds number and decreasing fin pitch-to-offset length ratio ($S/L$). The critical value for Reynolds number, which occurs at the point where the $j$-curve begins to deviate from flat-plate laminar boundary layer behavior, lies in the Reynolds number range in which the discrete vortices occur. The generation frequency of the vortices was found to increase with Reynolds number, in addition to $S/L$. The velocity and temperature measurements show that additional momentum and heat transfer occur due to wake flow instability.
Until 1997, numerical investigations and theoretical models ignored much of the time-dependent flow physics and associated heat transfer enhancement that occur in offset-strip arrays. Zhang et al. [22] were among the first to investigate the time-dependent flow regime by solving the unsteady Navier-Stokes and energy equations in two dimensions for a periodically repeating unit containing two staggered fins. The simulations showed that the velocity and temperature profiles approaching any fin are significantly distorted from the fully developed case. The increased gradients that result at the fin surface contribute to increased \( j \) and \( f \) factors. At low Reynolds numbers, the flow is steady. At a critical Reynolds number, however, the flow takes on an unsteady behavior with a single dominant frequency. An additional lower frequency is generated at higher Reynolds numbers, for which the flow becomes chaotic. The unsteady regime is characterized by vortices generated from the leading edge of the fins. The overall drag and friction factor were found to increase with increasing \( Re_D \) due to an increase in form drag and fin-wake interactions.

Zhang et al. [23] followed this work by developing an accurate computational method for the calculation of flow and heat transfer in compact heat exchangers. The method was implemented using a massively parallel Connection Machine. The inclusion of flow unsteadiness was found to be very important in accurately predicting \( j \) and \( f \). At high Reynolds numbers, overall heat exchanger performance is greatly influenced by the intrinsic three-dimensionality of the flow. Later work [24] showed that previous two-dimensional simulations significantly overpredict heat transfer and other RMS quantities due to the weakening of the spanwise vortices by streamwise vortices present in three-dimensional flows.

DeJong and Jacobi [1, 2] revealed the effects of boundary-layer growth and vortex shedding in offset-strip arrays using flow visualization and the naphthalene sublimation technique. Both local and surface-averaged heat transfer, along with pressure drop, were obtained for three offset geometries of varying fin density for \( 380 \leq Re_D \leq 1060 \). For steady laminar flow, the local Sherwood number was highest at the leading edge, and decreased with boundary layer growth. Once vortex shedding began, the Sherwood number increased to a maximum near a non-dimensional fin location of \( X^* = X/L = 0.2 \), and then decreased. Turbulent conditions produced similar results. Using row-by-row heat transfer data and flow visualization, the onset of vortex shedding was determined for the Reynolds number range studied. The shedding was observed to move upstream with increasing Reynolds number, as seen by Mochizuki and Yagi [19]. Shedding was achieved at lower Reynolds number for denser arrays. Friction factor also increased with increasing array density.

DeJong et al. [3] compared experimental results, previous and new, to numerical work done by Zhang et al. [22-24]. Overall heat transfer and pressure drop results, local Nusselt number behavior, and instantaneous flow structures and velocity profiles were compared. The comparison verified that the two-dimensional simulation method developed by Zhang et al. [23] captures the important features of the flow and heat transfer interactions over a range of conditions.

The \( f \) factor results for both the experiments and numerical simulations compared well to previous correlations by Joshi and Webb [14], although differences between the data sets existed and were attributed to a 30 percent smaller fin thickness-to-gap between fins ratio for the simulation. The \( f \) factors, however, did not compare as well to the correlations as did \( j \). The \( f \) factor difference was attributed to the imposed boundary
conditions, which have a much greater effect than geometrical differences on $j$. For the experiments, constant fin temperature was assumed, and the simulation assumed a constant heat flux. Below $Re_D = 1000$, the simulation reported $j$ factors up to twice as large as the experimental measurements. Above $Re_D = 1000$, the results were within ten percent of the experimental values. For $Re_D \geq 1300$, three-dimensionality becomes important and is a likely source of error.

The local Nusselt number behavior was compared using a Reynolds number based on length ($Re_L$). The experimental and numerical average Nusselt numbers agreed to within 3 and 12 percent for the low and high $Re_L$ cases, respectively. For a reported uncertainty of ±10 percent for local Sherwood number, the results agree exceptionally well. Great similarity between the unsteady flow structures was exhibited in the experiments and simulation. Once again, though, discrepancies were found between the experiments and simulation. Discrepancies in the velocity profiles exist due to geometrical differences, a numerical assumption of an infinitely large array, and three-dimensionality. For calculation of Strouhal number (St), the experiments predicted $St \approx 0.23$, while the simulation reported $St \approx 0.15-0.17$. This 40 percent discrepancy is attributed to the three causes listed above for velocity discrepancies, as well as an experimental approximation setting convective velocity equal to the mean velocity.

1.2.2 Vortex Generators

Jacobi and Shah [25] and Fiebig [26] have compiled extensive reviews of the vortex-induced heat transfer literature through 1994. These articles exhibit the complex design parameter space that challenges a complete understanding and useful implementation of vortex generators (VGs) and the resulting flow physics. Presented in this section will be a discussion of relevant literature studying wing-type vortex generators (Figure 1.2).

Among the first investigations of the enhancement potential of vortex generators was that by Edwards and Alker [27]. In 1974, these authors tested delta-winglets at $Re=61,000$, where Reynolds number is based on the mean velocity and the VG height. Various VG configurations were tested. A constant heat flux was applied to a flat plate, and local heat transfer coefficients were determined by using a luminescent phosphor technique. The winglets produced maximum local enhancements of 142%.

Russell et al. [28] used temperature-sensitive paint and pressure drop measurements to evaluate the enhancement potential of finned-tube heat exchangers with alternating rows of closely spaced delta and rectangular winglet VGs. The Reynolds number range varied from $200 \leq Re_D \leq 2200$, and the wing angle-of-attack ($\beta$) was 20°. Experimental data were compared to plain fin correlations from the literature, and for $1500 \leq Re_D \leq 2200$, the ratio of $j$ to $f$ exceeded 0.5. The heat transfer coefficient was reported to increase up to 50%, and the pressure drop by 40%.

In 1986, Turk and Junkhan [29] presented heat transfer measurements for a single row of rectangular-winglet pairs positioned where the oncoming boundary layer is laminar, over a range of VG spacings and heights. Reynolds numbers based on distance downstream from the leading edge varied between 50,000 and 300,000. Local heat transfer coefficients were determined by using thermocouples to measure local surface and air temperatures, and pressure drop was measured using static pressure taps. Enhancements of 250% were
achieved for the local span-averaged heat transfer coefficient, with enhancements increasing with a favorable pressure gradient. Correlations for the local and overall heat transfer coefficients were developed for the various VG geometries.

Yanagihara and Torii [30, 31] studied delta-winglet VGs in laminar boundary layers. The local heat transfer coefficient was measured over a constant heat flux surface using thermocouples and the naphthalene sublimation technique. Streamwise velocity fields were measured using hot wire anemometry, and the smoke-wire technique visualized the vortical structures created by the VGs. The angle of attack, $\beta$, was fixed at $15^\circ$ for VG pairs, but varied from $5^\circ$ to $60^\circ$ for single VGs. VG height was varied from 6 mm to 25 mm. The free-stream velocity was fixed at 4 m/s for a constant Reynolds number. Local enhancements of 100% were obtained. Local heat transfer enhancement was shown to increase with $\beta$.

Fiebig and co-workers [26, 32-51] have prolifically explored the broad parameter space of VGs. Their work has investigated the implementation of VGs in several heat exchanger elements, using both experimental and numerical methods. In 1986, Fiebig et al. [33] first began investigating wing-type vortex generators for heat transfer enhancement using delta-wing/winglet and rectangular-wing/winglet VGs in a channel flow over the range $1360 \leq Re_H \leq 2270$ (Reynolds number based on channel height). Visualization of the vortex structure was performed by laser sheet illumination. Unsteady liquid crystal thermography was used to calculate local heat transfer coefficients, and $f$ was inferred by using a scale to measure drag force. The angle of attack was varied between $10^\circ$ and $50^\circ$.

Flow visualization showed that a stable vortex core at high $\beta$ can only be achieved with low $\Lambda$ (aspect ratio) delta-wings. Drag force measurements were shown to be independent of $Re_H$, nearly independent of VG geometry, approximately proportional to $\sin \beta$, and proportional to the wing area. Heat transfer data showed that the highest $j$ to $f$ enhancement came from delta-wings at small $\beta$.

Additional experimental work by Fiebig et al. [35-38, 42, 43, 46], utilizing many of the same experimental methods, presents results for a wider range of parameters. Delta and rectangular wings and winglets in channel flow, with $1000 \leq Re_H \leq 2000$, $0.8 \leq \Lambda \leq 2$, and $10 \leq \beta \leq 60^\circ$, produce an additional drag which is independent of $Re_H$ and VG geometry, but is proportional to dynamic pressure and VG area [36]. The additional drag increases with $\beta$. The heat transfer ratio of the baseline fin and fin-with-VG is independent of $Re_H$ and increases with $\beta$. Delta-wing VGs were the most effective for heat transfer enhancement per unit VG area. In this study, the ratio of fin area to VG area, $A_f/A_{VG}$, was varied between 19 and 61. Delta-winglets were found to be the most effective VGs when both heat transfer enhancement and pressure drop are considered. Therefore, the additional studies by Fiebig et al. have focused on this VG geometry. Fiebig and his co-workers have provided additional insight to their experimental studies by performing numerical simulations of these flows and geometries [32, 34, 39-41, 44, 45, 47-51].

Biswa and co-workers [52-55] have presented additional numerical studies of VG-enhanced flows. Biswas and Chattopadhyay [52] extended the work of Biswas et al. [32] to include the effects of a punched hole underneath a delta-wing, and the influence of $\beta$ and $Re_H$ on heat transfer and skin friction using the Marker and Cell (MAC) numerical method. The effect of the hole was a 30% reduction in pressure drop, and a 24%
reduction in heat transfer (with respect to results in [32]). Heat transfer enhancement and pressure drop were shown to increase with increasing Reynolds number and $\beta$.

Biswas et al. [53] evaluated delta-wing and delta-winglet VGs in a channel with different $\beta$ and a wide range of operating conditions and considered heat transfer augmentation and flow losses. The numerical results were compared to the experimental work of Fiebig et al. [36]. Delta-wing VGs produced 20% higher heat transfer rates than the delta-winglets at the channel exit, but at the cost of 14% more pressure drop. The authors conclude that delta-winglet VGs are more practical for fin-tube and plate-fin crossflow heat exchangers. The delta-winglets produce less pressure loss, do not cause separation bubbles as in the case of delta-wings, and have smaller zones of poor heat transfer than the delta-wing. Similar studies [54, 55] investigated delta-winglet VG geometries, characterizing the heat transfer and pressure drop over a broader geometrical range, and validating the predicted flow structure with experiments.

Gentry and Jacobi [6-8] have performed extensive work on characterizing the delta-wing VG to better understand the relationship between flow structure and heat transfer. Gentry [6] studied the delta-wing VG on a flat plate at Reynolds numbers based on plate length ($Re_x$) of 5300, 6900, and 9000 for $0.5 \leq \Lambda \leq 2$ and $10 \leq \beta \leq 55^\circ$. Light-sheet flow visualization and a potential flow model were used to calculate a goodness factor that predicts relative enhancement of different VG geometries. Naphthalene sublimation and pressure drop experiments were performed to verify the goodness factor. The goodness factor analysis demonstrated that vortex location and strength are essential parameters to consider for VG heat transfer enhancement. For optimum configurations, average heat transfer enhancements of up to 43% were achieved.

Pressure drop measurements showed that increasing $\beta$, $\Lambda$, and $Re$ increased pressure losses, and that pressure drop increased by a factor of two in the worst case. Gentry and Jacobi [7] continued this work by expanding the $Re$ range to include $Re = 600, 800, and 1000$. Average heat and mass transfer enhancements of 50% to 60% were demonstrated. The implementation of the goodness factor in these studies offered excellent insight into the physics of delta-wing VG enhancement. The goodness factor provided a compact representation of the advective mechanisms of boundary layer interactions with streamwise vortices in a complex design space.

Gentry [8] furthered his investigations by implementing a delta-wing VG in laminar flat-plate and developing channel flows. Vortex flow field and heat transfer interactions were studied. Flow structure was visualized using dye-in-water experiments, and measured using a vane-type vortex meter. An electronic pressure transducer measured pressure drop. Naphthalene sublimation quantified local and average heat transfer enhancements. The test matrix included $300 \leq Re_C \leq 1300$ (flat plate), where $c$ is the chord length, and $300 \leq Re_D \leq 1300$ (channel flow), each with $0.5 \leq \Lambda \leq 2$ and $15 \leq \beta \leq 55^\circ$.

Among numerous observations of flow field interactions, such as the first report of vortex-tube waviness associated with a delta-wing tip vortex interacting with a flat-plate boundary layer, it was shown that vortex strength increased with $Re$, $\Lambda$, and $\beta$. The increase was 200% at its peak for flat plates, and 300% for channel flows. Local heat transfer enhancements as high as 300%, and average mass transfer enhancements as high as 80% were observed in areas affected by vortices for flat-plate flow. For channel flows, local heat
transfer enhancements of 150% occurred, with average mass transfer enhancements of up to 50%. Similar to the flat plate case presented in [6], pressure drop for the channel flow case increased with Re, $\Lambda$, and $\beta$, with a worst-case increase of a factor of two for $Re_D=2000$.

Felton [56] investigated heat transfer and pressure drop in a developing channel flow with delta-wing VGs for $\Lambda = 2$ and $\Lambda = 4$, and $20 \leq \beta \leq 45^\circ$ over $1700 \leq Re_D \leq 6300$. Experimental methods included a pressure transmitter for pressure drop, and liquid crystal thermography for local and average heat transfer enhancements. Pressure drop was nearly independent of $\Lambda$, with increases of up to 20% for $Re_D \leq 5200$, and 60% for $Re_D = 6300$. Local heat transfer enhancements of 100% and 200% were achieved for $\Lambda = 2$ and 4, respectively. Maximum average enhancements were 87% and 103% for $\Lambda = 2$ and 4, respectively.

Jeong and Ryou [57] investigated heat transfer and flow structure of delta-winglet VGs in a three-dimensional turbulent boundary layer on a flat plate using the space-marching Crank-Nicolson finite-difference method. A longitudinal vortex was shown to strongly perturb the velocity and temperature fields of the turbulent boundary layer. Heat transfer was affected over a long streamwise distance on the plate. The predicted mean temperature and velocity fields, friction factor, Stanton number, and turbulent kinetic energy compared favorably to experimental data from Pauley and Eaton [58]. An experimental investigation of the delta-winglet VG in a turbulent boundary layer by Inaoka et al. [59] found that the inclusion of a Large Eddy Break-Up (LEBU) plate in a turbulent channel flow reduced the wall heat transfer, but that this heat transfer could be recovered using VGs. A hole located behind the VG was used to simulate the effect of a punched VG. The effect of the hole was to augment the heat transfer and suppress the increase of momentum loss.

