Local Heat Transfer and the Effects of Turbulence on Interrupted-fin Surfaces

Project Overview

Interrupted-fin surfaces are used to enhance the air-side heat transfer performance in many compact heat exchangers. While many empirical correlations are available in the open literature for offset-strip and louvered-fin geometries, local heat transfer behavior on individual fins is not as well understood. A redesign of these surfaces may result in higher heat transfer. Inlet flow manipulation is another way to increase heat transfer. Increases in turbulence intensity have been shown to cause significant increases in flat-plate turbulent heat transfer and a reduction in the critical Reynolds number (Blair, 1983a and b, and Hancock and Bradshaw, 1983). If an increase in turbulence intensity causes vortex shedding to begin at a lower Reynolds number or causes the resulting vortices to be larger, heat transfer should show a significant augmentation (See DeJong and Jacobi, 1995; DeJong and Jacobi, 1999; and Gentry and Jacobi, 1995). However, it is uncertain whether or not these effects will be seen in the more complicated interrupted surface geometries. Thus, this project has two related objectives. First, local heat transfer behavior interrupted surface arrays is being analyzed. Second, the effects of an increase in turbulence intensity on heat transfer and pressure drop for these geometries is being quantified.

To achieve these results, a small induction wind tunnel has been constructed. An offset-strip geometry is being tested over a Reynolds number range of 500 to 2000. A removable square-bar, square-mesh biplanar lattice grid is inserted upstream to generate turbulence levels of up to 10%. Local heat transfer data are generated using liquid crystal thermography. Liquid crystals, which are applied to the fins, change color with temperature. Thus, if other necessary information is known, the heat transfer coefficient at a given location on the fin can be determined from the color. A new modified transient technique has been developed. In this technique, the wind tunnel is turned on and allowed to come to steady state. Then current is applied to a fast-response heater mesh near the wind tunnel inlet, causing an increase in temperature. By recording the color at a specific time with a CCD camera and frame grabber card, the time-history of the fin temperature for a given location can be determined. From these times and temperatures, local heat transfer coefficients can be inferred using a finite-difference data analysis program.

The impact of this work may be three-fold. First, it will advance knowledge in the field of heat transfer and the HVAC&R application. A more thorough understanding of local heat transfer may allow more efficient designs, and a knowledge of the effects of turbulence intensity on flow through interrupted surfaces may provoke improvements in systems which include these types of heat exchangers. Second, a new liquid crystal experimental method and data analysis procedure have been developed. These methods and software modifications will be made available to any ACRC member who is interested in using the liquid crystal technique (The original software is available only from the Air Force Academy and requires the use of Matlab.). Although these methods are time-consuming to develop, once developed, data can be acquired and analyzed relatively quickly. Third, this work is being performed in an undergraduate department at a primarily undergraduate institution (Baylor University) and in fact was the first experimental research project started in the department. This research provides an avenue for undergraduates to get involved both through laboratory and independent study projects. To date, eight students have worked on this project either as independent study students or as paid assistants. These opportunities result in students who are better prepared to make an informed decision about graduate school as well as working in the HVAC/R industry and who have a better understanding of how to solve ill-defined problems which are the norm in the working world. (Upon graduation, one of these students applied for work at several ACRC companies.).

Progress To Date

Progress in five main areas – wind tunnel development, liquid crystal image capture and calibration, experimental procedure and automated data analysis, turbulence generation, and flow visualization results -- will be highlighted. The NSF has granted a no-cost extension to the project until December 2002.

Wind Tunnel Development

A small induction wind tunnel has been designed and constructed specifically for this experiment as shown in Figure 1. The wind tunnel consists of a flow conditioning section (which includes screens and a contraction), a heater mesh powered by an arc welder that generates a temperature rise, a clear Plexiglas test section 4.78” by 3”, a diffuser, an in-line duct fan, and a flow measurement section. The flow rate is measured downstream of the fan using ASME standard orifice plates. The flow rate is regulated with a Variac attached to the duct fan. During Summer 2002 problems with temperature uniformity within the test section were noted. These problems were solved by insulating the test section and correcting an uneven leading edge on the test samples. The wind tunnel orientation has been switched from horizontal to vertical to mitigate natural convection effects. A National Instruments VXI data acquisition system has been developed and a LabView program written to record temperature and pressure data. The wind tunnel has been custom-built due to its small size and unique dimensions.

