Measurement of Air-Velocity Profiles for Finned-Tube Heat Exchangers Using Particle Image Velocimetry

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ABSTRACT

The performance of a finned tube heat exchanger is strongly affected by the velocity distribution of the air that passes through it. The air velocity distribution for finned-tube heat exchangers has gone largely undocumented because it is difficult to measure accurately. In this study, the air velocity distribution upstream of three heat exchangers installed in a horizontal duct is examined; a vertically oriented single-slab coil, a single-slab coil placed at an angle of 65º to the duct wall, and a two-slab A-Shaped coil with a 34º apex angle. The data was taken using a non-intrusive, laser based technique called Particle Image Velocimetry (PIV). The measurement results show that the air inlet velocity profile is strongly influenced by the heat exchanger's design and application.

1: INTRODUCTION

The performance of a finned tube heat exchanger is strongly affected by the velocity distribution of the air that passes through it. Chwalowski et al. (1987) measured the degradation in evaporator capacity to be as much as 30 percent in extreme cases. In another related study, Domanski et al. (2007) showed that nearly all of the capacity reduction due to non-uniformities in the velocity profile can be recuperated by optimizing the refrigerant circuitry, i.e. the sequence in which the heat exchanger's tubes are connected. These findings indicate the importance of knowing the approach air velocity profile when designing the refrigerant circuitry.

To date, the inlet air side velocity profile is largely left undetermined because it is difficult to measure accurately. Chwalowski et al. (1987) used smoke injection to qualitatively evaluate air flow fields in the vicinity of installed finned-tube heat exchangers. They also measured air velocity using a traversing pitot tube and showed the air distribution to be highly non-uniform. The historically available measurement tools (pitot tubes, hot-wire anemometers, rotating vane anemometers, etc.) are difficult to use and inaccurate because they must be placed within, and properly oriented to, the locality of interest. Furthermore, these devices themselves interfere with the flow that they are trying to measure. Current measurement technology has brought about a number of highly accurate, laser-based, non-intrusive options to characterize the air velocity profile of a heat exchanger's approach flow field. This study presents air velocity measurements obtained with Particle Image Velocimetry (PIV), which uses a laser sheet to illuminate a single plane within the flow field, and a synchronized high-speed camera to track the motion of particles within it.

2: EXPERIMENTAL SETUP AND DATA ACQUISITION

2.1 Air Flow Test Apparatus

The objective of this study was to measure the approach air velocity profile of different finned-tube heat exchangers operated under adiabatic conditions. The test apparatus, shown in Figure 1, was capable of delivering a specified air volume rate through a ducted heat exchanger. The air was pulled into the straight duct test section as depicted in the upper left portion of the figure, and continued clockwise through the apparatus. The view shown is from the top looking downward. The air passed through the finned-tube heat exchanger in the test section and was ducted to a flow straightener before entering a venturi nozzle where the volumetric flow rate was measured. After exiting the nozzle, the air was drawn through a variable-speed blower, and then discharged to the laboratory environment. The test section duct was made out of clear plexiglass to allow viewing of the in-duct air velocities by the externally positioned PIV camera.

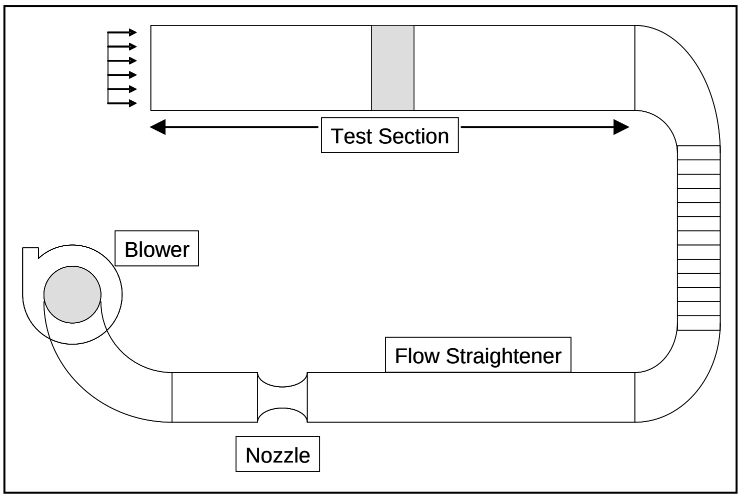

Figure 1. Schematic of the Air Flow Test Apparatus (Top View)