Liou et al. [60] performed a parametric study of 12 VG configurations using delta-wings and V-shaped angled ribs in a square channel. Laser Doppler velocimetry, transient liquid crystal thermography, and a pressure transducer were used to evaluate the VGs for a fixed $Re_D = 12,000$, and VG height-to-hydraulic diameter ratio and pitch-to-height ratio of 0.12 and 10, respectively. Of the 12 VGs studied, the $45^\circ$ V-shaped angled-rib VG had the highest heat transfer potential, followed by the upstream-facing delta-wing.

For constant pumping power, $Nu/Nu_o = 2.5$ for the $45^\circ$ V-shaped angled-rib VG, and for constant flow rate, the ratio was 3.7. Similarly, all other cases produced higher values of $Nu/Nu_o$ for constant flow rate. The associated friction loss ratio ($f/f_o$) for the $45^\circ$ V-shaped angled rib VG was 3.8. An upstream-facing delta-wing was found to yield $Nu/Nu_o = 2.7$, with $f/f_o = 1.3$ at constant flow rate. The third best $Nu/Nu_o$ came from a winglet pair. The winglet pair had the best $f/f_o$ of 1.28. When the single $45^\circ$ V-shaped angled-rib VG and upstream-facing delta-wing VG were replaced by arrays of VGs, the thermal performance, both at constant pumping power and constant flow rate, improved. Friction loss in the delta-wing case increased, but remained constant for the rib geometry.

1.3 Project Objectives

The offset-strip fin geometry naturally produces spanwise vortices when flow transitions past the laminar regime. Vortex generators can be used to generate streamwise vortices in channel flows and over flat plates. Offset-strip fin arrays and vortex generators have been extensively researched, yet the literature lacks an
investigation of the coupled effects of spanwise and streamwise vortices that would exist with the combination of these enhancement techniques.

This research differs from past studies because it is the first investigation of the coupling effects of spanwise and streamwise vortices focusing on the potential for heat transfer enhancement. The offset-strip geometry was chosen because it is easy to implement, and can be made symmetrical. Since a substantial pressure loss is incurred in the use of offset-strip arrays, delta-wings were chosen as the vortex generators to maximize the heat transfer enhancement. The concept developed in this research is thus deemed the vortex-enhanced interrupted fin (VEIF).

The VEIF geometry has been investigated experimentally to obtain a fundamental understanding of spanwise and streamwise vorticity flow field interactions. Flow visualization using dye-in-water experiments was performed to determine qualitative flow features. Full-field velocity data were also obtained using particle image velocimetry (PIV). Heat transfer data obtained in a separate study by Ge [61] are presented for comparison with the PIV and flow visualization results. The heat transfer data were measured using the naphthalene sublimation technique. The experimental results are used to develop guidelines for the optimal VEIF configuration, with respect to vortex generator placement for maximum heat transfer enhancement.

To reduce the parameter space, a symmetric ($S = L$) geometry was used for the offset-strip array (Figure 1.1), and the delta-wing vortex generator was fixed with $b = L$, $\Lambda = 2$, and $\beta = 25^\circ$ (Figure 1.2). A broad range of Reynolds number was investigated to provide a fundamental understanding of the VEIF’s potential to enhance air-side heat transfer in common HVAC/R applications.

### 1.4 Figures

![Figure 1.1: Offset-strip fin array geometry and parameters](image-url)
Figure 1.2: Wing-type vortex generators and nomenclature (Gentry [6])
Chapter 2: Facilities and Methods

2.1 Water Tunnel
Flow visualizations and PIV measurements were obtained using an Engineering Laboratory Design Model 501 recirculating water tunnel (Figure 2.1). The water tunnel is constructed of laminated fiberglass-reinforced plastic. The interior surfaces are glass smooth, and gel coated. The water tunnel test section has a free-water surface, and the dimensions are 15.24 cm wide by 15.24 cm high by 45.72 cm long, constructed from 1.27 cm thick, type GM, clear, acrylic Plexiglas. A perforated cylinder distributes flow to the inlet plenum, and stainless steel, perforated plates act as head loss baffles. Honeycomb and screens are placed immediately upstream of the tunnel contraction, which has an area ratio of 6:1. A Plexiglas end wall permits optical access from the downstream direction. A transistor inverter variable frequency controller regulates the speed of a 112 GPM, ½ HP AC centrifugal pump, which is used to circulate the water through the tunnel.

To confirm that the water tunnel produced a uniform mean velocity distribution and low turbulence, mean flow velocity and turbulence statistics were measured using a hot-film anemometer. The measurements were made using a TSI 1212-20W hot-film probe. The voltage signal from the constant temperature anemometer (TSI IFA-100) was digitized using a National Instruments AT-MIO-16E10 data acquisition board. A National Instruments LabView code, written by Kearney et al. [62], was used to analyze the digitized signal. Figures 2.2-2.5 indicate a very nearly uniform mean velocity distribution and relatively low freestream turbulence (~1%) for the water tunnel.

2.2 Test Section
The model offset-strip fin array has a 15.24 cm by 15.24 cm cross-section, and a length of 20.32 cm (Figure 2.6). In order to simulate a wide range of approach velocities and array sizes, this model was tested over a broad Reynolds number range, $400 \leq \text{Re}_D \leq 2450$. Two 3.175 mm thick Plexiglas base plates hold forty-eight 2.54 cm long (L) aluminum fins in the array. The fins have a thickness (t) of 3.175 mm and a spacing (S) of 2.54 cm for geometric symmetry (i.e., $S = L$). For the PIV experiments, three Plexiglas fins were inserted into the array to allow laser light to pass unobstructed through the array. Without transparent fins, a shadow develops behind fin 7 and continues upstream, obstructing the imaging of important recirculation and stagnation regions immediately near the fins (Figure 2.7). The remaining aluminum fins were anodized black to reduce reflection of laser light. The hydraulic diameter ($D_h$) of the fin array is 39.5 mm, as calculated from:

$$D_h = \frac{4 \cdot A_{\text{core}} \cdot L_{\text{core}}}{A_{\text{total}}} = \frac{2 \cdot (S - t) \cdot L}{(L + t)}$$

for which $A_{\text{core}}$ is the minimum free-flow area of the test array, $A_{\text{total}}$ is the total surface area of the test array, and $L_{\text{core}}$ is the flow length of the array.

The vortex generator (VG) is of the delta-wing style, with a span of $b = 2.54$ cm, an aspect ratio of $\Lambda = 2b/c = 2$, and an angle-of-attack of $\beta = 25^\circ$ (Figure 1.2). VGs with $\beta = 55^\circ$ were also tested, but were found to produce flow separation, thus rendering them ineffective at enhancing heat transfer in an offset-strip fin.
Two arrays are compared in this study: a baseline array and a Two-VG enhanced array (Figure 2.6). The Two-VG enhanced array consists of two delta-wing VGs attached to each of the leading fins of the baseline array (Figures 2.6 and 2.8). The wings are attached to the fins by double-sided tape.

### 2.3 Flow Visualization

Flow visualization experiments were conducted in the water tunnel by injecting dye through an 18-gauge, standard size, stainless steel micro-tube (1.27 mm OD, 0.8382 mm ID). The dye was made from a neutrally buoyant mixture of red food coloring and water. The injector location was controlled using a three-axis traversing mechanism (1 µm resolution) that was mounted to the water tunnel. For the baseline experiments, dye was impinged on the leading fin between channels 5 and 6 (Figure 2.6). Dye impingement for the VG-enhanced case was located on the apex of the VG.

The characteristic velocity for this study was the core velocity through the array ($U_c$). For the flow visualization experiments, the core velocity was measured by injecting a dye droplet into the water, and recording the time it took the droplet to travel the length of the array. A type K thermocouple and Omega Engineering 199A-KC-AX digital readout meter provided water temperature. A flood lamp illuminated the flow field, and a JVC GR-DVF31 digital video camera recorded the flow field. Video editing was accomplished with Digital Origin’s Intro DV software using a PC with a Pentium III processor.

### 2.4 Particle Image Velocimetry

#### 2.4.1 Background

Particle image velocimetry (PIV) is a laser-based velocity measurement technique. The basic concept of PIV is to seed a flow with small tracer particles (diameter on the order of microns) that are illuminated by two consecutive laser pulses, and to capture these images onto either photographic film or a CCD array. A correlation process is applied to the two images, and the distance of particle movement within each measurement volume is calculated. Knowing the time separation between laser pulses, and the distance of travel in each probe volume, the flow field velocity data can be calculated for each volume. The concept of PIV is illustrated in Figure 2.9. A thorough review of PIV seeding, light sources, image capture methods, correlation methods, post-processing, and application is given by Raffel et al. [63].

#### 2.4.2 Equipment

For the current study, a TSI PowerView Stereoscopic PIV system was used for data acquisition and analysis. The PowerView system consists of a Model 610034 Laser Pulse Synchronizer, Model 630147 PIVCAM 13-8 cross-correlation camera, Insight Stereo PIV v3.3 software, and a Dell Precision 410 workstation with two Pentium III 600 MHz processors and 512 MB RAM. Laser illumination was provided by a Continuum double-pulsed Surelite III PIV Nd:YAG laser.

#### 2.4.3 Data Acquisition

PIV measurements were obtained in the water tunnel. Optical access for side and end views of the array is provided by the Plexiglas test section and endwall. The water flow was seeded using Potters Industries SH400S33 silver-coated hollow glass spheres. The spheres have a true particle density of 1.6 g/cc. The particle size range is 10-30 µm, with a mean size of 15 µm. A particle solution was prepared by mixing 8 g of particles
with 400 mL of water and 5 mL of Kodak Photo-Flo 200 solution. The Photo-Flo solution reduces the tendency of the particles to agglomerate.

Due to the range in velocity (0.5 cm/s to 7 cm/s) required for the ReD range studied, neutrally buoyant particles are desired to eliminate possible velocity bias errors associated with particle settling. To acquire neutrally buoyant particles, the particle solution was poured into a graduated cylinder and allowed to settle for two hours. The heaviest particles sank to the bottom, and the lightest particles floated to the surface. The remaining, neutrally buoyant particles were removed from the cylinder by use of a syringe. This particle separation method was developed by Fernandes [64].

The Nd:YAG laser used in the experiments is a Continuum double-pulsed Surelite III PIV laser. The laser is mounted to a breadboard table. Interfacing with the Laser Pulse Synchronizer is accomplished using two BNC-to-serial cables with 50 ohm terminators. The laser has two oscillator heads, each producing 400 mJ of energy at a wavelength of 532 nm (green light). The optical layout of the laser is given in Figure 2.10. For the PIV experiments, only 30 mJ of energy were used due to the slow flow field velocities and relatively large particle size. The laser beam is steered from the laser by a series of 45°, 532 nm YAG mirrors, and into a Laser Mechanisms PLBDS0045 articulated laser light arm (Figure 2.11).

Attached to the end of the articulated light arm was a series of light sheet-forming optics. A 700 mm plano-convex spherical lens, -25 mm plano-concave cylindrical lens, and a 300 mm plano-convex cylindrical lens are used to form a light sheet with a maximum thickness of 1 mm, and width of 4 cm. For the experiments measuring streamwise-transverse velocity (spanwise vorticity), the light sheet was propagated into the water tunnel through the Plexiglas endwall, entering the array at fin 8 (Figure 2.11). For spanwise-transverse velocity measurements (streamwise vorticity), the sheet was propagated through the test section sidewall.

The PIVCAM 13-8 cross-correlation camera is Peltier cooled, has a 12-bit digital output, a framing rate of 8 Hz, and a view of 1280 (H) by 1024 (V) pixels. The pixels are 6.7 µm by 6.7 µm in size. The camera is capable of interframe times as low as 200 ns for two-frame cross-correlation. The camera interfaces with the Laser Pulse Synchronizer using a high-speed digital frame grabber board. For the side-view experiments, a 60 mm Nikon AF Micro Nikkor F2.8 lens was attached to the camera, while the end-view experiments required a 70 mm-210 mm Nikon AF Nikkor F5.6 adjustable lens. The camera was placed on a rotating camera mount. The mount was secured to a slotted board, which was subsequently secured to a stand. The stand was equipped with a three-axis traversing mechanism and leveling feet.

Insight Stereo PIV v3.3 software provided the platform for data acquisition. Through a connection to the Laser Pulse Synchronizer, Insight controls the laser pulse separation value (Δt), the pulse repetition rate, and the pulse delay. The laser pulse separation value is the time between two laser pulses. The pulse repetition rate specifies the time between the start of one laser pulse sequence and the start of the next laser pulse sequence. Pulse delay refers to the delay time from the trigger of the camera to the first laser pulse. For the current study, the pulse repetition rate was 2 Hz, and the pulse delay was 0.25 ms. Details of the laser pulse timing for the various configurations and Reynolds numbers investigated can be found in Table 2.1. PIV images were acquired by capturing 100 image pairs (frame “a” and frame “b”) per Reynolds number and location, and saving
the images to the hard disk. Image sequences of 100 provide statistical information for the velocity and vorticity fields, but are inadequate for turbulence statistics. The instantaneous velocity and vorticity fields are of primary interest in this research, while the turbulence statistics are of much less importance, particularly for the low Reynolds numbers studied here. Therefore, 100 images per Reynolds number and location are deemed adequate for describing the flow characteristics of the arrays investigated.

Table 2.1 also shows the locations in the test arrays where images were acquired. For the side view, the flow through the whole array was captured two fins at a time, including the flow immediately upstream and downstream of the fin array. In the end view, the dimensionless position, $X^*$, specifies the location of image capture. $X^*$ is defined as the ratio of the distance from the entrance of the array (X) to fin length (L), (i.e., $X^* \equiv X/L$). The light sheet was placed at several $X^*$ locations, as indicated in Table 2.1 and Figure 2.12.

### 2.4.4 Image Evaluation

Digital PIV image evaluation is performed by dividing the images into small interrogation areas, also known as interrogation spots. Statistical methods (i.e., cross-correlation, auto-correlation, etc.) are employed to determine the local displacement vector in each interrogation spot using the illuminated particles from the first and second laser pulses. Essentially, the shift (displacement) between the two images of the particles is calculated and stored as a two-dimensional distribution of gray levels. Velocity vectors are calculated using the displacement vectors and the known time separation between pulses. Details of the statistical evaluation methods are given by Keane and Adrian [65-69], Raffel et al. [63], and Westerweel [70].

