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WASTE HEAT RECOVERY FROM GAS TURBINE ENGINE AND CENTRIFUGAL COMPRESSOR VOLUTE DESIGN OPTIMIZATION

by

Aaron Santiago

December 2021

Thesis Advisor:	Garth V. Hobson
Co-Advisor:	Douglas L. Seivwright

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As the nation's top user of energy, the U.S. Department of Defense (DOD) has initiated ways to become more energy efficient. The Naval Postgraduate School contributes to this initiative by studying the possibilities of waste heat recovery from the exhaust stream of an Allison T63-A-700 gas turbine engine. Previous work centered on the design of two heat exchangers integrated into the exhaust duct work and using carbon dioxide as a working fluid. In support of this present work, modifications were made to the carbon dioxide flow path through the heat exchanger as well as the data acquisition system in order to provide further analyses of the heat exchanger's effectiveness. Baseline data measured in previous work on one of the heat exchangers was confirmed for this research, in addition to establishing new baseline data of the second heat exchanger. Additionally, this thesis expanded on previous computational fluid dynamics analysis of a centrifugal compressor and volute, studying the effects of compressor performance with varying rotational velocities and back pressures.

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WASTE HEAT RECOVERY FROM GAS TURBINE ENGINE AND CENTRIFUGAL COMPRESSOR VOLUTE DESIGN OPTIMIZATION

Aaron Santiago
Lieutenant, United States Navy
BS, United States Naval Academy, 2012

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December 2021

Approved by: Garth V. Hobson
Advisor

Douglas L. Seivwright
Co-Advisor

Garth V. Hobson
Chair, Department of Mechanical and Aerospace Engineering

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ABSTRACT

As the nation's top user of energy, the U.S. Department of Defense (DOD) has initiated ways to become more energy efficient. The Naval Postgraduate School contributes to this initiative by studying the possibilities of waste heat recovery from the exhaust stream of an Allison T63-A-700 gas turbine engine. Previous work centered on the design of two heat exchangers integrated into the exhaust duct work and using carbon dioxide as a working fluid. In support of this present work, modifications were made to the carbon dioxide flow path through the heat exchanger as well as the data acquisition system in order to provide further analyses of the heat exchanger's effectiveness. Baseline data measured in previous work on one of the heat exchangers was confirmed for this research, in addition to establishing new baseline data of the second heat exchanger. Additionally, this thesis expanded on previous computational fluid dynamics analysis of a centrifugal compressor and volute, studying the effects of compressor performance with varying rotational velocities and back pressures.

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LIST OF ACRONYMS AND ABBREVIATIONS

$\dot{m}$	Mass Flow
ΔT_{lm}	Log Mean Temperature
μ	Dynamic Viscosity
A	Surface Area
C	Specific Heat Coefficient
CFD	Computational Fluid Dynamics
D	Diameter
DAQ	Data Acquisition System
DOD	Department of Defense
DSA	Digital Sensor Array
EPI	Eldridge Valve Mass 400 Series Flow Meter
h	Heat Coefficient
k	Thermal Conductivity
M	Mach Number
NI	Nuclear Instruments
N_u	Nusselt Number
p	Outlet Carbon Dioxide Gas Pressure
p_o	Inlet Carbon Dioxide Gas Pressure
Pr	Prandtl Number
q	Heat Transfer
q_{max}	Max Heat Transfer
R	Gas Constant
Re	Reynolds Number
R_w	Tube Conduction
SDG8	Perle Iolan SDG 8 P Gateway
T_{ci}	Carbon Dioxide Gas Inlet Temperature
T_{co}	Carbon Dioxide Gas Outlet Temperature
T_{hi}	Exhaust Gas Inlet Temperature
T_{ho}	Exhaust Gas Outlet Temperature

T_o	Outlet Temperature
U_∞	Gas Velocity
UA	Overall Heat Transfer Coefficient
γ	Ratio of specific heats
ρ	Density

