Instrumentation

Heat Flux Measurements

The heated plate also has three heat flux sensors embedded just under the surface. They are at positions 14.91, 76.5, 138.1 cm from the leading edge, centered in the *z* direction. The sensors are 2.5 cm square and return a voltage that corresponds to a heat flux, with a calibrated sensitivity provided by the manufacturer, RDF Corp., Model 20457-3, and are arranged along the heated wall at z = 0. Their sensor area is 2.5 cm square. The sensors were calibrated by the manufacturer and have an uncertainty of 5% of reading. Information on this sensor is attached at the end of this document.

Temperature Measurements

The thermocouples were spaced every 5.08 cm in the heated plate in the stream-wise (corresponding to *x* positions and *u* velocity) direction and in the cross-stream direction (*z*,*w*). In the heated plate, there are 160 thermocouples and all are 0.15 cm (± 0.013) cm of the surface.

Each of the three polycarbonate walls has 7 stream-wise positions for thermocouples. The two side walls have the thermocouple closest to the heat plate 2.0 cm from the plate and 9.7 cm and 24.9 cm after that (±0.08 cm). The top polycarbonate wall has evenly spaced thermocouples at the same stream-wise positions, centered in the cross-stream direction and spaced 7.62 cm on either side of center.

National Instruments hardware including 5 NI-cDAQ-9188 chassis that hold 20 NI-9213 16 channel thermocouple modules is used to measure the temperatures and heat flux. All thermocouples were calibrated before installation to a 0.3°C source using an IsoTech Fast-Cal Temperature Calibrator. The thermocouple modules were calibrated by National Instruments.

The six resistive heaters, driven with three power supplies, sit under the heated plate and are capable of maintaining the plate at 150ºC with the mean velocity at 4.6 m/s. The power supplies are controlled on the plate temperature independently to keep the plate approximately isothermal.

A description to the manner in which the depth of the plate thermocouple holes was determined along with the depth values is attached to this document.

Pressure Measurements

The pressure drop through the test section measured using a 1-Torr thermally controlled capacitance- type pressure sensor. Pressure taps were fixed in the fiberglass inlet and outlet, both 75.438 mm from the leading and trailing edges of the test section. That makes the total distance between the pressure taps 2.07 m.

Particle Image Velocimetry Measurements

The particle image velocimetry (PIV) camera was an Imager Intense 12-bit digital camera from LaVision. The CCD sensor is 1376 X 1040 pixels with a pixel size of 6.45 micrometers square. The laser was a New Wave Research Solo PIV III 15. Two lasers at 50 mJ/pulse and 532 nm could fire up to 15 Hz. Data were acquired at 4 Hz in double-pulse mode.

Two different lenses wer used on the camera, depending on what measurement is being made. A 105-mm lens with an extension tube is used when acquiring images for the boundary layer flow over the heat flux sensors. A 28-mm lens is used when acquiring images for the inlet boundary condition. In both cases, a filter is placed over the lens to decrease reflections allowing only 532 nm light is passed through the filter. The system has two orientations to measure the inlet, and one to measure the velocity over the heat flux sensors.

PIV measurements were used both for inflow (at the inlet) and as system response quantities. The inlet profiles were measured with a time increment between the images *dt* that resulted in an average displacement of 8.5 pixels. The ratio of the streamwise velocity rms to the mean was found to be 6%.

The data were acquired and processed using DaVis 8.1.6. A ruler was used to calibrate the camera for the PIV data. For the inflow, the particle displacements were generally around 12 pixels in the free stream, with particle image diameters of 2 pixels. This diameter is near the optimum for small RMS errors due to particle diameter. The uncertainty method accounts for the variation in particle image diameter and displacement. The SRQ velocity data at the heat flux sensors had a particle image diameter of 2.6 pixels and a particle image density of 0.03 particles/pixel.

The images for the SRQ data used the entire imaging chip (1376 X 1040 pixels). The inlet data region of interest was generally 1376 X 256 pixels, with the focus being at the inlet of the test section. The images were processed using the following steps after the acquisition of the images:

1.The images were corrected for small vibrations and rotation using the wall as a reference (making the wall straight up and down and in the same position for every image).

2.The average image was subtracted from all of the images to decrease the background noise.