Figure 1 A photograph of the wind tunnel constructed for these experiments

Liquid Crystal Image Capture and Calibration

The image capture and processing system is in place and operational. Using a Sony DXC-950 color video camera which interfaces with the Matrox Meteor II video capture card, R, G, and B images are acquired. The interface software developed for this application allows variable rates of image capture, a desirable feature for transient techniques. Actual processing of these images is accomplished using Matlab and the Image Processing Toolbox feature. This software was developed initially by the University of California, Davis, (Anderson, 1998) but modifications to allow a variable rate of image capture have been developed for this project. A lighting system providing appropriate constant illumination has been set up.

Before images can be analyzed, a liquid crystal calibration file must be developed. This calibration is specific for each batch of liquid crystal. The calibration curve correlates the hue (color) with temperature. During Summer 2002 an improved calibration method was developed. First, a flow rate is established in the test section, and then the heater mesh is turned on. This provides a slow heating of the flat plate in the test section under the lighting used for the experiment over a period of 20 minutes. For this situation, at the end of the 20 minutes, a surface mounted thin thermocouple shows the temperature of the plate to be at the upper end of the liquid crystal color range. At that point both the heater mesh and air flow are turned off. Next, video images of the surface thermocouple are captured as the plate cools and, at the same time, the temperature of the thin thermocouple is recorded. Using the MatLAB image analysis program, each image is analyzed and the hue in the region of the surface thin thermocouple recorded. This hue value is matched with the recorded temperature to become the calibration file. Four separate calibrations were performed over several days; the results are shown in Figure 2. As can be seen from the data, the calibration shows excellent agreement between tests with a confidence that temperature from the hue can be used to determine temperature within 0.1^{o}C. This calibration file was input into the image analysis MatLAB program and used to analyze the camera images taken during an actual test run.

Experimental Procedure and Automated Data Analysis

At the beginning of each test, the data acquisition system is started and the initial temperatures read. The heater mesh power supply is set at the correct level to give the necessary gas temperature with the established test flow but not yet turned on. The wind tunnel is then turned on and the proper flow velocity established. The camera frame grabber file is loaded to acquire three frames per minute for fourteen minutes. Both the grabber file and heater mesh power supply are then turned on simultaneously. After approximately fourteen minutes, the test is completed and the images saved. The images are analyzed using the image analysis MatLAB program to give streamwise surface temperature distributions at specific times when the images were taken. The data acquisition time -temperature values are saved to provide the driving gas temperature history, orifice plate temperature, and surface temperature history. Comparing the thin-film thermocouple data with that determined from the liquid crystal images validates the calibration. A plot of actual surface temperatures vs time is shown in Figure 3. This plot shows a surface temperature distribution over a flat plate for 1 to 14 minutes after the heater mesh was turned on.

The MatLAB heat transfer prediction program is being developed by an undergraduate student with supervision by Dr. Van Treuren. The framework for this program was proven through the use of a finite difference technique applied using Excel. The spreadsheet modelled a two-dimensional fin with a convective boundary condition. The MatLAB program being written initially guesses the streamwise heat transfer distribution over the fin to be the same as that over a flat plate (using the Dittus-Boelter equation). The program then calculates the surface temperatures over the fin based on the convective boundary condition and the two-dimensional finite difference equations. These surface temperature predictions are then compared to the experimental data gathered during the test. If the temperatures do not match, the heat transfer coefficients are then adjusted either up or down and the process is started again. After several iterations, when the surface temperatures match the experimental data, the streamwise heat transfer distribution is known. This program is in its final stages of development. The program will be made available to any ACRC member interested in using liquid crystal thermography.