I. BACKGROUND

A. ENERGY NEEDS OF THE U.S. NAVY

With expanding demand in operational technology and increase in oil prices, the need for energy efficiency is no longer just an idea but a necessity. Not only is there a financial aspect to energy efficiency, but also a need for increases to operational effectiveness and energy security [1]. With the DOD being the leaders in energy consumption of all federal agencies, the need for energy efficiency is of extreme importance. In the past, the U.S. Navy accounted for 30% of DOD energy usage, in which 75% was used afloat [2]. Today 65% of energy ashore is generated from alternate means and 35% of energy afloat is generated from nuclear power and biofuels [3]. Though strides are being made in the right direction to become more energy efficient, there are other means that are worth exploring, which this thesis addresses.

B. WASTE HEAT RECOVERY ON U.S. NAVY SHIPS

Since the 1960s there has been over $100 million invested by the U.S. Navy into waste heat recovery from engine exhaust. Over those years three major programs were implemented but have since been removed due to requirements not being met. Two of the three projects utilized recuperators to recover engine exhaust, while the third utilized engine exhaust to heat distilled water to produce steam for shipboard systems. Though each project saved on fuel usage, challenges such as fouling, corrosion, and thermal stresses prevented its successive growth [3].

This research focuses on the effectiveness of utilizing exhaust heat through a pair of heat exchangers to heat carbon dioxide, which has fewer corrosive properties then wet steam. The heated carbon dioxide will then be utilized to drive a Brayton cycle as indicated in Figure 1. By decoupling the compressor and turbine, it allows each to run at its own independent speeds allowing electricity to be generated locally near the heat exchangers.

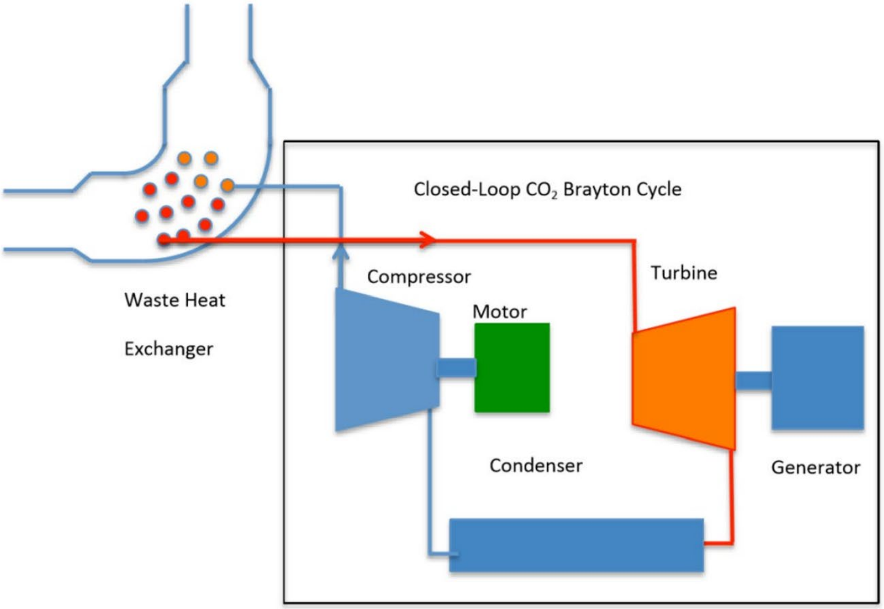


Figure 1. Illustration of Project End state. Adapted from [4].

C. PRECEDING THESIS WORK

(1) "Waste Heat Recovery from a Gas Turbine Engine Using a Heat Exchanger and Associate Centrifugal Compressor Volute Design and Simulation": Michael Kaim

Kaim's [4] thesis modified the tubing within the heat exchanger that was built by Buck [5] and designed by Poslinelli [6]. Kaim modified and duplicated Buck's design, adding a second heat exchanger to the engine exhaust ducts. Kaim also improved the data acquisition system (DAQ) initially developed in Belna's thesis [7], by utilizing local functions that took data from the main body of the script and organized it into six defined output files, which allowed for easy reference during data analysis. Finally, Kaim conducted a CFD analysis on a compressor to determine the pressure ratios achieved and associated efficiencies while operating at 100,000 RPM.