Interrogation in the present study was performed using a two-frame cross-correlation analysis. Cross-correlation consists of computing an average particle velocity over the interrogation spot. Two-frame cross-correlation uses two image frames with one pulse of light for each frame; thus, the interrogation spot windows are from separate frames. The first window is typically smaller than the second window, which is offset from the first by the mean displacement. The difference in spot size and the offset of the windows reduces the loss of particle pairs between frames. The reduction in lost particle pairs reduces the in-plane loss of correlation, and thus provides a stronger correlation peak. Directional ambiguity is eliminated by separating the two images of the particles into separate frames. Many correlation algorithms exist, but two-frame cross correlation performs best in terms of signal-to-noise ratio, spatial resolution, and dynamic range of velocity measurements.

Many methods exist to compute the cross-correlation of two images. The discrete cross-correlation function is the fundamental method. The discrete formulation of the cross-correlation function is given by:

$$\text{R}_{II}(x, y) = \sum_{i=K}^{K'} \sum_{j=-L}^{L'} I(i, j) I^*(i + x, j + y)$$  \hspace{1cm} (2.2)

for which $I$ and $I^*$ are the intensity values extracted from the images, and the region $I^*$ is larger than the region $I$. $I$ is shifted around $I^*$ (excluding edge regions), and a cross-correlation value $R_{II}(x, y)$ is calculated at each sample shift $(x, y)$. For shifts in which the images’ particles align with each other, the value of $R_{II}(x, y)$ will be high. $R_{II}(x, y)$ is a statistical measure of the degree of match between two images for a given shift. The highest value
of $R_{II}(x,y)$ indicates the appropriate shift for the sample images, and thus the particle displacement. This method can only be used to calculate linear shifts, so interrogation spots must be chosen accordingly.

Insight Stereo PIV v3.3 provides two software correlation engines for two-frame cross-correlation: Fast Fourier Transform (FFT) and the Hart Correlation. The FFT routine is used in most PIV evaluation methods because it is computationally more efficient than computing the cross-correlation function directly. The FFT method utilizes the fact that the cross-correlation of two functions is equal to the complex conjugate multiplication of their Fourier transforms, given by:

$$R_{II} \Leftrightarrow \hat{I} \cdot \hat{I}^*$$

for which $\hat{I}$ and $\hat{I}'$ are the Fourier transforms of intensities $I$ and $I'$, respectively.

The process is performed by taking the two-dimensional Fourier transform of the first interrogation spot and multiplying it by the complex conjugate of the second spot’s Fourier transform. The inverse transform is then calculated, giving the correlation function. The FFT method’s accuracy and efficiency are highly dependent on having fixed sample sizes (i.e., 32 x 32 pixel or 64 x 64 pixel interrogation spots) and the periodicity of the data, which introduce the potential for aliasing and bias error. Therefore, while the FFT method is quite accurate if the data are periodic and fixed sample sizes can be used, it cannot be employed for all PIV applications.

The Hart Correlation differs from other statistical evaluation methods because it uses a sparse array image correlation algorithm [71] that greatly reduces processing time for PIV images using image compression, and improves the sub-pixel displacement calculation. The sparse array technique takes advantage of the fact that the sub-pixel resolution of the particle displacement resides in the intensity of the pixels at the edges of the particle images. Therefore, it is not the absolute value of the pixel intensity that is important, but rather the relative change in intensity between the background and tracer particles. Low intensity, background pixels are eliminated from the data set using a threshold technique that sets a minimum intensity level for the pixels. Those values below the minimum are removed. Correlation speeds are greatly improved by encrypting the reduced data set into 32-bit integers, and using an error correlation function to eliminate multiplication, division, and floating-point arithmetic.

The Hart Correlation also differs from the FFT method by using correlation-based correction (CBC) processing [72], which allows the use of a recursive correlation scheme [73]. The FFT method, like many other methods, eliminates correlation errors by comparing vectors with their neighboring vectors to determine if they are statistically or physically consistent. The comparison relies on several assumptions [74], and discards correlation information before interrogation. Errors are eliminated from the data and are replaced by interpolated values.

CBC is a zero-dimensional correlation of two or more correlation tables in which errors can be eliminated before correlation information is discarded. A correlation table is first calculated from an interrogation region. Next, tables from additional regions, typically with 50% overlap with the first region, are calculated. The tables are multiplied together, and correlation values that do not appear in each table are
eliminated from the resulting table. The probability that the same anomalies (i.e., noise) would occur in different regions of the image is very low, and therefore correlation anomalies are eliminated from the data, regardless of their source. With the elimination of correlation values due to image anomalies, the peak correlation value is more easily discernible. The correlation peak found from CBC processing is weighted to the displacement of the tracer particles within the overlap of the combined regions, improving spatial resolution.

The size of the overlap region affects the ability of CBC processing to reduce correlation anomalies. As the size of the overlap region is decreased, the effectiveness increases. Insight Stereo PIV v3.3 uses a 50% overlap region. A 50% overlap region has been shown to produce exceptional results [72]. Most commonly used correlation algorithms also implement the 50% overlap region [75], and thus no increases in computational resources are required to implement this scheme.

The advantages of CBC processing over conventional techniques culminate in a reduction in bias errors and spurious vectors, with improved subpixel accuracy and greater vector yields. Spurious vectors often result from unmatched particle pairs, out-of-plane motion, particle overlap, inter-particle correlations, and electronic and optical imaging noise. CBC processing enhances signal-to-noise ratio, thereby increasing the number of valid vectors calculated, but also allowing spurious vectors to be more easily detected and removed. The increase in signal strength also allows the use of smaller interrogation spot windows (i.e., 4 x 4 pixel areas). The use of CBC processing allows the Hart Correlation to implement recursive correlation. Recursive correlation [73] iteratively solves for the local particle displacements. First, a region is correlated. Next, the interrogation window spot is reduced in size and offset by the previous result. Finally, the original window is re-correlated with the new spot window over a reduced region.

For the present study, images were loaded into Insight, and the appropriate $\Delta t$ (Table 2.1) was entered. The first step in evaluating the images was to calibrate the software to calculate velocity. The calibration factor for converting from pixel measurements to meters was computed by entering the distance (mm) between two objects in the flow field (i.e., fins) and measuring the number of pixels between the same objects using a cursor tool.

Next, a peak search/correlation algorithm was selected. For the results presented in this thesis, two-frame cross-correlation was performed using the FFT algorithm with a Gaussian peak-searching routine. While the Hart Correlation produced results identical in flow structure and magnitude for the side-view images, it failed to perform as well as the FFT for the end-view images. The end-view images show the development of the spanwise-transverse velocity distribution across the fins. The flow in these images contains large velocity gradients due to the introduction of streamwise vortices by the VGs. The Hart Correlation has been shown to perform poorly in high velocity gradient flows [72]. The spatial resolution that could be achieved by the Hart Correlation was superior to the FFT in all cases, but the benefit of additional spatial resolution was not required for these images.

Four parameters must be entered into Insight to perform the FFT: spot size, aspect ratio, x-distance between columns, and y-distance between columns. The spot window size in this technique is fixed between frames “a” and “b”, but the spot window from the second frame can be offset from the first window through
additional program options. The aspect ratio sets the ratio of the vertical to horizontal pixels in the interrogation spot. The aspect ratio was fixed at a value of unity in all processing performed in this study. The x-distance and y-distance between columns refers to the displacement of consecutive spot windows, and thus their overlap. For the current study, 32 x 32 pixel spot windows with overlaps of 50% were used for the majority of the end-view image processing, and for all of the side-view processing. For end-view images in which the tracer particle seeding was poor, or the light sheet did not adequately illuminate the full field of view, a spot window size of 64 x 64 pixels with an overlap of 75% was required (Table 2.2). In all cases, the Nyquist sampling criterion was satisfied. For PIV image sampling, the Nyquist criterion is as follows:

\[
\Delta X \leq \frac{\Delta X_o}{2} \\
\Delta Y \leq \frac{\Delta Y_o}{2}
\]

(2.4)

for which \(\Delta X\) is the x-distance between rows, \(\Delta Y\) is the y-distance between rows, \(\Delta X_o\) is the x-dimension of the spot window, and \(\Delta Y_o\) is the y-dimension of the spot window.

The values for the spot size parameters were approximated using estimates of the flow field velocity, and were optimized for each experimental data set by trial-and-error. To validate the correlation functions, several signal level parameters are required and are listed in Table 2.3. Spot window offsets were not employed in the FFT processing because the results were exceptionally good without the offset. Further, to implement an offset, an a priori knowledge of the flow field under investigation must be known. For the end-view images, this was not the case. Consistency in processing of the images was deemed more desirable than the slight benefit that an offset would have offered for the side-view images.

Areas in the images where fin boundaries exist produce poor correlation values. Tracer particles are often not seeded well in the corresponding boundary layers, or particles deposit on the surfaces. To eliminate the potential effects of the poor tracer particle behavior near the boundaries, the fins were removed from interrogation by Insight’s polygon editing tool. Polygon editing allows the user to select areas of the flow field that are not to be interrogated simply by drawing boxes around those regions. Correlation values are not computed in the edited regions.

Each velocity field calculated is further validated through a standard deviation filter and a local mean filter. The standard deviation filter eliminates vectors that have a standard deviation greater than the specified tolerance. In the present study, the tolerance was three. The mean filter computes an average of the U and V components of the velocity vectors surrounding a point which has been left blank from either failed signal-to-noise ratio or the through the use of the standard deviation filter. For the present study, the tolerance of the neighborhood mean filter was two. The holes were filled by interpolating over neighborhood sizes of 3 x 3 pixels.

2.4.5 Post-Processing

After image evaluation was performed, the velocity data were read into Tecplot v8.0 using TSI’s TecPIV macro. TecPIV allows the user to view Insight 2D and 3D vector files and compute flow properties.
Using the TecPIV macro, and other Tecplot features, instantaneous and averaged velocity and vorticity plots were created. The vorticity was calculated with a central differencing scheme applied to:

\[
\begin{align*}
\omega_Z &= \left( \frac{\partial V}{\partial X} \right) - \left( \frac{\partial U}{\partial Y} \right) \\
\omega_X &= \left( \frac{\partial W}{\partial Y} \right) - \left( \frac{\partial V}{\partial Z} \right)
\end{align*}
\] (2.5)

in which \(\omega_Z\) is the spanwise vorticity and \(\omega_X\) is the streamwise vorticity.

The areas where fins are located in the flow field images are indicated by the black rectangular boxes drawn in the plots. In the case of the side-view images, the flow within approximately 0.5 mm of the center fin was difficult to interrogate due to image distortion (Figure 2.13). The edges of the holes in the base plates where the fins are attached caused this distortion. The outlying fins do not have this problem because of image parallax. For the end-view images, the resolution of the velocity field near the fin surfaces fluctuates between image sets due to the variation of particle seeding and light sheet quality.

2.4.6 Measurement Uncertainty

Prasad et al. [76] performed the first extensive study on the effects of resolution on the accuracy of PIV measurements. The authors found that two types of errors are common in PIV measurements: mean bias errors and random errors. Mean bias errors occur from inadequate pixel resolution, while random errors result from particle imperfections, the recording process, and the interrogation process. The bias error was generally smaller than the random component, in some cases by an order of magnitude. The random component of the error was found to be approximately 10% of the particle image diameter, \(d_\tau\). The particle image diameter is defined as:

\[
d_\tau = \sqrt{(M \cdot d_p)^2 + (2.44 \cdot f^{\#} \cdot (M + 1) \cdot \lambda)^2}
\] (2.6)

for which \(M\) is the magnification, \(d_p\) is the true particle diameter, \(f^{\#}\) is the f-number defined as the ratio between the focal length and the aperture diameter, and \(\lambda\) is the wavelength of the laser light.

For the present study, \(d_\tau = 12.3 \mu m\) for the side-view images (\(M = 0.16, f^{\#} = 8\)), and \(d_\tau = 11.5 \mu m\) for the end-view images (\(M = 0.11, f^{\#} = 8\)). Using Prasad et al.’s [76] findings, the measurement uncertainty for the present study can be approximated as one-tenth of \(d_\tau\). For the side-view experiments, the maximum velocity experienced in the side-view images corresponds to a displacement of 180 \(\mu m\). The uncertainty in this case is therefore 6.8% for the side-view experiments. Similarly, the end-view experiments have a maximum displacement of 600 \(\mu m\), producing an uncertainty of 1.9%. 

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## 2.5 Tables

### Table 2.1: Timing parameters for PIV experiments

<table>
<thead>
<tr>
<th>Experiment:</th>
<th>Baseline Side-View</th>
<th>Two-VG Side-View</th>
<th>Two-VG End-View</th>
<th>Two-VG End-View</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>All locations</td>
<td>All locations</td>
<td>X' = 0, 0.5, 1, 1.5, 2, 5, 5.5</td>
<td>X' = 2, 4, 6, 8</td>
</tr>
<tr>
<td>Re</td>
<td>∆t [μs]</td>
<td>∆t [μs]</td>
<td>∆t [μs]</td>
<td>∆t [μs]</td>
</tr>
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<td>1025</td>
<td>5,000</td>
<td>5,000</td>
<td>17,000</td>
<td>20,000</td>
</tr>
<tr>
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<td>5,000</td>
<td>17,000</td>
<td>20,000</td>
</tr>
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<td>15,000</td>
<td>15,000</td>
</tr>
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<td>15,000</td>
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</tr>
<tr>
<td>1780</td>
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<td>3,000</td>
<td>10,000</td>
<td>10,000</td>
</tr>
<tr>
<td>2450</td>
<td>2,500</td>
<td>1,500</td>
<td>6,000</td>
<td>6,000</td>
</tr>
</tbody>
</table>

### Table 2.2: Interrogation spot parameters for end-view images

<table>
<thead>
<tr>
<th>X'</th>
<th>Spot Size [pixels]</th>
<th>Overlap [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>32</td>
<td>50</td>
</tr>
<tr>
<td>0.5</td>
<td>64</td>
<td>75</td>
</tr>
<tr>
<td>1</td>
<td>32</td>
<td>50</td>
</tr>
<tr>
<td>1.5</td>
<td>64</td>
<td>75</td>
</tr>
<tr>
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<td>32</td>
<td>50</td>
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<td>2.5</td>
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<td>75</td>
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<td>75</td>
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<td>32</td>
<td>50</td>
</tr>
<tr>
<td>8</td>
<td>32</td>
<td>50</td>
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</table>

### Table 2.3: Signal level parameters

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak/Zero Peak</td>
<td>0</td>
</tr>
<tr>
<td>Peak/Noise Peak</td>
<td>1.5</td>
</tr>
<tr>
<td>Peak/Avg. Intensity</td>
<td>0.1</td>
</tr>
<tr>
<td>Signal Cutoff</td>
<td>0</td>
</tr>
</tbody>
</table>
2.6 Figures