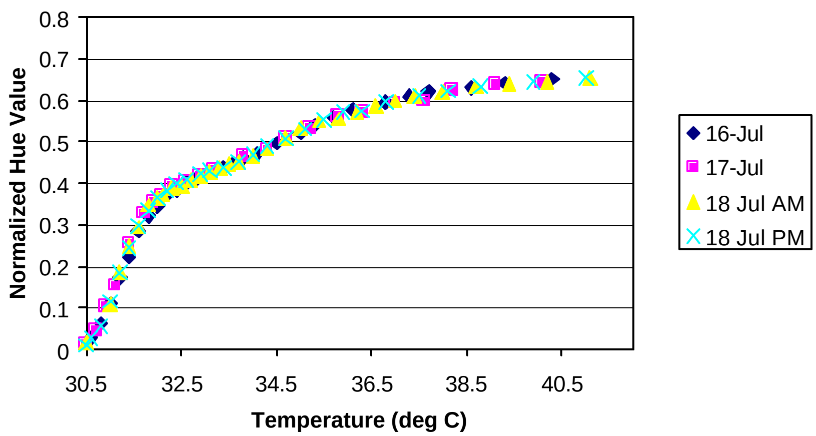

Figure 2 A calibration curve correlating liquid crystal hue with temperature.

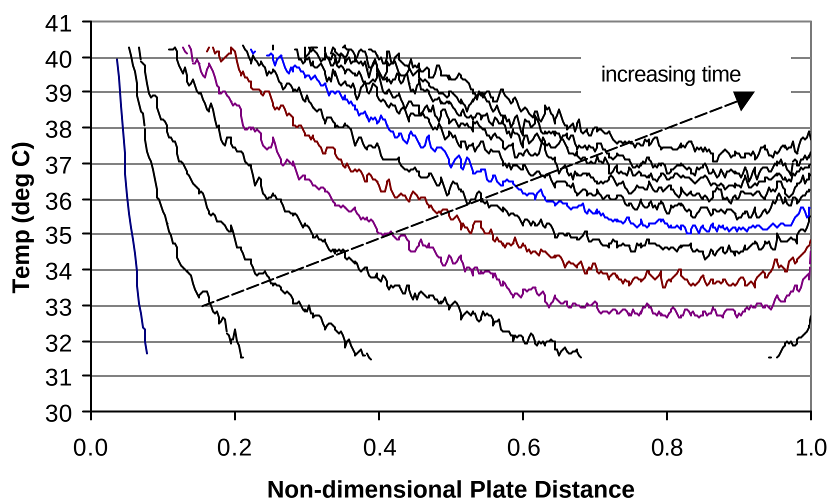

Figure 3 Temperature distribution over a flat plate after a change in air temperature (0=leading edge)

Flow Visualization

Flow visualization is being used to complement heat transfer results. By comparing the flow visualization results with the heat transfer results, the causes of specific heat transfer behavior can be determined. A water tunnel owned by Baylor University has been adapted to allow flow visualization by ink injection, and a mass flow-meter has been added. An example of the flow visualization results achieved is shown below.

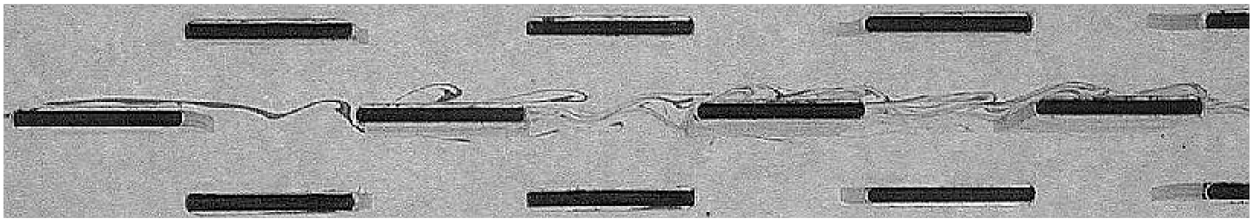

Figure 4 An example flow visualization photograph at Re=1000 for an offset-strip array.