(2) "Waste Heat Recovery System for a Gas Turbine Engine and Carbon Dioxide Compression Simulation": Coria Buck

Buck's [5] thesis utilized the heat exchanger design created by Polsinelli [6] and fabricated a prototype unit that included pressure and temperature ports along the length of the heat exchanger. Experimentally he was able to take baseline measurements during engine operations of a single exhaust heat exchanger, helping to determine the backpressure effects on the engine performance. Finally, Buck conducted an ANSYs modeling of a carbon dioxide compressor impeller focusing on the total pressure ratio and efficiency of the compressor. The compressor impeller will later be used to close the carbon dioxide Brayton cycle,

(3) "Waste Heat Recovery Analysis of a Gas Turbine Heat Exchanger": Denzel Reina

Reina's thesis modified the heat exchangers by adding gaskets between the clamshell mesh to prevent exhaust leaks from the heat exchanger shells [8]. Reina also made a modification to the data acquisition code by assigning specific date-time stamped folders for each output file. He also conducted cold run measurements of mass flow rates, temperatures, and pressures throughout the right side heat exchanger coils. Cold run data were utilized to create baseline pressure maps of the heat exchanger behaviors. With the installation of an onsite camera, Reina was able to conduct hot runs on a single meter, to map the effectiveness of the inner most (4") heat exchanger coil. Additionally, Reina produced a report on the Rankine cycle waste heat recovery system onboard the Cal maritime training ship Golden Bear. Finally, Reina designed and tested Peltier Coolers that would extract heat from engine exhaust, generating electric potential.

D. GOALS AND OBJECTIVES

This thesis focused on four critical areas of the waste heat recovery process. The first area focused on expanding the data acquisition system by establishing remote communication with four flow meters located in the test cell. This feature allowed hot runs to be conducted and data to be collected on all four coils simultaneously, providing a full analysis of the heat exchangers effectiveness. To meet this objective two task needed to be accomplished. First a proper gateway device that allowed TCP/IP to Modbus communication needed to be installed. Second the DAQ system needed to be updated to allow communication to occur with flow meters via the gateway.

The second focus area was evaluating the overall performance of the heat exchanger. Utilizing hot run pressure, temperature, and flow data, the overall efficiency of the right heat exchanger was analyzed.

The third focus area was reconfiguring the left heat exchanger for serial flow of the coils. Pressure, temperature, and flow data were collected during engine operation to calculate effectiveness of a series configured heat exchanger.

The fourth focus area was to expand on Michael Kaim's centrifugal compressor volute analysis [4]. The goal of the analysis was to compare total pressure ratio, total efficiency, and required power at varying angular velocities. Data collected from this thesis at angular velocities of 50,000 RPM and 75,000 RPM were compared to the 100,000RPM data collected by Kaim. The objective was to figure out if the designed volute could be operated at lower speeds, but still produce specifications that would be viable to drive the required compression.

II. EXPERIMENT SETUP

At the heart of the experiment is the Allison T63-A-700 gas turbine engine shown in Figure 2. The two exhaust pipes are connected to two individual cylindrical heat exchangers (right and left). Both heat exchangers are identically designed with four sets of coils, at four different diameters, 4, 6, 8, and 10 inches. See Figure 3. The working fluid, carbon dioxide passes internal of the coils, which is heated by engine exhaust as depicted in Figure 1. Flow path of the carbon dioxide can be seen in Figure 4. Majority of the data collected in this thesis, associated with objective II, was collected on the right heat exchanger. Alignment of the flow meters are shown in Table 1. Modification to the port heat exchanger can be found in objective IV.