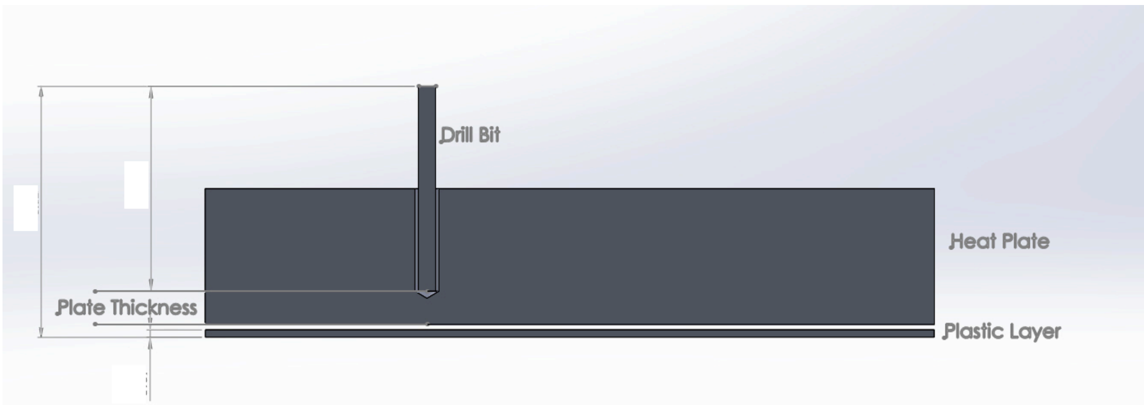
3.PIV Processing using 64x64 window with 1 pass, then decreased to a 32x32 windows with 75% overlap for 2 passes (the SRQ images were processed with image correction due to the dewarping calibration).

4.The PIV data were post-processed with an allowable vector range of 5 m/s (±5 m/s) in v and 0 m/s (±1 m/s) in u (w was not measured for the SRQ data). The vectors were deleted if the peak ratio was less than 2. A median filter was used to remove vectors for which the difference to the average was greater than 1.75xRMS of its neighbors and inserted (or reinserted) if the difference to the average was less than 2.5xRMS of its neighbors. Also, groups with less than five vectors were removed and the allowable vector range was computed again.

5.The average and standard deviation (RMS, $u'u'$, $u'v'$ or $v'v'$) were also computed.

The thermocouple junction lies below the surface by a small amount, and this distance is important to lag effects during transients. As such, their position in they *y* direction and its uncertainty must be known. The *x, z* location of the TCs was programmed in on a CNC milling machine, and thus has low uncertainty.

The measurement is made as shown below, with a drill bit of known length inserted into a hole, and the distance from the end of the bit to the far side is measured. We will denote the measurement *X*, the bit length *B*, and the plastic tape layer thickness *T*.



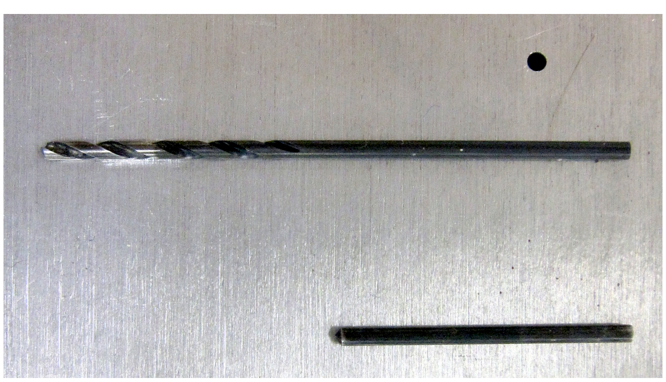
So, the thickness of the plate between the TC and the exterior is

$t = X - B - T$

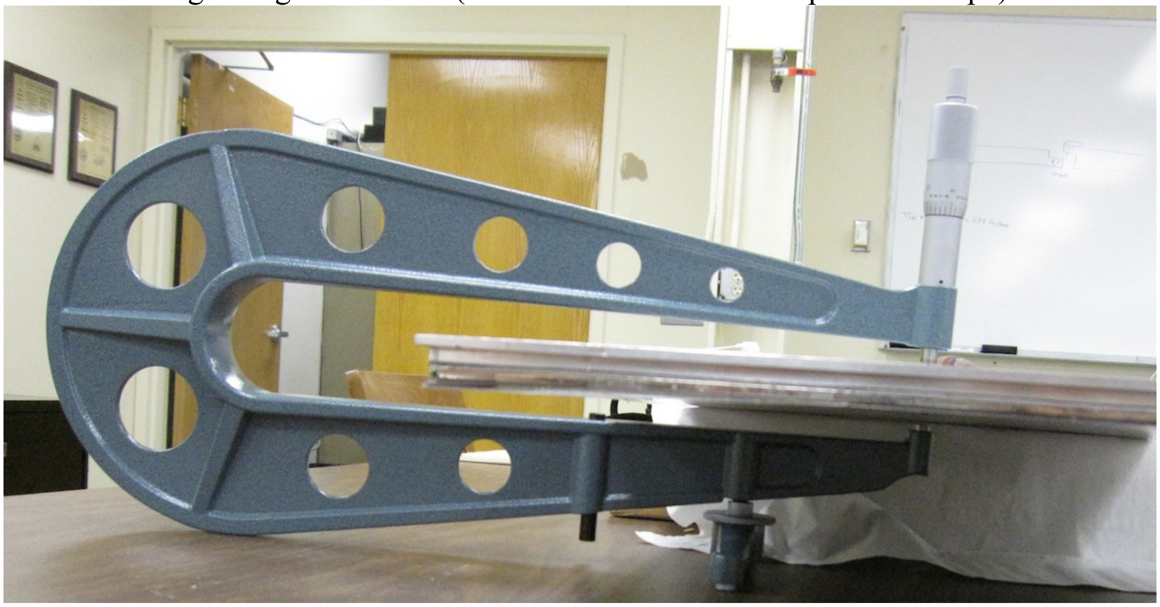
and since the derivatives are all unity, the error propagation formula gives that