2.2 Particle Image Velocimetry

PIV is an optically based measurement technique used to obtain flow distributions by tracking the motion of particles entrained within the flowfield. The basic principal of operation involves illuminating a plane of interest with a sheet of laser light, and using a synchronized camera to capture the change in location of particles within the illuminated plane. The PIV measurement system consists of four components: a particle generator, a pair of lasers, a double framed CCD camera, and a computer acting as a Programmable Timing Unit (PTU). Figure 2 depicts the layout of these components as installed around the air flow test apparatus.

The entire laboratory environment was filled with non-hazardous particles, which served as tracer particles for the flow measurements, using a theater-style fog generating machine. The laser system included two, pulsing output, solid state, class IV lasers (Nd: YAG); these lasers were mounted together in such fashion that their output beams were routed through the same set of lenses and they followed identical paths. By setting the laser system in this configuration, two identical laser blasts (one from each laser) were fired with the time delay between them shorter than a single flashlamp cycle; therefore full power illumination sheets were realized between consecutive laser pulses. The laser beams passed through a cylindrical lens which distorted the beam profile into light sheets, thus producing illumination planes. These illumination planes were fired downstream into the test section, aligned with the main flow direction of the air passing through the heat exchanger. A high-speed, double-framed camera was positioned outside of the test section, in such manner that it captured images in the illumination plane. The PTU synchronized the operation of the laser system and the camera so that the snapshots taken with the camera were captured during the laser pulses, i.e. laser pulse #1 coincident with camera frame #1 and laser pulse #2 coincident with camera frame #2. Velocity information for the illuminated plane was calculated from the displacement of the particles between consecutive images. The velocity field was measured one slice at a time by traversing the illumination plane throughout the measurement zone.

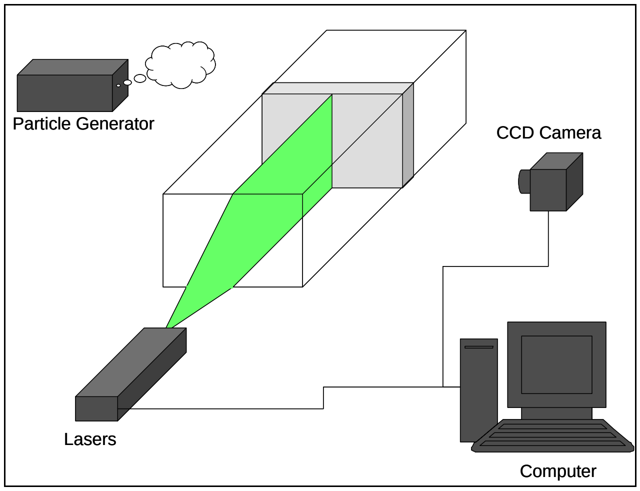

Figure 2. PIV Measurement Apparatus

3: MEASUREMENT RESULTS AND DISCUSSION

The inlet air velocity profiles were measured for three heat exchangers installed in a horizontal duct: a vertically oriented single-slab coil, a single-slab coil placed at an angle to the duct wall, and a two-slab A-shaped coil. A detailed description of this data, including the collection method, reduction, and uncertainty analysis is found in Yashar and Cho (2007).

3.1 Single-Slab Vertical Coil

The single-slab heat exchanger consisted of 72 tubes (4 depth rows of 18 tubes) with louvered fins. This heat exchanger was 455 mm tall, 455 mm wide, and 63.5 mm thick. The mounting brackets for this heat exchanger held it in a position such that its air side inlet and exit surfaces were perpendicular to the duct walls. Data was collected while testing at the manufacturers' recommended air volume rate of 0.30 m^3/s.