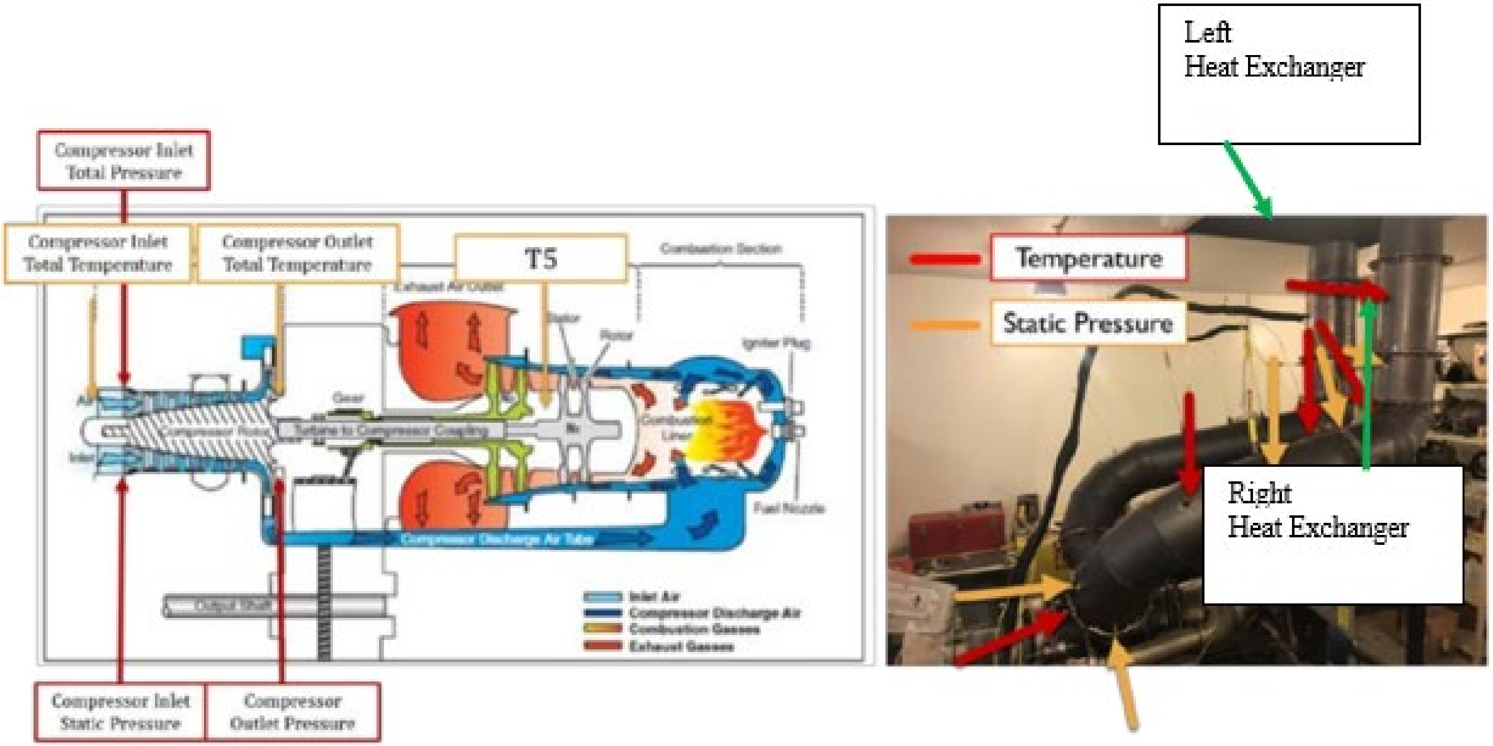


Figure 2. Allison T63-A-700 gas turbine engine. Adapted from [4].

Figure 3. Heat Exchanger Coil Alignment. Source: Reina [8].