Figure 2.1: Water tunnel schematic

1. Plenum
2. Honeycomb
3. Contraction
4. Test Section
5. Dye Reservoir
6. Electrical Cabinet
7. Pump
8. Return Plenum
Figure 2.2: Spanwise water tunnel mean velocity distribution

Figure 2.3: Vertical water tunnel mean velocity distribution
Figure 2.4: Spanwise water tunnel turbulence intensity (%) distribution

Figure 2.5: Vertical water tunnel turbulence intensity (%) distribution
Figure 2.6 Offset-strip fin array geometry and nomenclature for the current study. The placement of the VGs in the Two-VG array is indicated by the gold lines. $S = 2.54\, \text{cm}$, $L = 2.54\, \text{cm}$, $t = 3.175\, \text{mm}$

Figure 2.7: Laser sheet illumination of flow through the array (a) without transparent fins and (b) with transparent fins. Laser light enters the array from the right.
Figure 2.8: Two-VG enhanced fin and additional fin dimensions. \( L = 2.54 \text{ cm}, b = 2.54 \text{ cm} \)

Figure 2.9: Schematic showing the principle behind PIV. Schematic taken from Raffel et al. [63]
Figure 2.10: Optical layout of Surelite III PIV Nd:YAG laser

1. HR Mirror
2. Pockels Cell
3. λ/4 Plate
4. Dielectric Polarizer
5. Head
6. Gaussian Mirror Output Coupler
7. Compensator
8. Shaping Lenses
9. λ/2 Plate
10. 45° Mirror, 1064 nm
11. Polarizer
12. Second Harmonic Generator
13. 45° Mirror, 532 nm

Figure 2.11: Experimental setup for PIV

Flow

Test Section

Sheet-Forming Optics

Articulated Light Arm

CCD Camera

Turning Mirror

Nd:YAG Laser

Synchronizer

Computer
Figure 2.12: $X^*$ locations for end-view images ($X^* = X/L$)

Figure 2.13: PIV image distortion due to the base-plate holes where the fins are attached; fins 1 and 2
Chapter 3: Results and Discussion

Chapter 3 is divided into two sections. The first section discusses the results of the flow visualization experiments, and the second discusses particle image velocimetry (PIV) results. Both the flow visualization and PIV results are compared to naphthalene sublimation (i.e., mass/heat transfer) data provided by Ge [61].

Flow visualization provided initial guidance for the current study. Flow visualization results were used to identify Reynolds numbers at which the flow through the array was laminar, “turbulent,” or in a transitional range in which periodic, spanwise vortex shedding occurred at various fin locations in the array. The flow visualization results also provided a comparison with results from the literature [1]. PIV measurements were obtained in order to quantify the streamwise velocity and vorticity fields, something which flow visualization is incapable of providing. PIV also allowed visualization and quantification of the spanwise velocity and vorticity fields. Flow visualization was ineffective for this view due to diffusion of the colored dye. To the author’s knowledge, this is the first experimental work on interrupted-fin geometries in which PIV has been applied.

3.1 Flow Visualization

Experiments have been performed for a variety of cases for the baseline fin array and VG configuration. Initial experiments examined the offset-strip fin array used by DeJong [1] in order to validate the flow visualization methods. DeJong’s array differs from the array used in the current study only in the spacing between fins (S), which was 1.27 cm in DeJong’s study. Flow visualization experiments performed herein showed results similar to those published by DeJong. Experiments next focused on the baseline array. Vortex shedding in this array begins around Re = 1500, while DeJong’s array began shedding around Re = 500. This difference from the DeJong array prompted an investigation of flow around a single fin, and a single row of fins, to see if the spacing in the current array was too large, and thus the array was acting either as single fins, or as single rows of fins. The flow visualization results indicated that the array spacing was not so large as to cause the fins to behave independently of one another. Experiments then turned toward enhancing the baseline array by using VGs and varying the number and placement of the VGs. The following sections describe the flow visualization results for the baseline array and the Two-VG array, the best performing VG-enhanced array studied to date. The fin rows (vertically oriented) in the channels investigated are labeled one through eight, as indicated by Figure 3.1. Naphthalene sublimation data for a Four-VG array are also presented in this section. The Four-VG array performs better than the Two-VG array with respect to heat transfer. The Four-VG array was not investigated with flow visualization or PIV experiments because this configuration was conceived of much too late in the project.

3.1.1 Baseline Array

As described in section 2.3, dye was impinged on the leading fin between channels 5 and 6 (Figure 2.6). The results for the baseline array show that the flow through the array is laminar up to a Reynolds number near 1500. At Re = 1550, the flow becomes wavy at the last fin, fin 8. Figure 3.2 shows the waviness of the dye shed from the trailing fin at this Reynolds number. At Re = 1590, the flow through the array begins shedding periodic vortex structures at fin 3, as shown in Figure 3.3. Spanwise vorticity is clearly indicated by the periodic, alternate shedding of the vortices. The fluid sweeps across the leading edge of each fin, and rolls
up along the length of the fins. Due to limitations of the water tunnel controller, precise Reynolds numbers at which shedding first occurs for each fin in the channel could not be determined, but it is clear, nonetheless, that the transitional Reynolds number range of the fin array is very small. At \( Re = 1780 \), the dye begins to diffuse out of channels 5 and 6, effectively mixing with fluid in the neighboring channels; Figure 3.4 shows vortex shedding from fin 1, and larger spanwise vortex structures than at \( Re = 1590 \). The flow structure seen at \( Re = 1780 \) is referred to as “turbulent” in the literature, although this flow is not turbulent in the true sense of the word. The flow structure at higher Reynolds numbers looks similar to \( Re = 1780 \), and the mixing of fluid between channels continues to increase with increasing Reynolds number.

Naphthalene sublimation results provided by Ge [61] offer additional insight to the flow characteristics of the baseline array. A description of the naphthalene sublimation technique can be found in DeJong [1]. Using the naphthalene sublimation technique, the location of vortex shedding in the array is revealed by a dramatic increase in Sherwood number from one fin to the next. Therefore, when a fin in the array begins to shed vortices, the fin immediately downstream will experience a large increase in heat transfer. To make mass/heat transfer measurements in the offset strip array, selected fins were cast with naphthalene. The cast sides of the fins were oriented inward toward channels 5 and 6. Figure 3.5 shows the placement of naphthalene-cast fins in the array. The green surfaces indicate the “top” surfaces of the fins, while the red surfaces indicate the “bottom.” The naphthalene sublimation data will be presented in terms of top and bottom surfaces. The baseline array is symmetrical, and therefore only the inward-facing surfaces of channel 6 were investigated to determine the total heat transfer of the fins in this array.

Figure 3.6 shows the plot of Sherwood number as a function of fin number for the baseline array. As low as \( Re = 1020 \), Figure 3.6 indicates that vortex shedding may be present in the baseline array. At \( Re = 1020 \) and 1200, a slight increase in the Sherwood number (within the uncertainty of the measurement) from fin 6 to 7 suggests the possibility weak spanwise vortex shedding in the rear of the array. The flow visualization results do not show vortex shedding at Reynolds numbers below 1550; however, this lack of apparent shedding may be due to the inherently limited flow-structure resolution of the dye-in-water flow visualization technique. At \( Re = 1620 \), vortex shedding clearly occurs at fin 5, as indicated by the large increase in Sherwood number at fin 6. A slight increase in Sherwood number from fin 3 to 4 suggests that vortex shedding for this Reynolds number may be occurring at the third fin in the channel as well. This latter result is consistent with the flow visualizations, which show that vortex shedding occurs at all fins in the array by \( Re = 1590 \). Figure 3.6 suggests that the onset of vortex shedding moves to fin 2 at \( Re = 2040 \), which is also consistent with the flow visualizations. The naphthalene sublimation results thus compare favorably with the flow visualization data.

### 3.1.2 Two-VG Array

To investigate the impact of streamwise vortices on the offset-strip array performance, the addition of two VGs was made to each of the leading fins of the array. This enhanced array is thus called the Two-VG array (Figure 2.7). The spacing between VGs was two inches, tip-to-tip. Placing VGs across the inlet to the array is a realistic design configuration. For VGs to be effective in a large array, multiple VGs must be used. If only a few VGs are used in an array of hundreds of fins, the VG enhancements will be damped by viscous
effects in the array. Further, the inclusion of a single VG in the array requires an additional stamping process during the fin manufacturing process, and thus it would be more practical to make as many VGs in this extra process as necessary for the highest heat transfer enhancement. Only two VGs of the current size and spacing can be placed on each fin surface in our study due to the fin size (i.e., spanwise length). For the Two-VG experiments, the flow visualization dye was impinged on the apex of a VG located in channels 5 and 6 of the array (Section 2.3).

Flow visualization studies of the Two-VG array show that the flow through the array is laminar up to approximately Re = 1550, at which point the wake becomes wavy. At Re = 1610, oscillations begin from fin 7, and by Re = 1670, spanwise vortex shedding occurs throughout the array. Figures 3.7 and 3.8 show the trailing fins of the Two-VG array at Re = 1550 and 1610, respectively. Figure 3.9 shows the flow for the entire array at Re = 1670. Figures 3.10 and 3.11 show well-mixed flow in the Two-VG array at Re = 2040 and 2420, respectively. As for the baseline array, increasing the Reynolds number beyond 1670 enhances the diffusion of dye into adjacent channels. The spanwise flow structures are also seen to have enlarged, and are more distinct, at the higher Reynolds numbers.

The presence of streamwise vortices in the Two-VG array can be seen in the form of long spiraling strands of fluid in the top channel (channel 6). The strands appear coherent throughout the length of the array at Re ≤ 1610. Because spanwise vortices are absent, or very weak, at these lower Reynolds numbers, the effect of the streamwise vortices should only be beneficial to the fin heat transfer by complementing the natural boundary layer restarting that occurs in offset strip arrays. The potential for enhancement appears to diminish as the Reynolds number is increased beyond Re = 1610 in this array. At these higher Reynolds numbers, spanwise vortices begin to shed in the Two-VG array. The spanwise and streamwise vortices appear to interfere with each other. This interference is demonstrated by the destruction of the long spiraling strands of streamwise vortices (Figure 3.9). The long spiraling strands begin to thicken as the spanwise structures push away from the fin surfaces. This thickening is indicative of the strands diffusing away from their core. As Reynolds number is increased, the strands first begin to disappear near the rear of the array, where they are replaced by spanwise structures.

As Reynolds number increases further, the destruction of the strands continues to move back toward the leading fin of the channel, where the streamwise vortices persist at all Reynolds numbers investigated (Figures 3.9-12). The location where the spiraling strands first begin to break apart is shown by a sharp, upward bulge in the dye-streak. In Figure 3.9, the location of the bulge occurs over fin 5. A slight increase in Reynolds number pushes the location further upstream to fin 3 (Figure 3.12). At Reynolds numbers above approximately Re = 1720, the strands fail to reach the third fin before they are destroyed by interference from the spanwise vortices (Figures 3.10 and 3.11).

Comparing the flow visualizations of the baseline array to the Two-VG array, oscillations from the trailing fin are seen to begin at Re = 1550 for the baseline array, and at Re = 1610 for the Two-VG array. The oscillations are delayed in the Two-VG array due to the interference of the streamwise vortices with the spanwise vortices. Figures 3.4 and 3.12 show flow visualizations for Re = 1780 for the baseline array, and
Re = 1720 for the enhanced array, respectively. Streamwise vortex generation has clearly limited the growth of spanwise shedding in the top channel of the Two-VG array. Even at Reynolds numbers as high as 2420 in the Two-VG array (Figure 3.11), the growth of the spanwise structures fails to surpass the size of the structures seen in Figure 3.4 for the baseline array at Re = 1780. Thus, the flow visualization results over the Reynolds number range investigated indicate that the VGs may be effective for heat transfer enhancement at lower Reynolds numbers, for which the spanwise vortices are not dominant. However, at higher Reynolds numbers, the spanwise and streamwise vortices interfere, possibly degrading the heat transfer capability of the fins when compared to the baseline array.

The Two-VG array does not have the heat transfer symmetry between the top and bottom fin surfaces that occurs in the baseline array. To obtain the overall heat transfer of the fins in this array, both the top and bottom surface heat transfer were measured to determine the average for each fin (Figure 3.5). Figure 3.13 shows the average fin-by-fin Sherwood numbers over a large range of Reynolds numbers for the enhanced array. For Reynolds numbers of 1230 and smaller, the data indicate no vortex shedding. At Re = 1640, vortex shedding appears to occur at fin 5. At Re = 2040, the shedding has moved to fin 2. The naphthalene sublimation data in Figure 3.13 thus agree with the flow visualization results.

The heat transfer enhancement potential of the Two-VG array is illustrated in Figures 3.14-19, in which fin-by-fin heat transfer enhancement is presented for both sides of the fins using the nomenclature of Figure 3.5 for various Reynolds numbers. While the Reynolds numbers at which naphthalene sublimation data were acquired for the Two-VG array do not all match precisely with the baseline Reynolds numbers, the Reynolds number differences are quite small (within 3% for the worst case), and therefore they can be compared as if they were the same with confidence. The placement of fins in Figures 3.14-19 is not drawn to scale to facilitate readability of the figures. The VGs are attached to the leading edge of the top surface of fin 1. The three columns shown in each figure, in which a column represents the four fins that run left to right, represent a repeatable symmetry unit within the array. The enhancement is computed by dividing the top (green) and bottom (red) surface Sherwood numbers of the Two-VG array by their counterpart Sherwood numbers from the baseline array and converting the resulting enhancements to a percentage difference of the heat transfer in the two arrays.

Figures 3.14-19 show a positive enhancement to the Sherwood number on the top surface of fin 1 at all Reynolds numbers except Re = 410. The enhancement is clearly the result of boundary layer thinning from the streamwise vortices that are generated by the VGs. The spiraling motion of the vortices is responsible for circulating freestream fluid within channel 6, and thus pushing the flow into and away from the top and bottom fin surfaces of this channel. The small heat transfer decrement to the top surface of fin 1 at Re = 410 is most likely due to the relatively small magnitude of the velocity that enters the array, and the correspondingly weak streamwise vortices, at this Reynolds number. This hypothesis is supported by observations from Figures 3.20 and 3.21, which show flow visualizations of the Two-VG array at Re = 590 and 1180, respectively.