Each data set was taken with a specific laser illumination plane and camera position. The laser illumination plane was aimed at the heat exchanger in five separate locations, creating five separate vertical slices of the flow area. The locations used for this heat exchanger were 225 mm from the side wall (the midpoint), 155 mm, 95 mm, 50 mm, and 5 mm (near the wall). Each of these slices was further divided into four horizontally stacked overlapping segments; therefore the data was measured piecewise. In total, the air velocity vector fields were measured at 20 different stations along the inlet surface of the heat exchanger to produce a piecewise illustration of the measured vector fields from this coil.

Figure 3 shows a 1-dimensional representation of the component of the velocity perpendicular to the heat exchanger acquired during the measurements at location 95 mm from the duct wall. The measurements taken at the other lateral positions exhibited similar velocity profiles, indicating that this flow profile does not change in the lateral direction. The only difference found was the velocity profile measured at the closest location to the duct wall (5 mm from the wall); here, the distribution was similar to the other slices, but was about 20 % slower due to interactions imposed by the boundary. The ordinate axis in this figure corresponds to the vertical distance from the bottom of the heat exchanger. The air approach velocity is fairly uniform (approximately 1.3 m/s) with the exception of the areas near the top and bottom edges, where the heat exchanger's mounting brackets slightly affected the flow; these effects are more noticeable near the bottom where the mounting bracket blocks the flow, the figure does not map the data along the top mounting bracket.

Some of the data in Figure 3 displays a periodic pattern of high and low velocity. The periodic pattern corresponds to the absence or presence of tubes within the first depth row of the heat exchanger. Air approaching the heat exchanger at a location corresponding to a tube will move towards a location that corresponds to a position between adjacent tubes; therefore the high velocity points seen in the figure are located between tubes and the low velocity points are located directly upstream of the tubes.

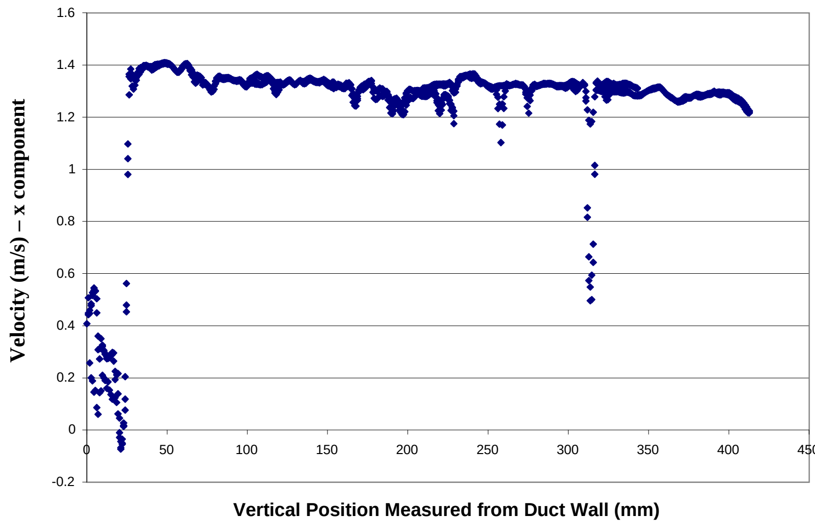

Figure 3. One-Dimensional Air Velocity at the Inlet to the Vertical Coil – 95 mm

3.2 Slant Coil

The slant coil was a single-slab heat exchanger positioned at an angle of 65º to the duct wall. It had 72 tubes (4 depth rows of 18 tubes) with louvered fins. This heat exchanger was 455 mm tall, 430 mm wide, and 65 mm deep. There was a plastic mounting bracket fastened to the lower portion of this heat exchanger that maintains the angle between the heat exchanger and the lower wall of the duct. A short metal sheet was attached to the upper edge of the heat exchanger for the same purpose. Figure 4 shows the position of the slant coil within the test section.