Table 1. Starboard Heat Exchanger Meter Alignment

Meter	Coil
1	4”
2	6”
3	8”
4	10”

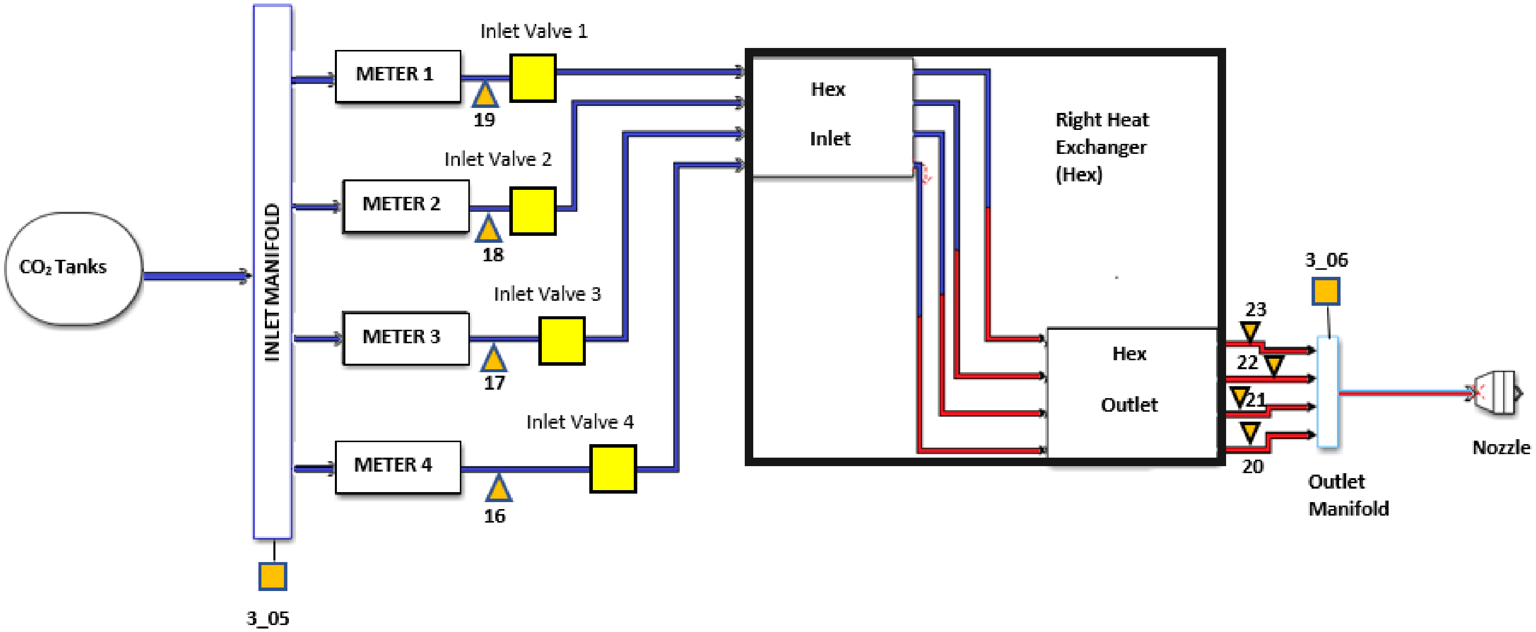


Figure 4. Carbon Dioxide Flow Path Schematic

III. OBJ 1: DATA ACQUISITION MODIFICATIONS

A. PREVIOUS WORK

Belna's thesis laid the foundation of the data acquisition (DAQ) system being utilized for data gathering on the T63 Gas Turbine engine [7]. The DAQ system program was generated utilizing MATLAB, with temperature and mass flow measurements gathered from national instrument (NI) hardware and pressure measurements gathered from Scanivalve digital sensor arrays (DSA). Kaim [4] further simplified the use of the DAQ system by utilizing local functions that took data from the main body of the script, and organized it into 6 defined output files, which then Reina [8] thesis assigned specific date-time stamps to each output file. See Reina's thesis for most current DAQ preceding work [8].