Elevated Turbulence Level Tests

An undergraduate student worked during Summer 2002 on the measurement of turbulence intensity and length scales in the Baylor University subsonic wind tunnel (different from the tunnel used for this project). Knowledge gained in this tunnel is being used to design and install a passive turbulence generation grid in the wind tunnel used for this project. The work is based on the report published at the United States Air Force Academy (USAFA) by Simon et al. (2000) using the IFA 300 Hot-wire Anemometer. The student applied Simon's techniques to an existing passive grid in the larger 8"x12" wind tunnel. From this original report, a low pass filter and sample rate appropriate for the passive grid were chosen and the wind tunnel tested for both velocity and turbulence intensity uniformity. Preliminary results at several downstream stations show uniform turbulence intensity generation and velocity across the test section. Several centerline stations were also tested downstream from the grid and the results compared to the Roach et al. (1985) prediction. Again, the grid behaved as predicted with respect to turbulence decay, but there was an almost 1% increase in turbulence over the Roach et al. prediction at all downstream locations (See Figure 4.). This is not surprising since the data used to determine the Roach correlation varies widely.

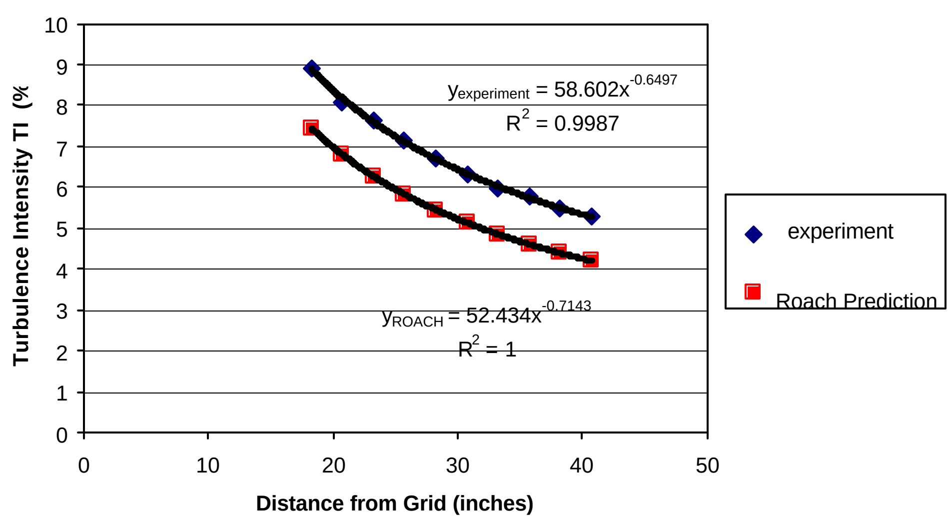

Figure 4 Comparison of experimental values of turbulence intensity to the Roach prediction

While the decay trend is predicted by Roach, it is always advisable to test the experimental grid to determine actual generated turbulence intensity and its uniformity. Also investigated were the characteristics of the IFA-300 in measuring the turbulence intensity. A dependence of reported turbulence intensity on low pass filter size was discovered. If the low pass filter is too low, then not enough of the signal is captured and the turbulence intensity recorded is too low. If the low pass filter is too high, then too much random noise is captured and the turbulence intensity is too high. This was confirmed by looking at the power spectrums for each condition. A parametric study of low pass filter and TI showed a region where this dependence on low pass filter was insensitive. The predictive methods developed by Simon et al. lead to the selection of a low pass filter in this region of insensitivity. The testing done by the student was done with a low pass filter of 20K Hz which is in this region. The procedures to calculate the micro and macro turbulence length scales were developed in addition to the turbulence intensity.

A second parametric study was done to determine the data block size needed to process the autocorrelation and the power spectrum. The autocorrelation is used in the calculation of the micro and macro turbulent length scales. The power spectrum is used to look at the frequencies captured by the IFA-300 to verify the choice of low pass filter. The IFA-300 software allows the correlation to be accomplished on block sizes of 256 to 256K. Since the files generated can be on the order of 2-4 Mb, the size of the data block determines the speed at which the data can be processed. The software processes the data using the block size specified and then averages the results of the different blocks. Usually, the largest block size possible is used to do the autocorrelation but this leads to long processing times (using 256K on a 2 Mb file means an 8.5 hour processing time on a Pentium four processor for one file). Figure 5 shows there may be an opportunity to reduce the block size without significantly changing the autocorrelation value. More investigation must be done or the data should be reduced another way, such as MatLAB.

