Introduction

A strong understanding of uncertainty propagation and analysis is critical to the design and implementation of experimental research. This assignment focused on the theoretical design of a measurement system for a phase change experiment. The primary goal of the project was to select suitable components for the measurement system and perform a design stage uncertainty analysis. Ultimate, the intent of this type of uncertainty analysis is to determine what measurements to the system is most sensitive too and where improvements should be made. As a results, a discussion detailing this sensitivity analysis will be included in this report.

The experiment of interest will examine both the steady state and transient phenomenon of water boiling on a thin film heater as presented in the project statement and depicted in Figure 1:

> A thin film heater is deposited on the bottom surface of a silicon wafer and a DC power supply is used to provide electric power to the heater ($q_{heater} = V*I$). The heater and wafer are of identical dimensions (diameter d = 5 cm). Ten thin film thermocouples are located on the top surface of the silicon wafer to provide local temperature data. The silicon wafer is placed in a chamber with the working fluid (water). A chiller/heater can be used to control the temperature of water in the chamber; this chamber temperature is measured using a thermocouple. The chamber pressure is also monitored using an absolute pressure transducer.

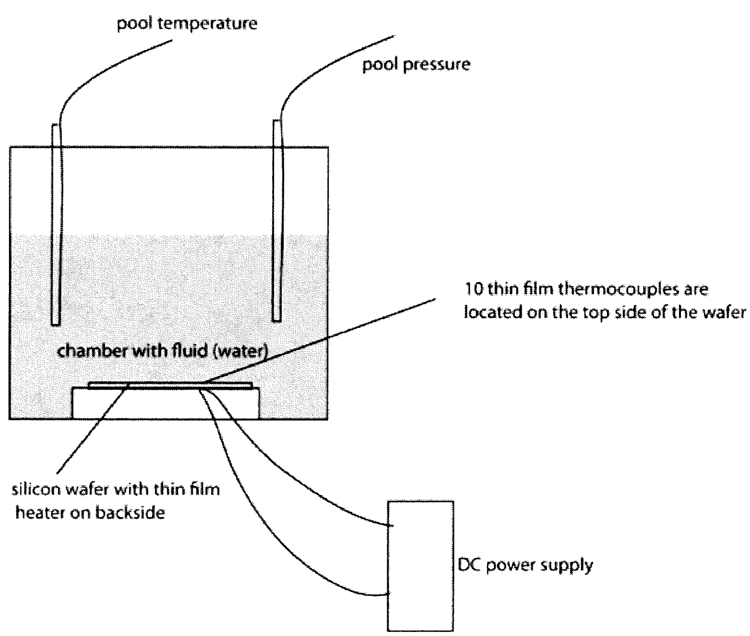


Figure 1: Experimental setup from problem statement

Component Selection

Also provided in the problem statement were the specifications for the thermocouple, heater power supply, and length measurements as well as expected nominal ranges and desired frequency of measurement for all variables (Table 1).

Table 1: Specification and Uncertainty Values for provided instrumentation

Measured variable	Nominal range	Sampling Frequency	Sensitivity	Uncertainty Provided
Heater Voltage	0-100 V	10	-	±0.01 V
Heater Current	0-2 A	10	-	±0.1 A
Fluid Temp	20-100 °C	1	0.1 mV/°C	±1 °C
Fluid Pressure	0.2-1 bar	1	See Table 2	See Table 2
Surface Temp	20-150 °C	2000	1 mV/°C	±2 °C
Diameter	0.1 mm - 10 cm	-	-	±0.01 mm

To complete the measurement system additional signal conditioning, data acquisition, and pressure sensing instrumentation was needed. Using the National Instruments website (http://www.ni.com/data-aquisition/) as a reference a complete signal conditioning and data acquisition system was selected to fulfill the measurement requirements highlighted in the problem statement, Table 2 summarizes these selections.

Pressure Transducer Selection

Also included with the problem statement was a data sheet for the Omega PX02/PXM02 series high-accuracy pressure transducers. Given the particular range of interest of 0.2-1 bar the PXM02MD0-1.6BARG5T was selected. This transducer covers a range of 0-1.6 bar and has a total calculated uncertainty of less that ±0.188% FSO with a 0-5 V dc output.

This range and output is ideal for the selected application. The wider rage allow for flexibility in the range of expected values but more importantly avoids sampling at either extreme of the range were linearity error may become a concern. Furthermore, the 0-5 V output is the result of amplification immediately after the sensor with will aid in noise reduction and provides a direct input into most DAQ systems without out the need for additional signal conditioning.