B. MODIFICATION GOALS

Prior to modifications, the DAQ system was only capable of gathering flow rates remotely from a single flow meter utilizing a RS232 interface or locally at the meter. To properly communicate with all four meters concurrently the system was modified to include a gateway server, which allowed simultaneous communication to occur with the four meters. The DAQ system modification goal was to utilize this installed gateway to continuously gather flow rate data of the heat exchanger coils.

C. INSTRUMENTATION SETUP

1. Flow Measurements

Four Eldridge value mass 400 series flow meters (EPI Meters) that measure flow in each coil of the heat exchanger had been previously installed. The flowmeters operate on a Modbus protocol allowing communication via RS232 or RS485 interface. In Kaim's research a RS232 interface was utilized to communicate with individual flow meters [4]. In order to communicate with all four meters simultaneously the RS485 interface needed to be utilized. Flow meter configuration setup can be found in Appendix B.

2. Gateway

TCP/IP to Modbus communication was accomplished utilizing a PERLE IOLAN SDG 8 P Gateway (SDG8) device. The gateway device has an ethernet connection on one end and 8 serial ports on the other end. Each serial port can be connected to corresponding slave devices via RS232, RS422, or RS485. Given the protocol of the flow meters, RS485 outputs were utilized. See Figure 5 for a general overview of the SDG8. SDG8 configuration setup can be found in Appendix B.

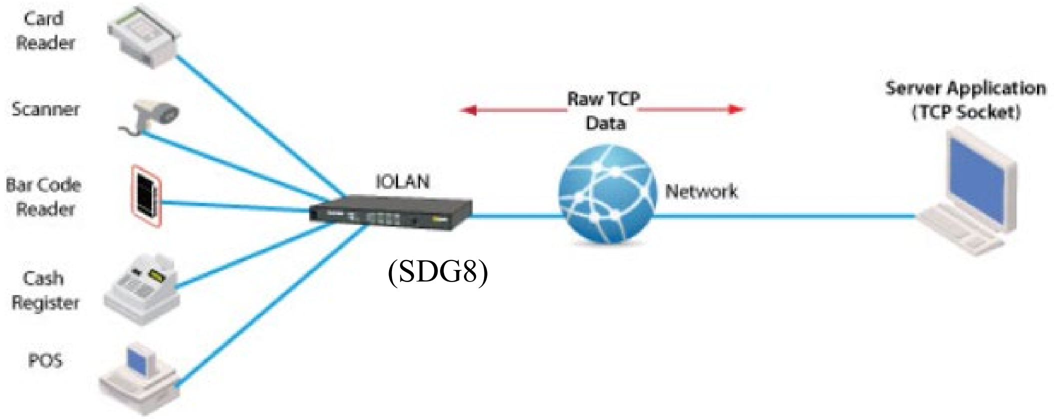


Figure 5. IOLAN SDG 8 P Gateway Infrastructure: Adapted from [9].

D. MATLAB CODING

The initial goal was to establish a separate MATLAB script that simply established communication with the slave devices. To do this the “Modbus” command was utilized, which designates the SDG8 as a TCP/IP object. Once the gateway object was created, communication could now be made between the workstation and the gateway. In order to read flow values from the meters, the “read” command was utilized. Once communication was verified and flow values were being generated, those lines of coding were incorporated into Kaim’s DAQ system [4]. See Appendix C. Kaim’s DAQ system took the average of ten different iterations of pressures and temperatures throughout the heat exchanger to record the behavior throughout the system. Read commands for flow were added to the