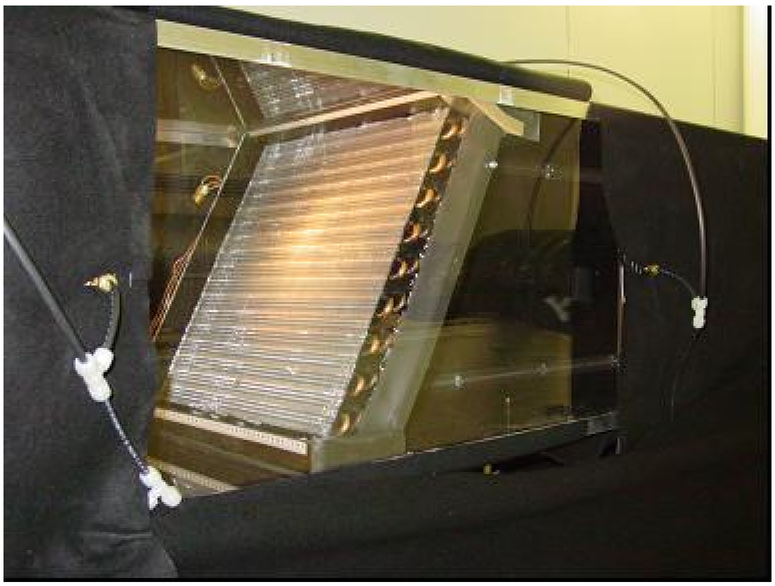

Figure 4. Slant Coil Test Section

The lasers were aimed to capture 5 vertical slices of the flow profile at locations corresponding to 215 mm (midpoint), 150 mm, 90 mm, 50 mm, and 10 mm from the outer edge of the heat exchanger. The profile of the heat exchanger was again measured piecewise by dividing the surface into 4 overlapping segments. The measurements were all taken at the manufacturer's rated air volume rate of 0.35 m^3/s.

The results for this coil showed that there was again very little variation between the measurements taken at different lateral positions. Therefore for sake of simplicity, Figure 5 only shows the component of the air velocity profile perpendicular to the coil surface measured at the heat exchanger's midpoint. Similar to that seen in Figure 3, although more pronounced here, the sinusoidal velocity pattern indicates the location of the tubes within the heat exchanger. What is much more interesting, however, is that the flow appears to have three distinctly separate regions, which illustrates the magnitude of the non-uniformity with which air flows through this heat exchanger. In the lower portion of the coil, corresponding approximately to the region less than 50 mm from the bottom, the air flow perpendicular to the coils surface is very slow. From there, it rapidly increases towards locations in the mid section of the coil. In the area between 50 mm and 250 mm from the bottom of the coil, the flow rate is relatively constant. In the upper portion of the heat exchanger, from 250 mm to 455 mm from the bottom, the figure shows a long gradual taper of the air flow rate.

It is interesting to examine the location of the maximum air velocity for this coil. As air approaches the heat exchanger near the bottom of the duct, it encounters the lower mounting bracket, which turns the flow upwards. The air in this region must then accelerate around the bracket, which causes the local maximum near the bottom of the coil. It is also interesting to see the decrease in the flow velocity near the top of the heat exchanger.

Figure 5 shows that the amount of air available for heat exchange with each tube is strongly related to the tube's position. The first tube near the bottom of the heat exchanger (and those occupying the same position within subsequent depth rows) receives very little air flow at all. In the region between 250 mm and 455 mm from the bottom of the heat exchanger, the amount of air flow approaching each tube is a strong function of its position; the tube nearest the top of the heat exchanger receives less than one third of air flow that a tube positioned in the middle receives.