The magnitude of the velocity is directly related to the thickness of the boundary layer that develops on fin 1. The boundary layer thickness at the trailing edge of fin 1, approximated with the Blasius solution for a
flat plate, is 6.5 mm at Re = 590 (Reₙ = 380). At Re = 1180 (Reₙ = 760), the boundary layer thickness is 4.6 mm. The flow visualization at Re = 590 shows the dye-streak of the streamwise vortices resting closer to the top surface of fin 1 than it does at Re = 1180 and above (Figures 3.7-12). This result, coupled with the 2 mm difference in boundary layer thickness, suggests that the streamwise vortices at Re = 590 are contained within the boundary layer of fin 1. Streamwise vortices confined within boundary layers are not capable of exchanging freestream fluid with the boundary layer fluid, and therefore do not enhance the fin heat transfer significantly. Thus, the only effect acting on fin 1 at Re = 590 is the blockage of channel 6 by the VGs, which is certain to cause recirculating regions immediately behind the VGs on fin 1. At Re = 1180 (Figure 3.21), the decrease in boundary layer thickness allows the streamwise vortices to escape the boundary layer and enhance the heat transfer on fin 1, as evidenced by the heat transfer results in Figure 3.16.

The bottom surface of fin 1 has opposite enhancement results than the top surface. At all Reynolds numbers, the bottom surface of fin 1 has a heat transfer decrement which can be explained with the help of Figure 3.22. Figure 3.22 illustrates the behavior of the flow entering the Two-VG array. The VG varies in depth-into-the-page, and the incoming flow to channel 6 is retarded where this blockage occurs. A high-pressure (HP) zone is created near the VG, and this HP region causes the flow that approaches channel 6 to divert into the lower channel flow (channel 5) where the pressure is lower (LP). The diversion of upper channel flow into channel 5 effectively pushes the lower channel flow away from the bottom surface of fin 1, and thus flow separation occurs on this surface.

Figures 3.14 and 3.15 show the enhancement behavior at Re = 410 and 1025, respectively. For both Reynolds numbers, the flow in the baseline array is laminar, with no spanwise vortex shedding. The heat transfer enhancement in both figures is positive at all fins after fin 1, with the magnitude of the enhancement higher for the higher Reynolds number. The top surfaces of the fins in channel 6 show the greatest overall enhancement in the array, with the maximum occurring at fin 3 for both Reynolds numbers. Gentry [6] states that the streamwise vortex circulation from VGs increases as Reynolds number increases, and thus improves the ability of streamwise vorticity to bring freestream fluid into the boundary layer. Gentry’s observations resulted from studies of VGs on a flat plate in channel flow, which differs from the present experiments. However, the observation also seems to hold true for the offset strip fin array in the laminar flow regime. The decrease in enhancement seen on the top surfaces in channel 6, moving downstream through the array, can be attributed to viscous effects damping the strength of the streamwise vortices. Although the VGs only induce streamwise vortices in channel 6 (within the array symmetry unit consisting of channels 5 and 6), heat transfer enhancement is seen on the bottom surfaces of channel 5 as well (except on fin 1) at the laminar Reynolds numbers Re = 410 and 1025.

Heat transfer enhancement can also be found in Figure 3.16, which shows the results for Re = 1230. Interestingly, the top and bottom surfaces of fin 2, and the bottom surface of fin 7, show a heat transfer decrement that is not consistent with the results at lower Reynolds numbers. The naphthalene sublimation data in Figure 3.6 suggest the possibility of spanwise vortex shedding at fin 6 in the baseline array. The occurrence of spanwise vortex shedding at fin 6 would explain the heat transfer decrement for the bottom surface of fin 7.
in the Two-VG array. Flow visualization at higher Reynolds numbers showed that the onset of spanwise vortex shedding was delayed in the Two-VG array due to an interaction of spanwise and streamwise vortices. Therefore, if spanwise vortices were sweeping over fin 7 in the baseline array at Re = 1230, their strength in the Two-VG array must be less, and perhaps the spanwise vortices are not even shedding from fin 6 in the Two-VG array, which seems consistent with the naphthalene sublimation data of Figure 3.13. This result would suggest that the interaction of spanwise and streamwise vortices has a negative impact on heat transfer in this Reynolds number range. The reason for a reduction in heat transfer at fin 2 for this Reynolds number is unclear from the flow visualization and naphthalene sublimation data. Similar to Figures 3.14 and 3.15 at Re = 410 and 1025, the maximum heat transfer enhancement for Re = 1230 also occurs on the top surface of fin 3.

The heat transfer enhancement at Re = 1630, Figure 3.17, differs from the results seen in the previous cases. At Re = 1630, only five of the fourteen surfaces show a heat transfer enhancement. The surfaces that show enhancement are the top surfaces in channel 6, along with the bottom surface of fin 2. Similar to Figures 3.14-16, the enhancement on the top surfaces of channel 6 decreases moving downstream through the array. The maximum enhancement, however, is on the top surface of fin 1. The bottom surfaces in channel 6 also show this trend, but differ from earlier Reynolds numbers because the enhancement at fin 2 quickly turns to a decrement at fin 4 and beyond. Enhancement on all of the surfaces in channel 6 is expected because the streamwise vortices spiral downstream in channel 6 and wash freestream fluid against both sides of the channel. Flow visualizations and the naphthalene sublimation data of Figure 3.13 both indicate the occurrence of spanwise vortex shedding at Reynolds numbers above 1610. As alluded to by the heat transfer results in Figure 3.16 at Re = 1230, the streamwise vortices and the development of spanwise vortices interact destructively in the Two-VG array for this Reynolds number range. The magnitude of the heat transfer decrement at Re = 1630 reflects the onset, and subsequent growth, of spanwise vortices between Re = 1230 and 1630.

The bottom surfaces of channel 5 at Re = 1630 show an opposite trend than the top surfaces of channel 6. These fin surfaces show improving heat transfer, with respect to the baseline case, moving downstream through the array, although the heat transfer is generally below that of the baseline. The increase can be attributed to the growing strength of the spanwise vortices in channel 5. The top surfaces adjacent to channel 5 also show a reduction in heat transfer at Re = 1630, as compared to the baseline case.

As for Re = 1630, the heat transfer results for Re = 2040 and 2450 (Figures 3.18 and 3.19) show some similarity to the trends established at Re = 1025 and 1230. The top surfaces in channel 6 show the same trend of decreasing enhancement moving downstream through the array. However, at both Re = 2040 and 2450 the data differ from earlier cases because the enhancement on these fin surfaces becomes a heat transfer decrement toward the end of the channel. This behavior was seen on the bottom surfaces of channel 6 at Re = 1630. The heat transfer behavior on the bottom surfaces in channel 5 at Re = 2040 and 2450 is similar to the behavior seen for Re = 1025, in which the difference in Sherwood number for the two arrays begins as a decrement, becomes an enhancement, and then decreases in enhancement magnitude moving downstream.

While the heat transfer behavior of fins 1, 3, 5, and 7 is consistent between Re = 2040 and 2450, the behavior of the remaining fins is not. At Re = 2040, the bottom surfaces in channel 6 show a heat transfer
decrement at all fins. The magnitude of the decrement decreases by the end of the channel. The heat transfer behavior of the top surface of fin 2 also shows a decrement, while the remaining top surfaces in channel 5 show an increasing enhancement moving downstream. This result is consistent with the heat transfer behavior observed at Re = 1025 and 1230. Interestingly, the maximum enhancement at Re = 2040 does not occur on the top surface of fin 3, as it did at Re = 1025 and 1230. Rather, the maximum enhancement is on the top surface of fin 1, as was seen for Re = 1630. At Re = 2450, the heat transfer trends for the remaining fins are opposite to Re = 2040, and instead are similar to Re = 1630, for which there was an increasing decrement for the heat transfer moving downstream through the array for fins 2, 4, and 6. The heat transfer for these fins at Re = 2450 decreases moving downstream, but the data still indicate enhancements, which differs from Re = 1630. The maximum enhancement in the array at Re = 2450 appears on the top surface of fin 1.

Figure 3.23 shows the Two-VG array performance-enhancement based on the average of all seven test-fins across the Reynolds number range investigated. Figure 3.23 includes data from an additional VG-enhanced array in which four VGs are located on each leading fin, thus called the Four-VG array. The Four-VG array is similar to the Two-VG array except that it employs an additional two VGs placed on the bottom surface and directly below the Two-VG delta-wings (Figure 3.24). The Four-VG array clearly demonstrates improved heat transfer at all Reynolds numbers, and lends credence to the trends seen in the Two-VG data: increasing enhancement with increased Reynolds number up to Re = 1025, then a decrease due to the onset of oscillations and spanwise vortex shedding, and finally an increase at high Reynolds numbers (Re > 1630). The maximum enhancement is on the order of 7% at Re = 1025 for the Two-VG array and 17% for the Four-VG array. Flow visualization experiments were not performed for the Four-VG array, but it is clear from the naphthalene sublimation data that the same trends seen in the Two-VG data would be expected for this array. Additional naphthalene data for Re > 2450, Figure 3.23, establish that the trend of returning enhancement for Re ≥ 1630 is real.

The trends established for the seven-fin average behavior of the Two-VG array present some interesting results. The enhancement of heat transfer at Reynolds numbers below 1025 establishes that the streamwise vortices can effectively improve mixing in the array, and therefore the heat transfer. This result is to be expected, as below Re = 1025, spanwise vortex shedding does not occur. The effect of the streamwise vortices is to couple with the boundary layer restarting enhancement that is characteristic of interrupted-fin geometries. Beginning at Re = 1230, and continuing through Re = 1630, the heat transfer data show a decrease for the Two-VG array, compared to that at Re = 1025. This Reynolds number range has been shown to produce wake oscillations (Re = 1550), and periodic, spanwise vortex shedding (Re > 1550) in the baseline array in both the flow visualizations and Sherwood number plot (Figure 3.6). Therefore, the decrement is indicative of a destructive interaction between spanwise and streamwise vortices.

The seven-fin average results at Re = 2450, which show a heat transfer increase, are inconsistent with the trends seen for the transitional Reynolds number range. At Re = 2450, spanwise vortex shedding still occurs in the baseline array. Thus, the physics of the interaction between the spanwise and streamwise vortices...
somehow change between \( \text{Re} = 2040 \) and 2450. A further investigation into the effects of the array geometry and flow field would be beneficial to understanding the phenomena presented at \( \text{Re} = 2450 \).

The flow visualizations and naphthalene sublimation data agree well for both the baseline and Two-VG arrays; however, the flow visualization technique is limited in resolution. The dye-in-water experiments illuminate large-scale flow structures well, but fail to show the smaller scale structures, which might provide great insight into the heat transfer characteristics of the arrays under investigation. The discrepancies seen between the flow visualizations and naphthalene sublimation data for \( \text{Re} = 1025 \) and 1230 are an excellent example. Flow visualizations for these Reynolds numbers do not detect any oscillations in the flow, yet the naphthalene data detect a small (within experimental uncertainty), but distinct, increase in Sherwood number at fin 6. PIV measurements, in contrast to the dye-in-water flow visualizations, highlight small-scale flow features, and therefore provide a much clearer explanation for the trends seen thus far. The PIV results of this study are presented in the next section.

3.2 Particle Image Velocimetry

3.2.1 Introduction

As described in section 2.4.3, PIV images of the baseline and Two-VG arrays were acquired two fins per image in the side view, and at several \( X^* \) locations in the end view. A preliminary study of the side-view images investigated the effect of light sheet position with respect to the VGs. Figure 3.25 shows the three light sheet locations that were investigated. At location 1, with the sheet bisecting the gap between the VGs, the PIV measurements of the Two-VG array demonstrated great similarity to the baseline array measurements. Results at location 3, centered on the VG vertex, were similar to location 1. Location 2, which is located at the junction of the base of the VG and fin, showed substantial differences in flow structure between the two arrays. As will be shown in the end-view results, the counter-rotating vortices produced by the VGs tend to follow a path along the line defined by light sheet location 2. Locations 1 and 3 do not distinguish themselves well from the baseline results because the streamwise vortices do not exist at these locations. Therefore, all of the side-view data presented will be from location 2.

Before a thorough discussion of the PIV results can be presented, the quality of these images must be addressed. The quality of the images is presented in the form of “choice codes” (CHC). Every velocity measurement has a choice code, as assigned by the TSI Insight software. The value of the choice code reflects the history of the measurement. For example, if the CHC reads “one,” then the velocity measurement was computed from a first-peak correlation, which is the highest correlation peak in the FFT calculation. A CHC value of “two” would indicate a second-peak correlation, and “three” would indicate a third peak. A value of “four” is assigned to vectors that were interpolated by the validation scheme described in Section 2.4.4. A “Zero” value identifies vectors that did not pass the validation criteria and are awaiting interpolation. “Negative one” refers to vectors failing the signal-to-noise ratio (SNR) validation criteria (Table 2.3), while “negative two” indicates removed points. The removed points are areas where vectors were not computed because of polygon editing. Therefore, images with the fewest number of interpolated vectors, code “four,” are considered high quality.
Figures 3.26-29 present a range of choice-code quality for both the side-view and end-view images. Figure 3.26 shows the side-view CHC for Re = 2450, fins 3 and 4. The number of interpolated vectors is six out of 2381 measured vectors, which is equivalent to 0.25% of the measured vectors. Figure 3.27 shows fins 5 and 6 of the baseline array at Re = 1550. In this image, 98 out of a possible 2503 measured vectors (3.9%) are interpolated. While Figure 3.27 has approximately 16 times the number of interpolated vectors as Figure 3.26, 96.1% first-peak vectors is still quite high, and is considered acceptable. Figure 3.28 shows the CHC for a sample Two-VG array end-view image, for which only one interpolated vector (far left side) was required out of a possible 1462 measured vectors (0.07%). Figure 3.29 shows the worst-case image for the Two-VG array end-view images. This image was obtained at X* = 1 for Re = 1590. For this worst-case, only 51 of 1529 measured vectors (3.3%) were interpolated. Once again, this maximum is acceptable.

While both the baseline and Two-VG arrays were fully characterized in the side-view, only the Two-VG array was fully characterized in the end-view. Preliminary baseline array end-view images demonstrated that the effects of three-dimensionality (spanwise-transverse velocity and streamwise vorticity) in the baseline array are minimal with respect to the Two-VG array. Figures 3.30 and 3.31 show end-view velocity magnitude and vorticity, respectively, for the baseline array at Re = 2450 and X* = 0.5. In both images, part (a) displays the results for the baseline array, while (b) shows the results for the Two-VG array. The gold triangles located above (b) indicate the spanwise location of the VGs in channel 6 of the Two-VG array, but do not reflect the transverse location, since the VGs are actually mounted on the middle fin in the end views at the entrance to the array (i.e., fin 1). The size of the triangles reflects the relative size of the VGs with respect to channel 6. In all end-view images, the main flow component (U) is directed out of the page. Velocity magnitude was computed by:

\[ \|V\| = \sqrt{V^2 + W^2} \]  

(3.1)

where V is the transverse flow component (along the y-axis), and W is the spanwise flow component along the z-axis. For the side-view images, W is replaced by U, the main flow component in the array, in Eq. 3.1.