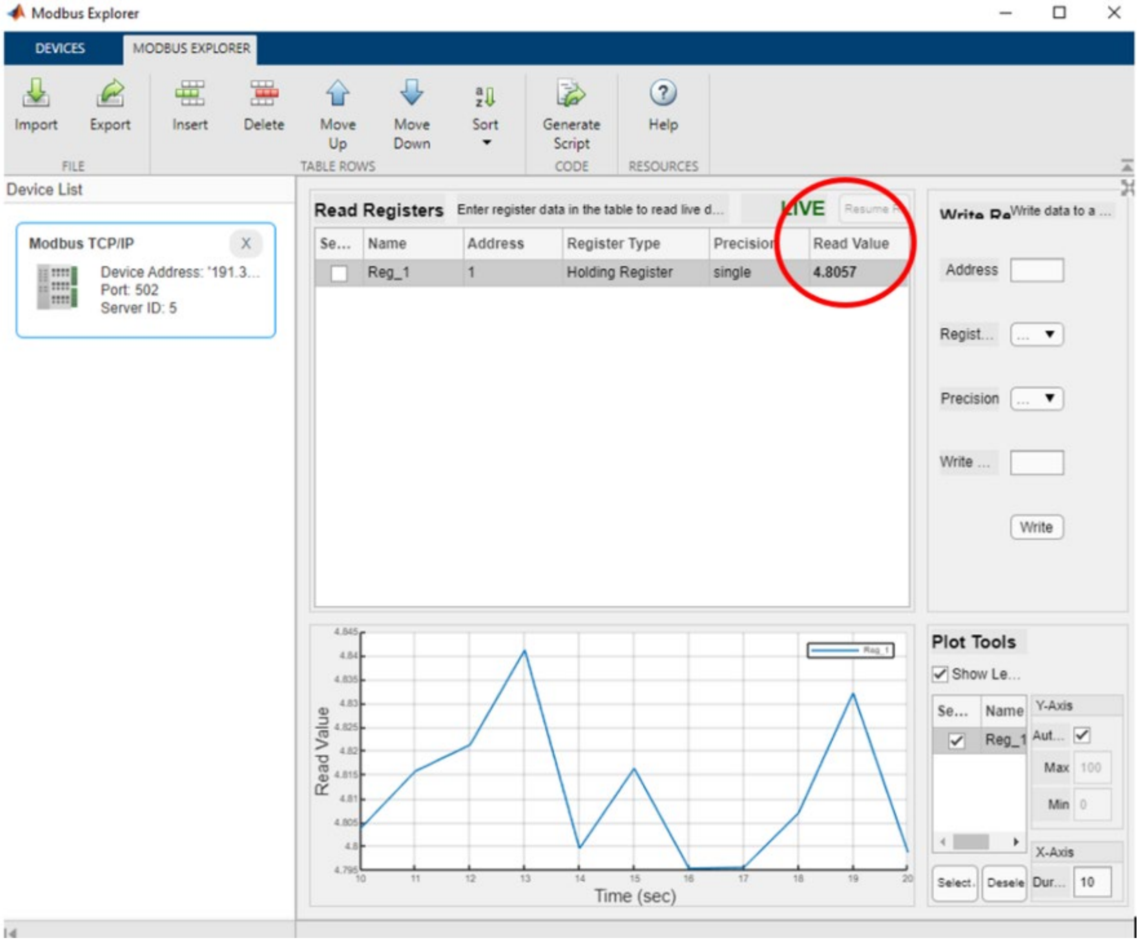
DAQ code such that flow would also be taken simultaneously with pressure and temperature and populated on a separate excel sheet.

Prior to establishing remote communication with the flow meters, operating the DAQ system was a two-person task. With the code modifications all data gathering can now be completed by a single operator. The MATLAB function "Modbus Explorer" opens the ModBus Explorer application within the Instrument Control Toolbox, which provides a live plot indicating flow of a specified meter. Therefore, when steady flow was observed on the application, the DAQ system would be placed in run, which started the information gathering. Given that the application is only setup to monitor a single meter, it was assumed that once steady flow was established in one-meter, steady flow was established in all meters. See Figure 6. Exact steps of data gathering can be found in Appendix C.