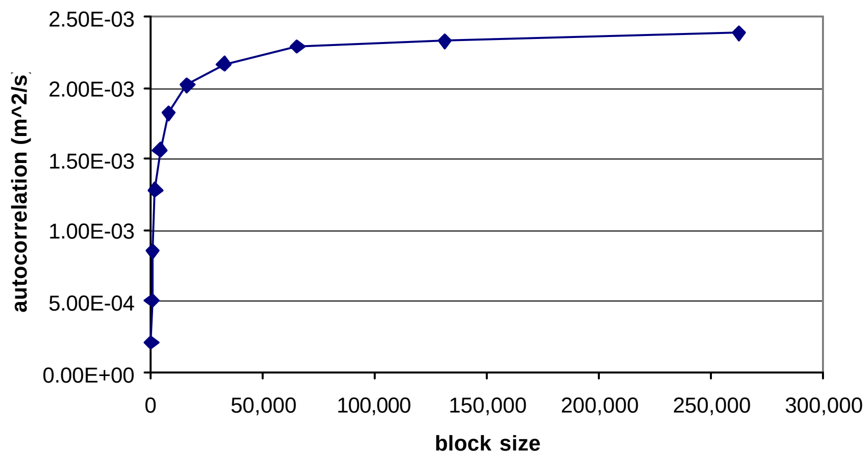

Figure 5 Block size vs. autocorrelation function (10K Hz low pass filter, 50K Hz sample, 20 seconds of data collection)

Future Work

1) The MATLAB automated data analysis program should be finalized shortly and the heat transfer coefficient distribution over the flat plate compared to theory for validation purposes.
2) Following validation, heat transfer distributions will be calculated for the interrupted surface geometry over a range of Reynolds numbers.
3) After tests with minimal background turbulence have been completed for one geometry, a lattice mesh to generate turbulence will be inserted in the wind tunnel, and similar tests will be performed with elevated turbulence intensities. Development of turbulence intensity and turbulent length scale measurement methods must be completed.

References

Anderson, M., 1998, Image Processing of Liquid Crystal Images Using MATLAB and Overview of a Liquid Crystal Image Processing Toolbox, USAF Academy Aeronautics Research Center Report No. HTL-07.

Blair, M.F., 1983, “Influence of Free-Stream Turbulence on Turbulent Boundary Layer Heat Transfer and Mean Profile Development, Part I—Experimental Data,” J. Heat Transfer, Vol. 105, pp. 33-40.

Blair, M.F., 1983, “Influence of Free-Stream Turbulence on Turbulent Boundary Layer Heat Transfer and Mean Profile Development, Part II—Analysis of Results,” J. Heat Transfer, Vol. 105, p. 41.

DeJong, N. C. and Jacobi, A. M., 1995, “An Experimental Study of Flow and Heat Transfer in Offset Strip and Louvered-Fin Heat Exchangers,” ACRC TR-91, University of Illinois at Urbana-Champaign.

DeJong, N. C. and Jacobi, A. M., 1999, Flow, Heat Transfer, and Pressure Drop Interactions in Louvered-Fin Arrays,” ACRC TR-146, University of Illinois at Urbana-Champaign.

DeJong, N. C., 1998, “A Complementary Experimental and Numerical Study of the Flow and Heat Transfer in Offset Strip-Fin Heat Exchangers,” J. Heat Transfer, Vol. 120, pp. 690-698.

Gentry, M. C. and Jacobi, A. M., 1995, “Heat Transfer Enhancement on a Flat Plate Using Delta-Wing Vortex Generators,” ACRC TR-82, University of Illinois at Urbana-Champaign.

Hancock, P.E. and Bradshaw, P., 1983, “The Effect of Free-Stream Turbulence on Turbulent Boundary Layers,” J. Fluids Engineering, Vol. 105, p. 284.

Roach, P. E., 1987, “The Generation of Nearly Isotropic Turbulence by Means of Grids,” J. Heat and Fluid Flow, Vol. 8, No. 2, pp. 82-92.

Simon, T. W., Van Treuren, K. W., and Byerley, A. R., 1999, "Flow Field and Turbulence Measurements," USAFA Department of Aeronautics Laboratory Report 8-99-01.