Cold-Junction Compensator – NI SCXI-1328

A cold-junction compensator (CJC) provides a reference value for thermocouple measurements using a thermistor and is crucial to accurate temperature measurements. The selected CJC, part # NI SCXI-1328 was chosen primarily as it is the recommended CJC for use with the selected voltage amplifier. In addition the SCXI-1328 provides 8, isolated, isothermal channels for thermocouple inputs and provides an absolute uncertainty of ±0.5 °C between 15°C and 35°C. Thus, this CJC provides optimal performance when joined with the other signal conditioning components. Two of these components will be needed for the measurement system.

High-Voltage Terminal Block – NI SCXI-1327

The selected high-voltage terminal block allows for a input voltage of ±300 V to the selected voltage amplifier and attenuator, and is recommended by national instruments. This component simply provides a high-voltage shield and fuse to protect the remaining components in the event of a voltage overload and is required for input voltages above ±10 V to the NI SXCI-

1125 amplifier. However, because of this requirement the uncertainties of these components is related and presented as a single absolute value in National Instruments manual. OK

Voltage Amplifier and Attenuator – NI SCXI-1125

The selected voltage amplifier uses 8 isolated channels with programmable gain values varying from ±0.005 V to ±2000 V and was selected to amplify the thermocouple signals and attenuate the voltage supply measurement to within a range of ±5 V to be compatible with the selected low pass Butterworth filter. This type of signal conditioning is important as it allows you to utilize the full capabilities and resolution of your measurement system. For example using an ADC with a ±10 V to measure a signal range of 0-5 V will only allow for use of ne quarter of the possible analog to digital conversion range and as a result will result in a greater uncertainty. To minimize this type of uncertainty all input signals are being converted to a 0-5 V range. This range was selected as a standard input and output range for each signal conditioning and DAQ component selected. Two of these components will be needed for the measurement system.

Low Pass Butterworth Filter Module – NI SCXI-1143

The selected filter module has a programmable cutoff range between 10 Hz and 25 kHz and was selected to provide an anti-aliasing filter for the surface thermocouple measurements. The desired sampling frequency for these thermocouple measurements is 2000 Hz; this means that by sampling at that rate the system will only be able to accurately capture signal fluctuations at 1000 Hz or slower. Thus to prevent aliasing that may result from sampling faster signals a 1000 Hz low pass filter was selected.

In addition to its programmable filter cutoff range, the NI SCXI-1143 offers an absolute uncertainty of ±500 μV, allows for simultaneous sampling at a 333 kHz, and provides a stable output voltage of ±5 V making it optimally compatible with the other selected components. Furthermore, the simultaneous sampling feature eliminates the need for a multiplexer reducing cost and eliminating a potential source of error. Two of these components will be needed for the measurement system.

NI PXIe-6368 – 16 Ch. Simultaneous sampling DAQ

The selected DAQ offers 16-bit resolution with a simultaneous sampling rate of 2 MHz across 16 channels. Furthermore, it allows for input ranges of ±1 V, ± 2.5V, ±5 V, and ±10 V providing both compatibility with the other components and flexibility if the measurement system is modified in any way. Additionally, the high simultaneous sampling feature eliminates the need for a multiplexer reducing cost and eliminating a potential source of error. Finally, the 16-bit resolution offers a low uncertainty resulting in accurate analog to digital conversion.