In Figure 3.30, the velocity magnitude range in the Two-VG array is 0-0.025 m/s, which is nearly eight times the scale in the baseline array. The streamwise vortices, which are so clearly present at Re = 2450 in the Two-VG array, are non-existent in the baseline array. The baseline measurements appear to have increased three-dimensionality (i.e., V-W velocity magnitude) toward the sides of the image, but this increase in velocity magnitude is only due to the effects of the water tunnel sidewalls. Figure 3.31 similarly shows that the baseline images contain no organized streamwise vorticity as compared to the Two-VG measurements. The vorticity scales differ by a factor of 15. The results demonstrated by Figures 3.30 and 3.31 are not surprising, considering the highly two-dimensional nature of the offset-strip geometry. As a result, the enhancement potential of streamwise vortices in the Two-VG array can be assessed without a characterization of the end views for the baseline array, since Figures 3.30 and 3.31 demonstrate extremely small V-W velocity magnitudes and \( \omega_X \) vorticity magnitudes for the baseline array at the highest Reynolds number studied.
PIV measurements were obtained at six Reynolds numbers and at a total of 15 locations between the end and side views. The Reynolds numbers were chosen to correspond with different flow regimes, as detected from the dye-in-water flow visualizations, and from the naphthalene sublimation data. Due to the large number of PIV measurements obtained in this investigation, the results are presented in order of increasing Reynolds number, and images that show similar trends to Re = 1025 are not repeated.

3.2.2 Re = 1025 Results

The flow for Re = 1025 and all lower Reynolds numbers is steady, and therefore the results for Re = 1025 are representative of all lower Reynolds numbers. The side-view characterization of the baseline and Two-VG arrays for Re = 1025 is given in Figures 3.32-41. Figures 3.32-36 show the velocity magnitude as the flow moves downstream through the arrays, beginning at fins 1 and 2, and ending in the wake of the array. At fins 1 and 2, Figure 3.32 shows laminar flow for both arrays. The range of values in the velocity magnitude are identical for the baseline and Two-VG arrays; however, there are differences in the structure of the flow passing over fin 1. The baseline array has a symmetrical velocity magnitude distribution, but the Two-VG array shows an asymmetry between channels 5 and 6. Channel 6 for the Two-VG case encounters a velocity magnitude deficit compared to the baseline case, especially above fin 1. The flow immediately behind the VG is significantly reduced in U velocity, as is clearly demonstrated by the large green contour region above fin 1. This finding correlates well with the flow visualizations, which show spiraling strands of fluid (presumably streamwise vortices) over fin 1 at Re = 1025.

The green velocity-deficit region for the Two-VG array disappears by fins 3 and 4, but the velocity deficit is still present; see Figure 3.33. Maximum values of velocity magnitude above fin 3 approach 0.03 m/s for the Two-VG array, but reach as high as 0.035 m/s for the baseline array. The baseline array results are still symmetrical, and remain symmetrical throughout the array. A slight increase in velocity magnitude is experienced for both the baseline and Two-VG arrays at fins 5 and 6, Figure 3.34, but the reduced-velocity magnitude region persists in channel 6 for the Two-VG array. Similar results occur at fins 7 and 8, and in the wake of the array, Figures 3.35 and 3.36. The slight velocity increase with streamwise position may be due to the growth of the sidewall boundary layers, which would reduce the core area of the array and thus require higher velocity for the same volumetric flow rate.

A closer look at the PIV results at fins 1 and 2, Figure 3.32, shows that the boundary layer thickness on the bottom surface of fin 1 is approximately 3 mm for the Two-VG array, while the corresponding thickness in the baseline array is about 2 mm. The thickening of the boundary layer in the Two-VG array was suggested by the naphthalene sublimation data (Figures 3.14-19), where a decrement in heat transfer on the bottom surface of fin 1 persists at all Reynolds numbers. Thus, the PIV measurements provide confirmation of the naphthalene sublimation data that the dye-in-water flow visualizations could not. The boundary layer thicknesses at all other fins are very similar between the two arrays. In summary, the velocity magnitude contours for both the baseline and Two-VG arrays suggest no instabilities or oscillations at Re = 1025. The flow is steady and laminar at this Reynolds number and all lower Reynolds numbers.
Spanwise vorticity contours provide some additional insight of the flow field at Re = 1025 (Figures 3.37-41). The vorticity contours for the baseline array are once again symmetric throughout the array, with the magnitude of the vorticity decreasing slightly moving downstream, Figures 3.37 (a)–3.41 (a). Similar to Figures 3.32-36, the most significant differences between the baseline array and the Two-VG array are found above fin 1. Whereas the spanwise vorticity above fin 1 in the baseline array shows a large approximately zero-vorticity region, the vorticity contours for the Two-VG array show two strands of negative-value vorticity. Between the two strands lies a core region with zero vorticity. The upper strand is clearly due to the vortex shed from the base of the VG in the laser-sheet illumination plane, while the lower strand is due to the boundary layer on the top of fin 1. The presence of the upper strand is the result of the streamwise vortex that passes over fin 1 in the laser sheet, but the strand itself does not define the streamwise vortex. The image is merely a “slice” through the vortex structure in which the negative vorticity is the result of the spiraling motion seen in the flow visualization results.

At fin 3, Figure 3.38, the upper strand is not present for the Two-VG array, and the majority of the spanwise vorticity in channel 6 has a zero value. The size of this zero-value region is significantly larger than in the baseline image. The baseline image shows a negative region in channel 6 that fills about half of the channel height from the top surface of fin 3 up. The negative region is expected due to the way in which the flow rolls over the top surface producing vorticity with direction into the page, in contrast to the lower surface where the opposite result (positive spanwise vorticity) occurs. Moving downstream through the array, Figures 3.39-41, the vorticity contours of the Two-VG array become increasingly similar to the baseline array, and in the wake of the Two-VG array, the vorticity contours are nearly identical.

The side-view results are naturally complemented by the end-view images obtained throughout the Two-VG array (Figure 2.12). Figures 3.42-3.52 detail the end-view results at Re = 1025. For each figure, the velocity magnitude is shown in (a), and the streamwise vorticity is shown in (b). Figure 3.42 shows the measurements obtained at X∗ = 0. At this location, large transverse velocities occur near the fin surfaces due to the diversion of freestream flow around fin 1 and into the array. A high-velocity region, similar to the VG in size and shape, is directed downward in channel 5 just below the VGs, Figure 3.42 (a). At this Reynolds number and location, all of the images in the ensemble were essentially the same: no oscillations or unsteadiness. In the discussion of heat transfer decrement on the bottom surface of fin 1 in section 3.1, the hypothesis of a high-pressure and low-pressure zone was presented, and Figure 3.22 was used to illustrate this. Figure 3.42, along with the boundary layer thickening seen in Figure 3.32, confirms the separation behavior hypothesized there.

Figure 3.43 reinforces these concepts at X∗ = 0.5. In channel 5, the dark blue contour regions indicate a uniform flow along the x-axis (perpendicular to the image), not to be mistaken as stagnating flow over fin 1 [part (a)]. In the remaining regions of channel 5, a heat transfer decrement on the lower surface of fin 1 is suggested by the direction of the velocity vectors. The flow that approaches the middle fin (fin 1) is turned horizontal to the fin surface. Heat transfer enhancement occurs on the top surface of fin 1, as seen in Figure
3.15. The enhancement is clearly the result of the downward motion of the counter-rotating vortices in channel 6. The flow remains steady at this location and throughout the array until the exit.

As the flow moves past fin 1 and into the gap between the top and bottom surfaces of fin 2, the vectors in channel 5 change direction and move up towards the leading edge of fin 3 (Figure 3.45). At the bottom surface of fin 3, where the heat transfer was consistently higher than at fin 1, Figure 3.47 shows the vectors in channel 5 moving down toward channel 4. Figures 3.43, 3.45, and 3.47 suggest that as the flow enters the array and experiences the pressure gradient imposed by the VGs, a large portion of the flow approaching channel 6 diverts into channel 5, separating the flow on the bottom surface of fin 1. The flow moves past fin 1, and is forced upward into the low-pressure zone which results on the downstream side of the VG. This upward flow washes against fin 3, and reduces the boundary layer thickness on the bottom surface of fin 3 from 2.5 mm to 2 mm. The downward vector motion seen in Figure 3.47 represents flow re-entering channel 5 after the pressures in the two channels equalize. Thus, the direction of the vectors in channel 5 at fins 1, 2, and 3 further reinforces the hypothesis presented in Section 3.1.

The remaining $X^*$ locations shown in Figures 3.44, 3.46, and 3.48-52 further describe the development of the velocity magnitude as the flow moves downstream through the array. The structure of the flow at $X^* = 1, 2, 4,$ and 6 is similar to that of $X^* = 0$, but the direction of the vectors oscillates up and down between different $X^*$ locations, and the strength of the flow structures decreases slightly moving downstream. The oscillations depend on whether the flow is leaving or approaching a central fin between channels 5 and 6. Similarly, the flow structure at $X^* = 5.5$ follows the trends set at $X^* = 0.5, 1.5,$ and 2.5, and experiences changes in flow direction and strength. Figures 3.51 and 3.52, obtained at the array exit, $X^* = 8$, present an interesting deviation from the previous images: the flow has become unsteady.

Figures 3.51 (a) and 3.52 (a) show two instantaneous images of the end-view velocity magnitude, and Figures 3.51 (b) and 3.52 (b) show the corresponding streamwise vorticity contours. Figure 3.51 (a) shows a large high-velocity pocket of fluid leaving channel 5 and entering channel 6, while Figure 3.52 (a) shows a smaller pocket leaving channel 6 and entering channel 5. Part (b) of Figure 3.36, the side-view image of velocity magnitude for the Two-VG array, does not show oscillations in the wake of the array; however, minor oscillations can be seen when the set of 100 images for this Reynolds number and location is examined. The corresponding set of side-view images for the baseline array reveals similar oscillations. The oscillations seen at the exit of the baseline and Two-VG arrays at this Reynolds number are most likely due to the sudden expansion of the flow as it leaves the arrays.

The naphthalene sublimation data of Figure 3.6 suggest the possibility of weak vortex shedding at fin 6 in the baseline array for $Re = 1020$, but not in the Two-VG array (Figure 3.13). Therefore, due to the general similarity of the flow fields between the baseline and Two-VG arrays, the determination of whether vortex shedding actually occurs at fin 6 in the baseline array at $Re = 1020$ remains unresolved. However, the slight increase in Sherwood number for the baseline array in Figure 3.6 is most likely due to the exit effects of the flow leaving the array. The streamwise vortices in the Two-VG array may be interacting with these exit effects, and therefore the naphthalene sublimation data of Figure 3.13 do not show an increase in Sherwood number.
Referring to the streamwise vorticity contours of the end-view images highlights additional information about the flow field interactions. Figures 3.42 (b) and 3.43 (b) show the VG-induced counter-rotating vortex pairs over fin 1. The vortex cores are centered approximately 4 mm above fin 1. In Figure 3.37, the presence of the spiraling vortices was detected through the laser-sheet “slice” over fin 1. A comparison of Figures 3.42 and 3.43 with Figure 3.37 shows that a green strand is located approximately 5 mm above fin 1, and thus the height of the vortex core can be correlated between the side-view and end-view images. It is important to note that if the side-view light sheet location had been placed on the opposite fin/VG junction, the flow would be spiraling in the opposite direction, and the green strand would have been red.

Similar to the velocity magnitude, the strength of the peak streamwise vorticity decreases from a maximum near 6 s\(^{-1}\) at the entrance of the array to a maximum of about 0.5 s\(^{-1}\) at the exit. Figure 3.53 shows the ensemble-averaged peak vorticity for Re = 1025 for several X* locations. The size of the vortices remains nearly constant between the entrance and exit, but the distance between the cores of the vortex pairs grows. The increase in the vortex core separation for Re = 1025 is shown in Figure 3.54. The figure shows a relatively sharp increase in separation distance between locations X* = 0 and 2, in which the distance grows from approximately 10 mm to 21 mm. This initial growth is then followed by a relatively constant 4 mm increase between locations X* = 2 and 8. These measurements were obtained using vorticity averages over 100 images at each location, including Figures 3.42-52. Because the flow is steady throughout the array, the mean vorticity images produce similar results as the instantaneous images presented. An example ensemble-averaged vorticity image is presented in Figure 3.55 at X* = 0.5 for comparison to Figure 3.43.

Figure 3.54 further establishes the need for the side-view light sheet to be located at the fin/VG junction, i.e., location 2 in Figure 3.25. The 15 mm increase in separation distance through the array indicates that the vortices each move a distance of 7.5 mm outward. With the distance between VGs equal to 25.4 mm, it is clear that streamwise vortices will not interact in the gap between VGs, making light-sheet location 1 inferior to location 2. Likewise, with the base length of the VGs also equal to 25.4 mm, no interaction will be seen at location 3, which is centered on the VG vertex.

### 3.2.3 Re = 1230 Results

The PIV measurements for Re = 1230 reveal similar trends to those at Re = 1025. At all locations, the velocity magnitude and vorticity measurements are proportionally higher than at Re = 1025, but the flow structure remains similar. The thickness of the boundary layer on the bottom surface of fin 1 remains larger in the Two-VG array than for the baseline array. Once again, the large VG wake region (green contour region above fin 1) is responsible for thinning the boundary layer and thereby enhancing the heat transfer on the top surface of fin 1. The velocity deficit region in the VG wake, which is present at Re = 1025, also remains. To avoid redrawing the same conclusions found for Re = 1025, only instances in which deviations from the Re = 1025 case occur will be discussed in this section.

The first deviation from Re = 1025 found at Re = 1230 occurs in the wake of the baseline array, as shown in Figure 3.56 (a). The increased velocity magnitude at Re = 1230 produces an unsteady flow with an oscillating wake shed from the trailing edge of fin 7 in the baseline array. The high-velocity flow appears to
bulge out of channels 5 and 6 and into other channels starting about one fin length downstream of the array. While very weak oscillations were noticeable in the wake for Re = 1025 due to the sudden expansion at the exit, the oscillations for Re = 1230 result from shear layer instabilities. Figure 3.57 shows two instantaneous vector fields of the baseline array wake flow. The mean velocity (U and V components from the vector-field average) has been subtracted from each vector. Several vortices are noticeable. The vortices roll up from each side of the trailing fin (fin 7). This behavior was not observed at Re = 1025.

The naphthalene sublimation data of Figure 3.6 suggest weak vortex shedding at fin 6. The PIV measurements indicate that the cause for the slight increase in Sherwood number is a result of shear layer instabilities in the wake. Oscillations were not observed in the dye-in-water flow visualization at Re = 1230 for the baseline array. Clearly, the PIV measurements surpass the ability of the dye-streak visualizations to detect small-scale oscillations in the flow.