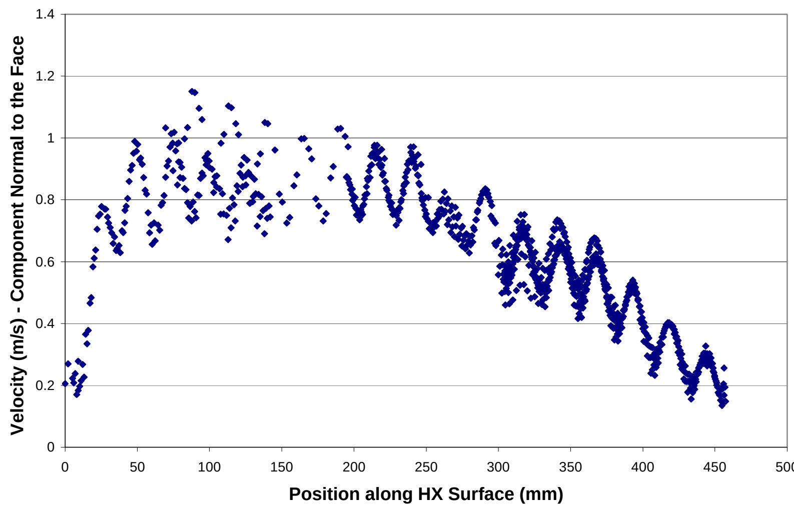

Figure 5. One-Dimensional Air Velocity at the Inlet to the Slant Coil – 215 mm

3.3 A-Shaped Coil

The third heat exchanger examined in this study was a two-slab heat exchanger, with the slabs assembled in an A-shape configuration. Figure 6 shows a photograph of this coil mounted in the test section.

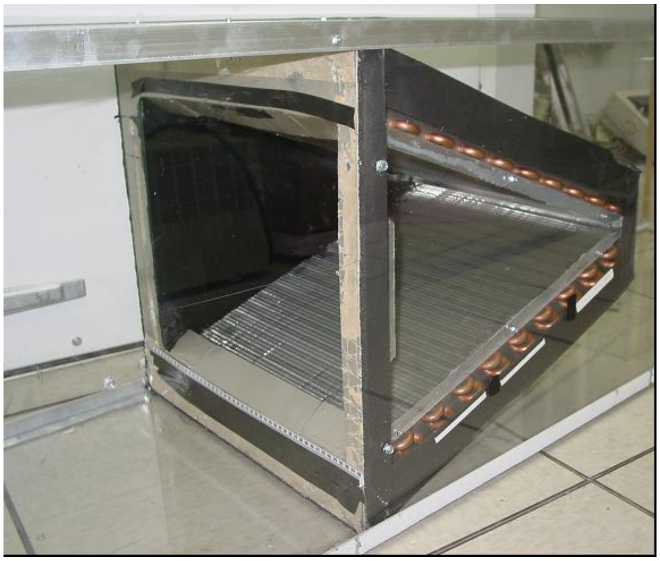

Figure 6. A-Shaped Coil Test Section

This heat exchanger represents a typical configuration found in residential air conditioning systems. Each slab in the assembly had 60 tubes (3 depth rows of 20 tubes) with louvered fins, giving a total of 120 tubes in the dual-slab A-shaped coil. The dimensions of each slab were 520 mm in height, 400 mm in width, and 65 mm in thickness. The slabs were attached together with an apex with an angle of 34º between them. The leading side of the condensate pan (attached to the open area between the slabs) fully occluded the plexiglass duct and had outer dimensions of 511 mm x 495 mm. The heat exchanger was mounted in the duct with foam rubber padding along the sides to prevent air leakage around the coil.

PIV measurements were taken along four vertical slices corresponding to positions of 190 mm (the midpoint), 120 mm, 60 mm, and 40 mm from the edge of the heat exchanger. Again the results showed that the flow field was essentially 2-dimensional (i.e. no traverse dependence), so only the data taken at the midpoint is displayed for analysis. Each data set was measured in three segments. The measurements were taken at the manufacturers rated air volumetric rate of 0.65 m^3/s.

The measurements uncovered the presence of a recirculation zone caused by the attached condensate pan. This recirculation zone hinders the performance of this heat exchanger because it effectively blocked the air flow to a substantial portion of the coil. As air flows over the pan's edge, it is turned inwards towards the coil and continues to circulate between the coil and the pan. Figure 7 shows a raw data image and the computed vector field from the triangular region between the edge of the condensate pan and the 4^{th} and 6^{th} heat exchanger tubes in the first depth row, it provides a detailed illustration of this recirculation zone.