hmm

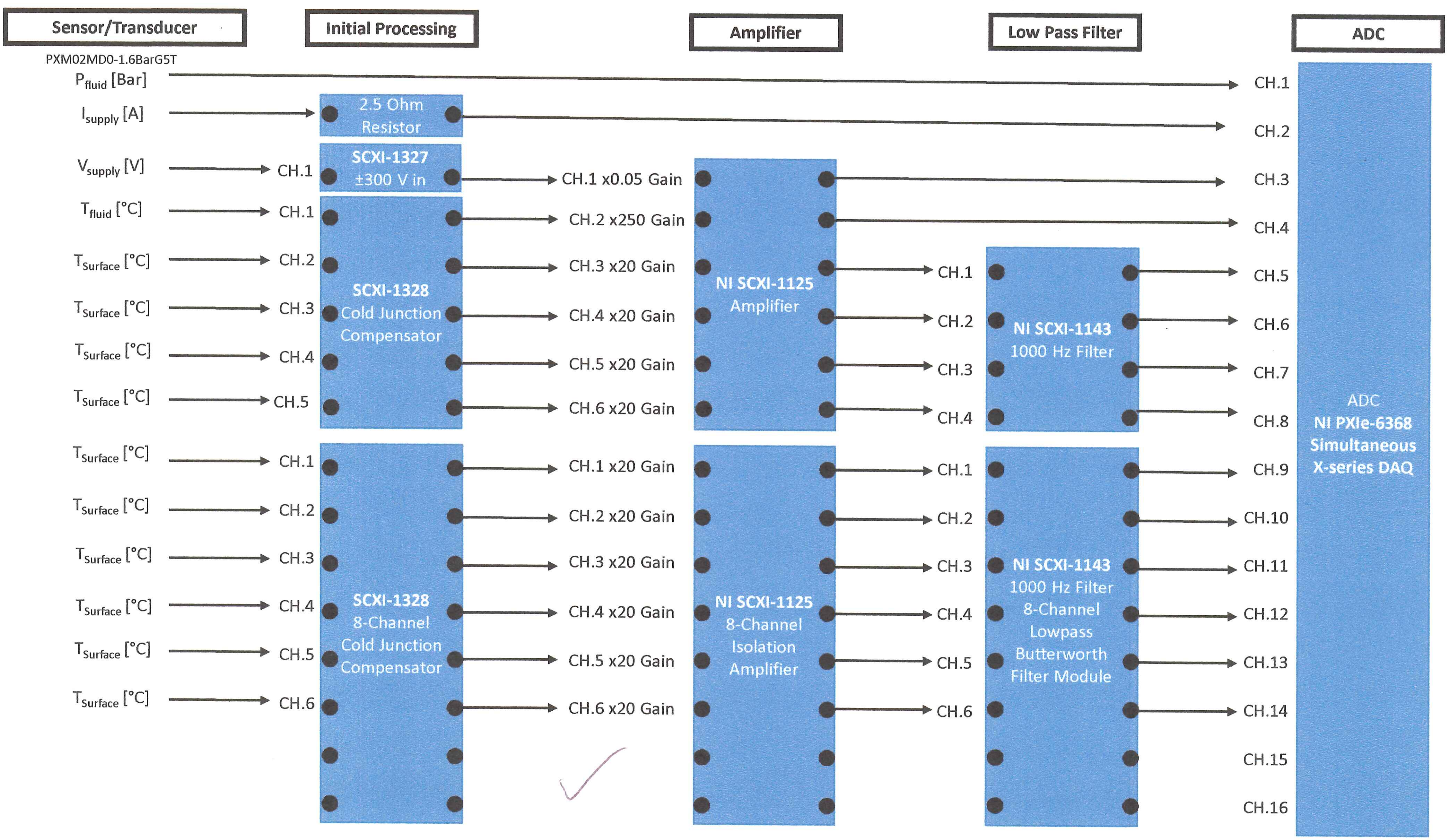
Schematic

Figure 2 provides a schematic view of the measurement system with the component specifications and uncertainties summarized in Table 2.

Table 2: Summary of signal conditioning and DAQ component specifications

Component	Input Range	Output Range	Sampling Rate	Resolution	Addition Information	Published Uncertainty
PXM02MD0-1.60BAR5T Pressure Transducer	0-1.6 bar	0-5 V	-	3.125 V/bar	-	Linearity ±0.15% FSO Hysteresis ±0.1% FSO Repeatability ±0.05% FSO
SCXI-1328 - Cold Junction Compensator	-	-	Continuous	-	Isothermal Channel Isolation	±0.5 °C from 15-35 °C
SCXI-1327 - High Voltage Terminal Block	±300 V	±300 V	Continuous	-	-	±1.0138 V FS input
NI SCXI-1125 - 8-Channel Isolation Amplifier - Gain 0.05	±100 V	±5 V	Continuous	-	-	
NI SCXI-1125 - 8-Channel Isolation Amplifier - Gain 20	±0.25 V	±5 V	Continuous	-	-	±2.39 mV FS input
NI SCXI-1125 - 8-Channel Isolation Amplifier - Gain 250	±0.02 V	±5 V	Continuous	-	-	±0.121 mV FS input
NI SCXI-11438-Channel Low pass Butterworth Filter - 1000 Hz	±5 V	±5 V	333 kHz Simultaneous	-	10 Hz - 25 kHz cutoff range	±500 µV
NI PXIe-6368 Simultaneous X Series Data Acquisition	±1 V, ±2.5 V, ±5 V, ±10 V	-	2 MHz 16 Ch. Simultaneous	16-bit	-	±0.153 mV

Measurement System Schematic



Uncertainty Discussion and Sensitivity Analysis

The calculated uncertainty for both measured and calculated values is presented in Table 3 while all calculations are presented in Appendix A. It is important to note that all uncertainty values for the selected components were taken from National Instruments Published manuals. Furthermore, the manual for the NI SCXI-1125 amplifier indicates that inclusion of the uncertainty values should be done prior to amplification of the signal. Appendix A demonstrates this calculation.