Naphthalene sublimation data of the Two-VG array did not suggest any vortex shedding or instabilities for Re = 1230 (Figure 3.13), and Figure 3.56 (b) confirms this result as well. The flow from channels 5 and 6 exits the array uniformly and remains within the confines of the boundary layers of fin 8. The weak oscillations seen in the wake of the Two-VG array for Re = 1025 remain at Re = 1230 because of the sudden expansion. As suggested in Section 3.1, the suppression of oscillations at fin 7 in the Two-VG array is thus the cause of decreased heat transfer for Re = 1230 as compared to Re = 1025 (Figures 3.15, 3.16, and 3.23), and is certainly the cause of the heat transfer decrement on the bottom surface of fin 7. Of course, the top surface of fin 7 retains a decreased enhancement (relative to that at Re = 1025) due to the presence of streamwise vortices in channel 6. Figure 3.58 is included to further illustrate the development of oscillations in the wake of the baseline array. End-view images of the flow at Re = 1230 are similar to those at Re = 1025. The flow remains steady throughout the array until the exit, where the flow becomes unsteady. The separation between the vortex cores for Re = 1230 follows the same growth pattern shown in Figure 3.54 for Re = 1025, with a slight increase in separation distance at most locations.

3.2.4 Re = 1550 Results

The first deviation of the Re = 1550 measurements from both Re = 1025 and 1230 occurs at fins 5 and 6, as shown in Figures 3.59 (velocity magnitude) and 3.60 (vorticity). At this location, the flow between fins 5 and 7 in the baseline array has become unsteady. Oscillations first occur from fin 5, instead of in the wake of the array, and the oscillations appear greater in amplitude than the oscillations seen in the wake for Re = 1230 [Figure 3.56 (a)]. The Two-VG array does not experience oscillations until the wake (Figures 3.61 and 3.62). The oscillations in the wake of the Two-VG array have grown minimally from the Re = 1230 case [Figure 3.56 (b)], and now show some shear layer instability about one fin length downstream of the array exit when the ensemble of the modified vector fields is studied. The instabilities are similar to those of Figure 3.57, but not as strong. Along the x = 28 mm plane, Figures 3.61 and 3.62 show some odd patches of velocity and vorticity that seem out of place. These patches are due to image distortion from the downstream edge of the base plate that holds the fins in the array. The patches occur in areas in which the signal from the tracer particles was not
strong enough to be seen through the distortion at the plate edge. Despite the patches, the physics of the wake flow are easily detected.

Dye-in-water flow visualization indicated that oscillations began in the wake of the baseline array at Re = 1550. While the flow visualization is correct in showing oscillations in the wake, it did not show oscillations from fin 5. The differences noted from the flow visualizations between the baseline array and Two-VG array, however, hold true in the PIV measurements: suppression of oscillations for the Two-VG array. These results provide great insight into the heat transfer data of Figure 3.17. At Re = 1630, only five fin surfaces experienced a heat transfer enhancement within the Two-VG array. The remaining nine surfaces suffered a reduction of heat transfer, as compared to the baseline. Section 3.1 argued that the spanwise and streamwise vortices must be destructively interfering at Re = 1630. Despite the fact that the PIV measurements were obtained at a Reynolds number of 1550, the images corroborate the results of Section 3.1 and Figure 3.17 by establishing a trend in this transitional flow regime. In contrast to the flow visualization results, interference between the streamwise vortices and spanwise oscillations begins at fins 5 and 6 for the Two-VG array, as opposed to the wake, and thus the heat transfer at the fin surfaces upstream of the exit should be expected to decrease in comparison to the baseline, as shown in Figure 3.17. The trends seen in previous end-view images remain the same for Re = 1550.

3.2.5 Re = 1590 Results

For Re = 1590, oscillations within the baseline array begin at fin 3, where spanwise vortices roll off the trailing edge. The oscillations at fin 3 are clearly spanwise vortices, as demonstrated by the flow visualization results in Figure 3.3. Figures 3.63 and 3.64 show the velocity magnitude and spanwise vorticity, respectively, for Re = 1590 at fins 3 and 4. Once again, the Two-VG array does not experience the oscillations that are seen in the baseline array. The Two-VG array does not have oscillations until the wake; however, the oscillations are much larger in amplitude than for Re = 1550, and compare more favorably to the baseline results. Figures 3.65 and 3.66 show the wake of the baseline and Two-VG arrays. Interestingly, the Two-VG wake flow appears to bulge out of channel 6 and into channel 7 at the upper edge of the image. At the bottom of Figure 3.65 (b), a thin region of flow separation behind fin 8 also exists. A possible explanation for the exit behavior of the flow could be that the streamwise vortices have gained enough strength by Re = 1590 to persist throughout the array without being fully destroyed by the development of the spanwise vortices. The baseline wake flow shows a slight bulge downward toward channel 4, but this behavior is clearly the result of spanwise vortices, as seen by the oscillations in the vector field near the bottom edge of the image.

The heat transfer behavior in the Two-VG array at Re = 1590 is expected to approach the behavior at Re = 1630, due to the small difference in Reynolds number. The upstream movement of the onset of spanwise oscillations from fin 5 to fin 3 supports this belief. At Re = 1550, the end-view images offered no new insight into the heat transfer behavior. In contrast, the end-view images for Re = 1590 provide useful information. Figure 3.67 shows the velocity magnitude for both Re = 1550 [part (a)] and Re = 1590 [part (b)] at X* = 6. Figure 3.68 shows the corresponding plots of streamwise vorticity. The distribution of high-velocity flow at Re = 1550 (Figure 3.67) is uniform across the top of the middle fin, while the high-velocity flow at Re = 1590
exists in pockets behind the VGs. The primary difference between the two Reynolds numbers, however, is not discernible from one instantaneous image because the flow at Re = 1590 is unsteady and oscillatory, while at Re = 1550 it is steady.

At lower Reynolds numbers, unsteadiness was always present at X^* = 8, and was most likely due to the sudden expansion of the flow exiting the array. For unsteadiness to occur at X^* = 6, something else must be the cause. Perhaps the cause is related to how the strength of the spanwise vortices influences their interactions with the streamwise vortices. At Re = 1590, shedding begins at fin 3, and therefore has several fin lengths to develop before reaching X^* = 6, whereas at Re = 1550, oscillations begin near X^* = 6.

At Re = 1550, the top surface of fin 7 experiences a relatively uniform, and steady, distribution of high-velocity flow, similar to Figure 3.67. The flow structure changes as Reynolds number is increased to Re = 1590. At this Reynolds number, the high-velocity V-W flow exists in pockets that have a width approximately equal to the base dimension of the VGs. The location of the pocket changes with time, alternating from the top surface of fin 7 to the bottom. In Figure 3.67, this pocket is located on the top surface of fin 7 immediately behind the VGs. In addition, the small increase in Reynolds number from 1550 to 1590 produces a large increase in velocity magnitude (9 mm/s maximum to 14 mm/s). The streamwise vorticity contours for Re = 1550 and 1590 at X^* = 6 (Figure 3.68) are more similar in magnitude than the velocity magnitude; however, the unsteadiness at Re = 1590 introduces more random, larger magnitude, streamwise vorticity adjacent to the fins. The counter-rotating pairs at Re = 1550 are still discernible at Re = 1590, but the areas between these structures are speckled with increased small-scale vorticity.

PIV measurements at X^* = 8 present more profound differences between the flow at Re = 1550 and 1590. Figures 3.69 and 3.70 show the end-view velocity magnitude and streamwise vorticity at X^* = 8, respectively, for the Two-VG array. The velocity magnitude for Re = 1550 shows a flow dominated by the stagnating V-W flow (blue contours), whereas Re = 1590 has large high-velocity V-W magnitude pockets located in the center of channels 5 and 6 that span almost the entire fin. Figures 3.69 and 3.70 are representative of the ensemble averages for the respective Reynolds numbers and location. Both flows are unsteady, and so the only difference between the two cases that could influence the flow field so strongly is the growth of spanwise vortex shedding for Re = 1590. The dye-in-water flow visualizations indicated that the small increase in Reynolds number from Re = 1550 to 1590 caused shedding to move from fin 7 to fin 2 in the baseline array, and, therefore, that this is a transitional range. The PIV measurements of Figure 3.69 certainly agree with this result, but the effect on the spanwise-transverse velocity distribution is more profound than the flow visualizations suggest. The effect of this transition on heat transfer is unclear without detailed naphthalene sublimation data at both Re = 1550 and 1590.

The streamwise vorticity contours of Figure 3.70 shows the effects of this transition on vorticity. In general, the differences are not as great for vorticity as for the V-W velocity magnitude. The vorticity plots at both Re = 1550 and 1590 show similar placement of the streamwise vortex cores. Only the magnitude of the vorticity differs, and does so marginally at best.
3.2.6 Re = 1780 Results

The onset of spanwise vortex shedding in the baseline array remains fixed at fin 3 for Re = 1780, while the Two-VG array still does not shed spanwise vortices, experiencing only oscillations in the wake. Figure 3.71 shows side-view velocity magnitude distributions of the two arrays at fins 3 and 4, while Figure 3.72 shows the corresponding spanwise vorticity contours. Figures 3.73 and 3.74 show the velocity magnitude and spanwise vorticity in the wake flow, respectively. The oscillations created by the vortex shedding at fin 3 in the baseline array are much stronger than they were for Re = 1590 (Figures 3.63 and 3.64). Similarly, the oscillations in the wake of both arrays for Re = 1780 are stronger than their counterparts at Re = 1590 (Figures 3.65 and 3.66), and the oscillations for the baseline array are clearly much stronger than those for the Two-VG array.

As for Re = 1590, the wake flow of the baseline array appears to stay predominantly within the region between the boundary layers on fin 8 at Re = 1780. At Re = 1590, however, a slight bulge was seen at the bottom edge of the image, with oscillations to confirm the behavior. This bulge is not present at Re = 1780. An investigation of all 100 images recorded at this Reynolds number and location revealed consistent behavior as seen in Figures 3.73 and 3.74. The bulging effect is clearly seen in the wake flow of the Two-VG array at Re = 1780, as the vectors at the top edge of the image turn upward toward channel 7. The flow is obviously affected by the streamwise vortices, which must have sufficient strength at Re = 1780 to persist downstream through the array to the exit flow, similar to the behavior at Re = 1590. The thin region of flow separation following fin 8 that was seen for the Two-VG array at Re = 1590 [Figure 3.65 (b)] also occurs at Re = 1780.

The increasing strength of the streamwise vortices at Re = 1780 is easily detected in Figure 3.75, which shows the velocity magnitude at fins 1 and 2 for the Two-VG array at Re = 1590 [part (a)] and Re = 1780 [part (b)]. The flow behavior over fins 1 and 2 is similar in both images; however, the flow at fin 2 shows signs of growing streamwise influence with increasing Reynolds number. At Re = 1780, a large yellow pocket of velocity magnitude exists in channel 6 between fins 1 and 3. A similar structure is seen for the flow at Re = 1590, but the relative strength of this pocket in the VG wake region over fin 1 is much smaller than at Re = 1780. The effect of this behavior can be seen in Figure 3.76, which shows the corresponding spanwise vorticity contours. The vorticity contours show increased positive vorticity in the VG wake between fins 1 and 3 (channel 6) for the Re = 1780 case. The increase of positive spanwise vorticity in this region indicates that the interaction of spanwise vortices with streamwise vortices has developed further, and this result lends itself to explanation of the VG wake-flow velocity magnitude behavior of Figure 3.75.

The end-view images of Re = 1780 show some interesting results as well. The flow through the array is similar to that of Re = 1590 up to X* = 6. At X* = 6, the flow at Re = 1590 was unsteady [Figure 3.67 (b)]; however, the ensemble of end-view images at Re = 1780 shows that the flow has returned to the steady-state behavior last seen at Re = 1550. Figure 3.77 shows representative end-view images of the V-W velocity magnitude and streamwise vorticity for Re = 1780 at X* = 6. The flow structure in the velocity magnitude image [part (a)] is similar to that for Re = 1590, with a large pocket of high-velocity magnitude fluid that spans the width of the VG base (see Figure 3.67). The streamwise vorticity contour plot [part (b)] is also quite similar to that for Re = 1590 (Figure 3.68). A possible explanation as to why the flow would stabilize at Re = 1780 is indicated by previous results. The strength of spanwise vortex shedding has grown significantly from
Re = 1590 to 1780 (35 \text{s}^{-1} to 50 \text{s}^{-1}) at fins 7 and 8. The streamwise vorticity also grows, but only from 4 \text{s}^{-1} to 6 \text{s}^{-1}. The relative strength of spanwise to streamwise shedding, therefore, has not remained the same. The ensembles for the side-view images at Re = 1590 and 1780 do not offer any additional obvious differences in flow structure between the two cases.

The steady flow behavior continues at X^* = 8, which also deviates from the unsteady behavior at Re = 1590. In terms of end-view velocity magnitude, Figure 3.78 (a) shows that the flow structure at Re = 1780 is nearly identical to Re = 1590 [Figure 3.69 (b)]. The pockets of high-velocity magnitude (V-W) at Re = 1780 correspond with similar regions at Re = 1590; however, the size of these pockets is reduced at Re = 1780. Overall, the end-view velocity magnitude is larger at Re = 1590 than at Re = 1780. As at X^* = 6, the streamwise vorticity contours are very similar for these two Reynolds numbers [Figures 3.70 (b) and 3.78 (b)].

Because the PIV images at Re = 1590 are very close to the flow conditions of Figure 3.17 (Re = 1630), and Re = 1780 approaches the conditions of Figure 3.18 (Re = 2040), a comparison of PIV images at these respective Reynolds numbers yields some insight into the heat transfer behavior at Re = 1630 and 2040. Recall from Section 3.1 that the heat transfer behavior at Re = 2040 was, in general, improved over the Re = 1630 case. Obviously, the flow velocity through the Two-VG array increases with Reynolds number, and this was seen to increase the strength of the wake oscillations. The increased strength of spanwise vortex shedding in channel 6, observed in the baseline images, corresponds to the decrease in heat transfer on the top surfaces for the Two-VG array. Similarly, this increase in spanwise vortex strength corresponds to improved heat transfer on the bottom surfaces of channel 5. These results compare favorably with analysis given in Section 3.1. The reduced heat transfer on the top surface of fin 3 and the bottom surface of fin 2 at Re = 2040 can be attributed to the differences seen between Re = 1590 and 1780 in Figures 3.75 and 3.76. These figures showed increased streamwise influence through a pocket of fluid near fin 2, and increased positive spanwise vorticity for Re = 1780.

Perhaps the most significant difference between Re = 1590 and 1780 for the Two-VG array is the change from unsteady to steady flow. Recall that even at Re = 1025, the flow was unsteady at the exit of the array in the end view, and oscillatory in the side view. For Re = 1780, the flow remains oscillatory in the side view, but is steady in the end view at both X^* = 6 and 8. Figure 3.18 shows a large increase in heat transfer on both surfaces of fin 6 at Re = 2040 compared to Re = 1630. The increase in heat transfer is surprising, because steadier flow is indicative of less mixing. Naphthalene sublimation data are not available for fin 8, but the results should follow the trend seen at fin 6.