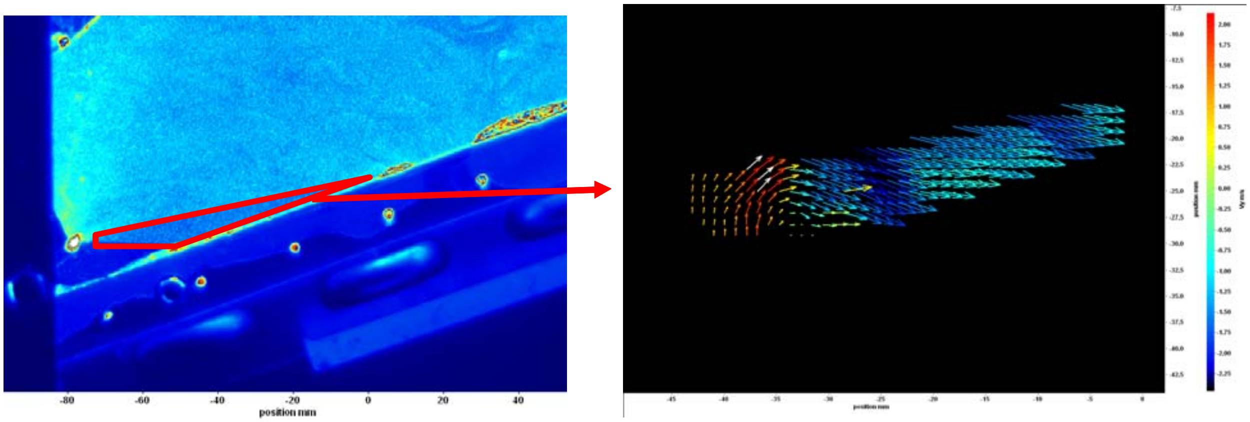

Figure 7. PIV Measurement showing A-Coil Recirculation Zone

Figure 8 shows the profile of the perpendicular component of velocity measured along the midline of the heat exchanger. Note that for this set of data, it was only possible to record data within line of sight, therefore the velocities within the shadowed region behind the condensation pan could not be captured. For this reason, the data shown below was taken along the path closest to the heat exchanger but still within the illuminated area (as shown in Figure 7, left). Close examination of the data points near the entrance of the heat exchanger shows that there is a very steep velocity gradient in this region. Here, each data point represents a single interrogation window used in the PIV data reduction algorithm. The locus of data points corresponding to the points measured closest to the coil surface is the set that shows negative velocity in Figure 8; the set of data lying directly above this corresponds to the set of interrogation windows one step further from the coil surface, etc. These large velocity gradients are the one-dimensional representation of the recirculation zone. Upon examining the velocity in this area, the steepest gradients occur in the vicinity of the 3rd tube from the bottom of the coil, with flow away from the coil at the nearest measured point.