Table 3: Calculated Uncertainty Values for measured and calculated variable

Variable of Interest	Nominal Range	Calculated Uncertainty
$T_{surfrace}$ (Instantaneous)	20-150 °C	±3.16 °C (of measure)
T_{fluid}	20-100 °C	±1.64 °C (of measure)
P_{fluid}	0.2-1 bar	±3 mbar ±0.188% FSO
V_{supply}	0-100 V	± 1.02 V (of measure)
I_{supply}	0-2 A	± 0.117 A (of measure)
q''_{heat}	0-10.19 W/cm^2	± 0.615 W/cm^2 ± 5.94% FSO
$T_{surfrace\ ,average}$	20-150 °C	±1 °C (of nominal)
Wall Super Heat	0 - 120 °C	±1.92 °C (of nominal)
Diameter	5 cm	±0.01 mm

Table 3 clearly indicates four primary sources of uncertainty in the measured values namely, $T_{surface}$, V_{supplu}, I_{supply}, and q''_{heat}. Beginning with $T_{surfacec}$ the primary source of error is from the x20 amplifier and the thermocouple itself, little can be done to improve either of these sources of error shot of replacing each component with a more accurate equivalent. Due the dramatic cost of amplifying signal conditioners it is recommended that the thermocouples themselves be replaced. Currently the thin film thermocouples have a nominal uncertainty of ±2 °C, this is highly inaccurate and could be improved. It should be noted that averaging the surface temperature measurement does result in a dramatic reduction in uncertainty, however do this also eliminates the system's ability to measure local frequency fluctuations and would not solve the problem with the transient measurements.

calibration could help w/ unc.

Similarly to the surface temperature V_{supply} has a large source of uncertainty in the voltage attenuator that reduces the signal to a range readable by the DAQ. A low cost alternative would be to implement a simple voltage divider resistor network. This achieve a similar result and likely reduce the uncertainty significantly. In addition, although the voltage has a significant uncertainty it does not dramatically affect any of the other measurements, including the heat flux as shown in Appendix A. Thus, although the uncertainty is high it not a high priority to improve.

The heat flux has the highest uncertainty by far and is highly sensitive to both the current and length measurements. Little can be done in the case of the current as the nominal uncertainty of the supply current is fixed at ±0.1 A or ±0.1 5% FSO. This uncertainty value is the single largest contributor to the systems uncertainty, but could only be reduced by selecting a more accurate power supply. Alternatively, the length measurement could be easily reduced by simply purchasing a more accurate measurement device. Such devices are inexpensive and an improvement in this area would significantly improve the over uncertainty in the heat flux calculation. That being said, if cost is not a concern improving the uncertainty in the current measurement is top priority.

Appendix A - Calculations

Measured Uncertainties

$T_{surface}$ — CJC — ×20 Amplifier — 1000 Hz low Pass Filter — ADC

±2°C	±0.5°C		From manuals	±5V
1 mV/°C	1 mV/°C			$\frac{10V}{2^{16}} = 0.153mV$
±2mV	±0.5mV	±2.39mV	±500µV	±0.153mV

$$\sqrt{\left(20\sqrt{.002^2+.0005^2+.00239^2}\right)^2+.0005^2+.000153^2} = \pm 0.0631V$$

$$1mV/°C\,(\underset{gain}{20}) = 0.02V/°C \qquad 0.02V/°C\,(0.0631V) = \boxed{\pm 3.16°C}$$

P_{fluid} 0–1.6 bar 3.125 V/bar 0–5V output

Linearity	±0.15% FSO	±.0024 bar	±.0075V
Hysteresis	±0.1% FSO	±.0016 bar	±.005V
Repeatability	±0.05% FSO	±.0008 bar	±.0025V

$$u_p = \sqrt{.0075^2+.005^2+.0025^2+\underbrace{.000153^2}_{ADC}} = \pm .00935V$$

$$= \boxed{\pm 3mbar}$$

T_∞ — CJC — ×250 Amplifier — ADC

±1°C	±0.5°C	From manuals	
0.1 mV/°C	0.1 mV/°C		
±0.1mV	±0.05mV	±0.121mV	±0.153mV

$$u = \sqrt{\left(250\sqrt{0.0001^2+.00005^2+.000121^2}\right)^2+.000153^2} = \pm 0.041V$$

$$0.1 mV/°C\,(250) = 0.025 V/°C \quad \therefore \quad \boxed{\pm 1.64°C}$$

V_{meas} — High Voltage Terminal Block — ×0.05 Attenuator — ADC

±0.01V	±1.0138V	±.153mV

$$u = \sqrt{\left(0.05\sqrt{.01^2+1.0138^2}\right)^2+.000153^2} = \pm 0.0513V$$

$$V_{actual} = V_{measure}(20) \Rightarrow u(20) \Rightarrow \boxed{\pm 1.02V}$$

I — [Resistor 2.5 Ω ± 0.5% convert to Voltage] — [ADC]