As mentioned before, the total heat transfer on fin 7 decreases from Re = 1630 to 2040, and this occurs despite the change in flow steadiness that was beneficial to fin 6. Fin 7 differs from fin 6 in a subtle way. Fin 7 is located in a column of fins that has VGs placed on the leading fin, while the column of which fin 6 is a part does not have any VGs. Therefore, all of the results presented thus far (flow visualization, naphthalene sublimation, and PIV) show that the heat transfer behavior on fins 1, 3, 5, and 7 (fins in the middle column) are most severely affected by the interaction of spanwise and streamwise vortices. The result of these interactions
between Re = 1230 and 1780 is heat transfer degradation. The fins in the outlying columns show varying results.

3.2.7 Re = 2450 Results

The results at Re = 2450 show several differences from previous Reynolds numbers. Spanwise vortex shedding in the baseline array begins at fin 1. The flow in the Two-VG array appears to be weakly shedding vortices at fin 1. Figures 3.79 and 3.80 show the side-view velocity magnitude and vorticity contours for fins 1 and 2 at Re = 2450. While a hint of spanwise vortex shedding in the Two-VG array occurs at fin 1, Figures 3.81 and 3.82 definitively show vortex shedding from fin 3. The remaining fins in the Two-VG array experience spanwise vortex shedding as well. Similar to Re = 1780, the yellow pocket of fluid near fin 2 in the velocity magnitude plot shows increased influence of streamwise vorticity in the array [Figure 3.79 (b)]. This influence is so great at Re = 2450 that it persists into the next viewing location, fins 3 and 4 in Figure 3.81 (b). Figures 3.71 and 3.72 showed a similar presence, but not nearly as strong as at Re = 2450. This flow feature shows effects as far downstream as fin 4. Figures 3.80 and 3.82 show that positive spanwise vorticity in channel 6 appears to grow at Re = 2450, both in magnitude and downstream persistence, as compared to lower Reynolds numbers.

The wake flow at Re = 2450 is also different than at Re = 1780. Figures 3.83 and 3.84 present velocity magnitude and spanwise vorticity measurements in the wake for Re = 2450. The baseline array wake is clearly rolled up into alternating vortices, but the Two-VG wake only shows oscillations. The oscillations are weak vortex shedding, as shown in the flow visualization results (Figure 3.11). Major differences in the structure of the wake oscillations are also apparent between the baseline and Two-VG arrays. The flow in the baseline array experiences oscillations at both the top and bottom edges of the image, but the Two-VG array is asymmetric in this regard. The boundary layer on the top surface of fin 8 clearly separates from the fin leading edge, and the separated region grows into channel 5. This asymmetry suppresses the oscillations at the lower edge of the Two-VG wake. The separated region could in fact be out-of-plane (W) motion induced by the streamwise vortices in channel 4, immediately beneath the image’s viewing area. Similar separated regions are seen for Re = 1590 and 1780, Figures 3.65 (b) and 3.73 (b), respectively. However, the regions are significantly thinner than at Re = 2450.

Further differences between Re = 1780 and 2450 are detected in the end-view images. Up to Re = 1590, flow through the Two-VG array was steady until the exit location, $X^* = 8$, where it became unsteady. At Re = 1590, the flow unsteadiness moved back to $X^* = 6$, but disappeared entirely at Re = 1780. For Re = 2450, flow unsteadiness begins on fin 3 at $X^* = 2.5$. Because the flow behavior at Re = 2450 differs vastly from the other Reynolds numbers, Figures 3.85–94 are presented. These figures show the end-view velocity magnitude and streamwise vorticity contours at $X^* = 2.5$–8. For each figure, either two images of velocity magnitude or two images of streamwise vorticity are shown to demonstrate the unsteadiness.

Figure 3.85, for example, shows the velocity magnitude at $X^* = 2.5$. Part (a) differs from (b) in the manner in which the flow in channel 5 behaves. Near the bottom of the image in part (b), the flow shows a significant amount of rotation as compared to part (a). The magnitude of the rotation is small, however. Part
(a) instead shows pockets of high-velocity magnitude downward-directed flow at the corresponding locations. Part (b) also shows more blue regions in channel 5 than part (a), which indicates increased stagnating V-W flow for this image. The vorticity contour plots of this case in Figure 3.86 show the rotation in channel 5 more clearly. Similar differences occur at the other X locations presented in Figures 3.87-94.

Comparing Figures 3.18 and 3.19, it is clear that the heat transfer on all fins except fins 3 and 5 is significantly improved at Re = 2450 compared to Re = 2040. The improvement, therefore, must be a result of the enhanced flow unsteadiness and spanwise vortex shedding at Re = 2450. The first major improvement in heat transfer appears at fin 1. Fin 2, which precedes the flow unsteadiness by one fin length, and is the location where transverse oscillations begin to appear in the Two-VG array side-view images, also shows significant improvement. The combination of these factors improves the heat transfer of fin 2 from an average decrement of 4.25% to an enhancement of 6.35%. Similar to fin 2, fins 4 and 6 show comparable improvements. The heat transfer performance of fin 3 remains virtually unchanged, and this is likely due to the streamwise and spanwise interactions becoming balanced at Re = 1780 and persisting at Re = 2450. Fin 5 experiences a decrease of heat transfer from an average enhancement of 3.30% to 1.80%. Fin 7 differs from both fins 3 and 5 because the decrement on the top surface decreases by roughly one-half. Perhaps the cause of this improvement is the return of unsteadiness to the rear of the array.

3.3 Figures

![Figure 3.1: Fin labeling](image1)

Figure 3.1: Fin labeling

![Figure 3.2: Trailing fins of the baseline array at Re = 1550](image2)

Figure 3.2: Trailing fins of the baseline array at Re = 1550

![Figure 3.3: Baseline array at Re = 1590](image3)

Figure 3.3: Baseline array at Re = 1590
Figure 3.4: Baseline array at Re = 1780

Figure 3.5: Placement of cast fins for naphthalene sublimation experiments

Figure 3.6: Baseline array naphthalene data

Figure 3.7: Trailing fins of the Two-VG array at Re = 1550
Figure 3.8: Trailing fins of Two-VG array at Re = 1610

Figure 3.9: Two-VG array at Re = 1670

Figure 3.10: Two-VG array at Re = 2040

Figure 3.11: Two-VG array at Re = 2420

Figure 3.12: Two-VG array at Re = 1720
Figure 3.13: Two-VG array naphthalene data

Figure 3.14: Two-VG Sherwood number enhancement at Re = 410

Figure 3.15: Two-VG Sherwood number enhancement at Re = 1025
Figure 3.16: Two-VG Sherwood number enhancement at Re = 1230

Figure 3.17: Two-VG Sherwood number enhancement at Re = 1630

Figure 3.18: Two-VG Sherwood number enhancement at Re = 2040

Figure 3.19: Two-VG Sherwood number enhancement at Re = 2450
Figure 3.20: Two-VG array at Re = 590

Figure 3.21: Two-VG array at Re = 1180

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Figure 3.23: Seven-fin average Sherwood number enhancement
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Figure 3.29: Choice codes at $Re = 1590$, $X^* = 1$, for the Two-VG array
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Figure 3.33: Instantaneous velocity magnitude for (a) baseline array and (b) Two-VG array at Re = 1025, fins 3 and 4
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Figure 3.35: Instantaneous velocity magnitude for (a) baseline array and (b) Two-VG array at Re = 1025, fins 7 and 8
Figure 3.36: Instantaneous velocity magnitude for (a) baseline array and (b) Two-VG array at Re = 1025, downstream
Figure 3.37: Instantaneous spanwise vorticity for (a) baseline array and (b) Two-VG array at Re = 1025, fins 1 and 2
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Figure 3.39: Instantaneous spanwise vorticity for (a) baseline array and (b) Two-VG array at Re = 1025, fins 5 and 6
Figure 3.40: Instantaneous spanwise vorticity for (a) baseline array and (b) Two-VG array at $Re = 1025$, fins 7 and 8.
Figure 3.41: Instantaneous spanwise vorticity for (a) baseline array and (b) Two-VG array at \( \text{Re} = 1025 \), downstream
Figure 3.42: Two-VG array instantaneous (a) velocity magnitude and (b) streamwise vorticity at Re = 1025, $X^* = 0$
Figure 3.43: Two-VG array instantaneous (a) velocity magnitude and (b) streamwise vorticity at Re = 1025, $X^* = 0.5$
Figure 3.44: Two-VG array instantaneous (a) velocity magnitude and (b) streamwise vorticity at Re = 1025, $X^* = 1$. 

(a)

(b)
Figure 3.45: Two-VG array instantaneous (a) velocity magnitude and (b) streamwise vorticity at Re = 1025, $X^* = 1.5$
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4.1 Conclusions

The vortex-enhanced interrupted fin (VEIF) is a novel idea that seeks to improve heat transfer in interrupted fin geometries by combining spanwise and streamwise vorticity. The VEIF has been investigated for potential heat transfer enhancements using dye-in-water flow visualization and PIV, and the results have been compared with naphthalene sublimation (i.e., mass/heat transfer) data provided by Ge [61]. Spanwise vorticity was created using an offset-strip fin array, and streamwise vorticity was induced using delta-wing VGs.

The VEIF investigated in this study consisted of a fin with two VGs located symmetrically about the fin’s spanwise centerline. Several VEIFs were placed across the inlet to an offset-strip fin array, and thus the array was termed the Two-VG array. The Two-VG array was compared to a baseline offset-strip fin array that did not include any VGs. The flow visualizations and heat transfer data showed that the combination of spanwise and streamwise vortices in the Two-VG array had mixed results. At low Reynolds numbers (Re ≤ 1025), heat transfer enhancement occurred throughout the array. At Re = 1230, the enhancement began to disappear at certain fin locations, and an overall heat transfer decrement resulted at Re = 1630. Finally, the enhancement returned at Re = 2450.

The PIV measurements showed transverse oscillations that first occurred in the wake of the baseline array at Re = 1230, and not at Re = 1550, as initially suggested by dye-in-water flow visualizations. The subsequent growth of spanwise vortex strength within the array in the Reynolds number range 1230 ≤ Re ≤ 1780 corresponds to the decrease in heat transfer enhancement seen in the naphthalene sublimation data for the Two-VG array. The spanwise structures that were dominant in the baseline array over this Reynolds number range did not occur in the Two-VG array.

End-view PIV data for the Reynolds number range 1230 ≤ Re ≤ 1780 captured intriguing flow-structure phenomena at several locations in the Two-VG array. Up to Re = 1550, the flow in the Two-VG array became unsteady at the exit of the array (fin 8). At Re = 1590, the onset of unsteadiness moved to fin 6. The flow behavior at Re = 1780 was substantially different than all preceding Reynolds numbers. At Re = 1780, the flow remained steady throughout the array, but by Re = 2450, the unsteadiness began at fin 3 and continued downstream to the exit of the array.

Another interesting result of the end-view PIV data for the Two-VG array was the difference in spanwise-transverse (i.e., end-view) velocity magnitude between Re = 1550 and 1590 at fin 8. The velocity magnitude at Re = 1550 was dominated by the U velocity (out-of-plane component), thus resulting in very small velocity magnitudes for the in-plane components. The flow at Re = 1590, however, had much higher in-plane velocity components. The high velocity flow was concentrated in large pockets that spanned almost the entire surface of fin 8. The flow at both Reynolds numbers was unsteady, and thus the only difference that could significantly influence the flow field was the growth of spanwise vortex shedding from Re = 1550 to 1590.
The onset of spanwise vortex shedding in the PIV images was seen to move from fin 5 to 3 between $Re = 1550$ and 1590 in the baseline array. Similarly, the dye-in-water flow visualizations showed the onset of shedding moving from fin 7 to 2. The dramatic changes in the flow field behavior over such a small Reynolds number range indicate a narrow transitional Reynolds number regime. The combination of spanwise and streamwise vorticity (Two-VG array) within this transitional regime decreased the heat transfer, and thus the spanwise and streamwise vortices interfered destructively.

An explanation for the return of heat transfer enhancement at $Re = 2450$ was not apparent from the flow visualizations or PIV data; however, two observations from the PIV data offer some insight into the flow field physics. First, the spanwise vortex shedding within the Two-VG array at $Re = 2450$ closely matched the behavior of the baseline array. As for the baseline array, spanwise shedding began at fin 1, but the oscillations in the Two-VG array were smaller in amplitude than in the baseline array. Second, flow unsteadiness within the Two-VG array began at fin 3. Unsteadiness began at fin 7 or 8 for all preceding Reynolds numbers (except $Re = 1780$ for which the flow was steady). Thus, a combination of increased spanwise and streamwise vortex shedding within the array was most likely responsible for the return of the heat transfer enhancement, but the specific details of their interactions are unclear.

While the discovery that spanwise and streamwise vorticity interact destructively in the transitional Reynolds number range is disappointing from an applications standpoint, several important observations of the flow field behavior with combined vorticity components have been contributed by this investigation. The first of these observations is that the addition of streamwise vortices to the offset-strip fin geometry offers additional heat transfer at Reynolds numbers in which spanwise vortex shedding does not occur, or is very weak. Second, heat transfer enhancement does occur at Reynolds numbers well beyond the transitional range ($Re = 2450$ in this investigation). Finally, this initial attempt at combining spanwise and streamwise vorticity demonstrated the power of the PIV technique in understanding the flow field physics and heat transfer phenomena. PIV measurements proved to be invaluable for providing insight into the flow field interactions of spanwise and streamwise vorticity, and facilitated an understanding of the naphthalene sublimation data that could not be obtained using the traditional dye-in-water flow visualization technique.

### 4.2 Recommendations

This investigation of combined spanwise and streamwise vorticity provides a foundation upon which future investigations can be built. The concept of the VEIF already shows promise under specific operating conditions. The goal of future work should be to further develop the VEIF concept through additional studies that more precisely identify the flow field interactions within the transitional Reynolds number range and between $Re = 1780$ and 2450. A parametric study of VG aspect ratio and angle-of-attack with Reynolds number in the Two-VG configuration would be a natural starting point. The investigation of additional VG configurations is also merited due to the substantial improvements of the Four-VG configuration over the Two-VG configuration.

PIV post-processing could be improved by implementing a new scheme for computing vorticity. The central differencing scheme used in the current study results in a loss of data around the image boundaries.
Changing the vorticity scheme to an integration-based method or an alternate one-sided differencing scheme could reduce the loss of data around the fin surfaces. The additional vorticity data could prove to be insightful for understanding the heat transfer behavior of the fins.
References


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