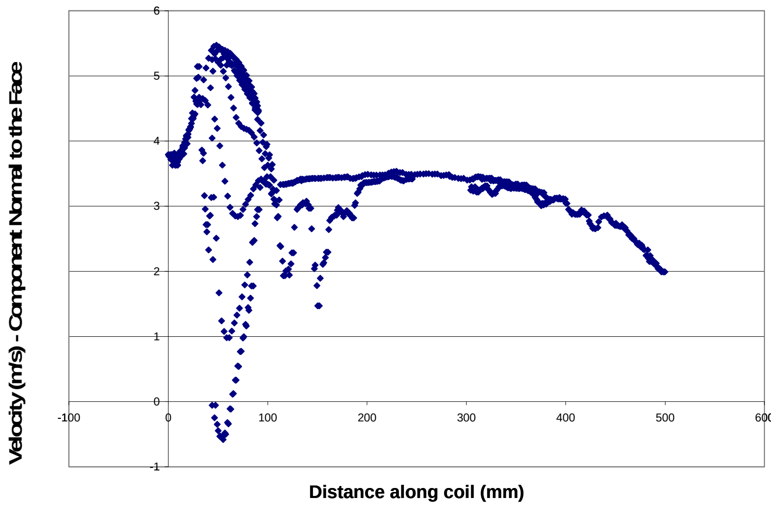

Figure 8. One-Dimensional Air Velocity at the Inlet to the A-Coil– 190 mm

These figures illustrate that the closest three or four tubes to the entrance do not receive a significant amount of air flow at all. This inefficient portion of the heat exchanger indicates the importance of knowing the air flow distribution prior to designing heat exchangers. If no air interacts with a particular tube, it can not facilitate any heat transfer. The manufacturer of this coil bore the expense of assembling these tubes into this product without the benefit of additional performance. In fact, these tubes may actually impede the overall product performance because of the refrigerant pressure drop induced by flowing through these unproductive tubes. Had this air flow distribution pattern been known during the design phase of this heat exchanger, the manufacturer could have designed around it by either cutting costs through elimination of tubes that receive no air flow, by reducing the penalty by providing a spacer for the recirculation zone between the condensate pan and the heat exchanger so that the heat exchanger is separated from this region, or by some other means.

4: SUMMARY AND CONCLUSIONS

This study examined the air side inlet velocity profiles of three common finned-tube heat exchanger installations using Particle Image Velocimetry. With the exception of the installation with the single-slab vertical coil, the air flow was not uniform. The fins and tubes of the heat exchanger provide resistance to the air flow, which in general, has the affect of evening out the distribution; however, our measurements show that other factors are more influential. The presence of any irregularities in the duct boundaries or heat exchanger mounting has a much more profound impact.

With the first single-slab heat exchanger, the test section was relatively free from any boundary discontinuities. The heat exchanger had mounting brackets which effectively reduced the ducts' cross sectional area right at the heat exchanger interface. But this reduction was very small and occurred right at the point of transition to the introduction of the flow resistance; therefore this did not largely impact the air flow. The measurements showed that the air flow distribution through this heat exchanger was fairly constant at any location.

The slanted single-slab heat exchanger showed a very different air flow distribution pattern because the heat exchanger was not positioned perpendicularly to the air flow, and abrupt area changes were introduced by the mounting brackets. The measurements showed a high-flow region caused by the acceleration of the air flow around the lower mounting bracket. Also, the measurements showed about half of the coil to be subject to a somewhat linearly declining air velocity profile.

For the A-shaped coil, the velocity profile had a lot of similarities to that of the slanted coil. The A-shaped coil showed a relatively linearly declining air velocity profile as we moved closer towards the apex, although not as pronounced as seen on the slanted coil. More importantly, though, the condensate pan attached to this coil was an obstructive feature, much more so than the ones attached to the slanted coil, and therefore its effects were more pronounced. The metal plate used to catch the condensate running off the coil acted as an airfoil and caused the presence of a recirculation zone between it and the coil. This recirculation severely impeded the air flow to a substantial portion of the entire heat exchanger.

The observation that was common to each test specimen is that the velocity profile did not change significantly as the image plane is traversed within the duct. This outcome is consistent given all of the heat exchangers effectively had 2-dimensional geometry; the geometry of the duct and heat exchanger changed dramatically in the downstream and vertical directions, but not in the lateral direction. This point, however, will probably not hold true for heat exchanger installation configurations other than purely pressure driven situations. In many typical household installations, a blower module is attached very close to the coil assembly, which would cause three dimensional velocity variations. These effects did not come into play in this study because the blower module was located very far downstream from the test section, with two 90º bends and a venturi flow meter between them. The effect of a blower on the inlet air velocity profile should be examined in detail in future studies.

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ACKNOWLEDGEMENT

The authors would like to thank Dr. Rodney Bryant of NIST's Fire Research Laboratory for his guidance and the use of his PIV measurement equipment. The authors would also like to thank Mr. Brian Dougherty of NIST's Heat Transfer and Alternative Energy Systems Group and Mr. Robert Uselton of Lennox Industries for their constructive review of this manuscript.