$u_t = \sqrt{u_X^2 + u_B^2 + u_T^2}$.

The nickel plated outside surface of the plate was covered by the protective tape during the measurements. The manner in which the tape thickness is accounted for in the measurements is shown below. Measurements were made with the back of the plate was upwards exposing all the holes into which the thermocouples would eventually be placed. The fluted section of a drill bit of the same size used to drill the holes was removed and the bit's length was measured a micrometer. The remainder of the bit was measured with a micrometer and its length found to be 0.96125 inches. This measurement was repeatable and so the resolution of the micrometer of 0.00025 inches is assigned as u_B.



The drill bit rod was inserted into each hole and the thickness of the plate and bit was measured using a long micrometer (this thickness includes the protective tape).



The measurement described above was repeated to establish random uncertainty in the measurement. It was found that the measurements repeated to within 0.002". So, the uncertainty of X is the root sum of the bias and random uncertainty, or

$u_X = \sqrt{0.00025^2 + 0.001^2} = 0.001$ inches.

The tape thickness (0.0065 inches) was found repeatable, so, again, the micrometer accuracy is assigned as the uncertainty.

Therefore, the uncertainty in the measurement is dominated by the repeatability of the overall measurement, or $u_t = 0.001$ inches. In the table below, row 1 is near the leading edge of the plate, column 3 corresponds to $z = 0$, and z increases from 1-5.

t [inches]	**1**	**2**	**3**	**4**	**5**
1	0.078895625	0.056895625	0.052195625	0.057395625	0.066595625
2	0.078095625	0.056295625	0.050895625	0.054395625	0.056195625
3	0.075495625	0.069495625	0.077795625	0.057895625	0.063395625
4	0.061295625	0.068995625	0.049795625	0.051995625	0.058295625
5	0.054195625	0.046595625	0.045695625	0.044895625	0.052495625
6	0.052395625	0.040995625	0.041595625	0.038695625	0.046695625
7	0.051095625	0.038695625	0.038595625	0.036295625	0.046295625
8	0.054395625	0.039295625	0.037495625	0.037295625	0.050195625
9	0.067695625	0.041995625	0.041195625	0.041795625	0.087995625
10	0.088695625	0.052995625	0.043195625	0.056995625	0.065395625
11	0.062795625	0.044595625	0.042095625	0.043895625	0.062195625
12	0.047995625	0.034795625	0.045395625	0.034895625	0.046595625
13	0.039395625	0.026495625	0.030695625	0.030795625	0.038995625

14	0.037595625	0.026995625	0.030595625	0.028995625	0.037595625
15	0.032295625	0.030695625	0.034395625	0.033595625	0.041795625
16	0.057995625	0.039895625	0.039095625	0.041095625	0.051895625
17	0.074295625	0.053095625	0.042795625	0.053795625	0.060795625
18	0.068795625	0.048595625	0.041595625	0.047795625	0.059895625
19	0.042095625	0.031395625	0.032095625	0.041595625	0.055395625
20	0.033995625	0.075595625	0.028895625	0.031095625	0.051395625
21	0.035095625	0.025895625	0.028695625	0.035095625	0.051395625
22	0.039995625	0.028195625	0.029795625	0.039295625	0.056995625
23	0.045695625	0.033995625	0.033195625	0.046795625	0.065295625
24	0.077495625	0.046395625	0.039595625	0.057195625	0.076895625
25	0.069295625	0.039595625	0.038895625	0.055595625	0.075495625
26	0.050695625	0.033395625	0.033995625	0.048095625	0.066595625
27	0.041295625	0.029895625	0.032395625	0.045295625	0.062895625
28	0.036695625	0.027995625	0.031795625	0.044095625	0.061695625
29	0.038695625	0.029795625	0.033695625	0.044395625	0.063395625
30	0.052195625	0.032495625	0.033295625	0.045595625	0.062395625
31	0.064795625	0.044395625	0.041995625	0.054495625	0.068695625
32	0.068695625	0.069795625	0.065295625	0.070295625	0.073795625