± 0.1A   ± 0.0125 Ω   ± 0.153 mV

0-2A

$V = IR \qquad \frac{\partial V}{\partial R} = I \qquad \frac{\partial V}{\partial I} = R$

$$u = \sqrt{\left(\frac{\partial V}{\partial R}U_R\right)^2 + \left(\frac{\partial V}{\partial I}U_I\right)^2} = \sqrt{(2(0.0125))^2 + (2.5(0.1))^2} = 5V \pm 0.25V$$

$$U_T = \sqrt{0.25^2 + 0.153^2} = \pm 0.293V$$

$I = \frac{V}{R} \qquad \frac{\partial I}{\partial V} = \frac{1}{R} \qquad \frac{\partial R}{\partial V} = \frac{-V}{2R^2}$

$$U = \sqrt{\left(\frac{.293}{2.5}\right)^2 + \left(\frac{5(.0125)}{2(2.5)^2}\right)^2} = \boxed{\pm 0.117\,A}$$

Calculated Values.

$q'' = \frac{VI}{A}$

$q'' = \frac{VI4}{\pi D^2} = \frac{100(2)(4)}{\pi(5^2)} = 10.19\, W/cm^2$

V   I $A = \frac{\pi D^2}{4}$

D

$\frac{\partial q''}{\partial V} = \frac{I4}{\pi D^2} \qquad \frac{\partial q''}{\partial I} = \frac{V4}{\pi D^2} \qquad \frac{\partial q''}{\partial D} = \frac{-8VI}{\pi D^3}$

$$u = \sqrt{\left(\frac{\partial q''}{\partial V}U_V\right)^2 + \left(\frac{\partial q''}{\partial I}U_I\right)^2 + \left(\frac{\partial q''}{\partial D}U_D\right)^2}$$

$$= \sqrt{\left(\frac{2(4)}{\pi(5)^2}(1.02)\right)^2 + \left(\frac{100(4)}{\pi(5^2)}(0.117)\right)^2 + \left(\frac{-8(100)(2)}{\pi(5)^3}(.001)\right)^2} = \boxed{\begin{gathered}\pm 0.608\, W/cm^2 \\ \pm 5.94\%\, FSO\end{gathered}}$$

$\frac{\pm 0.605}{10.19} = .0594 \qquad q'' = 0 - 10.19\, W/cm^3$

Sensitivity Analysis

$\frac{\partial q''}{\partial V} = \frac{I4}{\pi D^2} = \frac{2(4)}{\pi(5^2)} = 0.102$ units?

$\frac{\partial q''}{\partial I} = \frac{V4}{\pi D^2} = \frac{100(4)}{\pi(5)^2} = 5.09$

$\frac{\partial q''}{\partial D} = \frac{8VI}{\pi D^3} = \frac{8(100)(2)}{\pi(5)^3} = 4.07$

$$T_{surf,AVG} = \sum_{n=1}^{10} \frac{T_{i surf}}{10} \qquad \frac{\partial T_{SAVG}}{\partial T_{i surf}} = \frac{1}{10}$$

$$U_{T_{SAVG}} = \sqrt{\sum_{n=1}^{10} \left(\left(\frac{u_{T_{i surf}}}{10}\right)\right)^2} \Rightarrow \sqrt{10\left(\frac{3.16}{10}\right)^2} = \pm 0.999°C \Rightarrow \boxed{U_{T_{SAVG}} = \pm 1°C}$$

Wall super heat.

$$WSH = (T_{SAVG} - T_{fluid}) \qquad \frac{\partial WSH}{\partial T_{SAV}} = 1 \qquad \frac{\partial WSH}{\partial T_{fluid}} = -1$$

$$U_{WSH} = \sqrt{U_{T_{SAVG}}^2 + U_{T_f}^2} = \sqrt{0.999^2 + 1.64^2} \Rightarrow \boxed{U_{WSH} = \pm 1.92°C}$$