Due to the noise and heat levels of hot runs, Reina utilized a camera stationed at the individual meter vice a second person to analyze for steady flow [8]. This proved to be very cumbersome and very unrealistic to evaluate all four meters simultaneously. Therefore, with the addition of remote communication, hot run evaluations of the heat exchangers are now possible.

E. COLD RUN TESTING

Prior to conducting data runs, local readings of each meter were compared to live meter readings being populated on the ModBus Explorer screen as depicted in Figure 6. This process helped to ensure proper remote communication was established between workstation and the flow meters. Verification of the updated DAQ code was accomplished by repeating carbon dioxide cold runs conducted in Reina's [8]. The conclusion from these runs were that the meters had a linear response of flow rate with an increase in pressure. See Appendix D.



Modbus TCP/IP

Device Address: '191.3...
Port: 502
Server ID: 5

Se...	Name	Address	Register Type	Precision	Read Value
☐	Reg_1	1	Holding Register	single	4.8057

Se...	Name
☑	Reg_1

Aut... ☑
Max 100
Min 0
Dur... 10

Figure 6. Modbus Explorer Application

IV. OBJ 2: ENGINE AND HEAT EXCHANGER TESTING ANALYSIS AND RESULTS

A. PREVIOUS WORK

The T63 Rolls Royce gas turbine helicopter engine shown in Figure 7 operates with two exhaust stacks each containing a cylindrical heat exchanger designed by Coria Buck [5] and slightly modified by Michael Kaim [4]. Each heat exchanger has four sets of coils that are wounded downwards in a circular fashion from the top to bottom as seen in Figure 3. Diameters of the wounded coils are four, six, eight, and ten inches. Previous hot run testing and analyses conducted by Reina focused on performance of the right heat exchanger with only the four inch diameter coil in operation [8]. Data gathered by Reina and additional test results will be discussed in subsequent paragraphs.

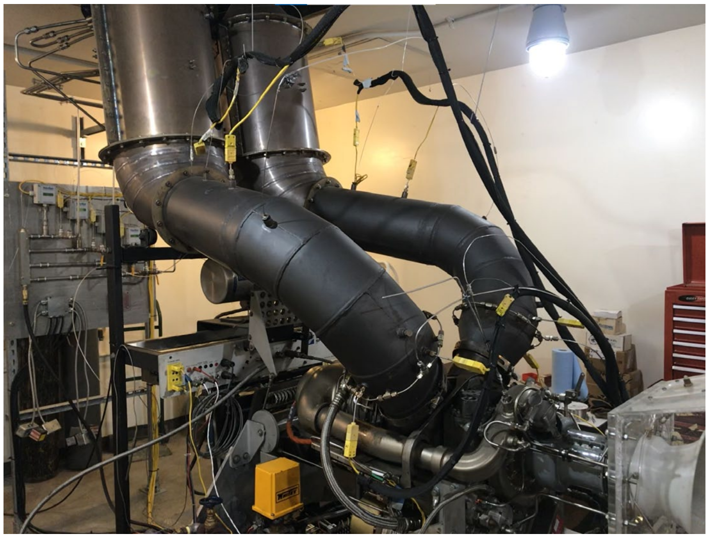


Figure 7. T63 Rolls Royce gas turbine helicopter engine

B. INSTRUMENTATION

1. Static Pressure

Static pressure throughout the engine is measured via three digital sensor arrays or pressure bricks, each with different maximum pressures (10” H_2O, 2.5 PSID, 100 PSID), which are used to detect pressures at component locations along the gas flow path of the engine. The bricks also were used to monitor pressure of the carbon dioxide as it passed along the flow path of the heat exchanger. See Appendix E. Specifically, pressure brick three port five (gas inlet manifold pressure) and pressure brick three port six (gas outlet manifold pressure), were utilized in heat exchanger performance calculations. Figures 8 and 9 show the locations of these pressure readings.

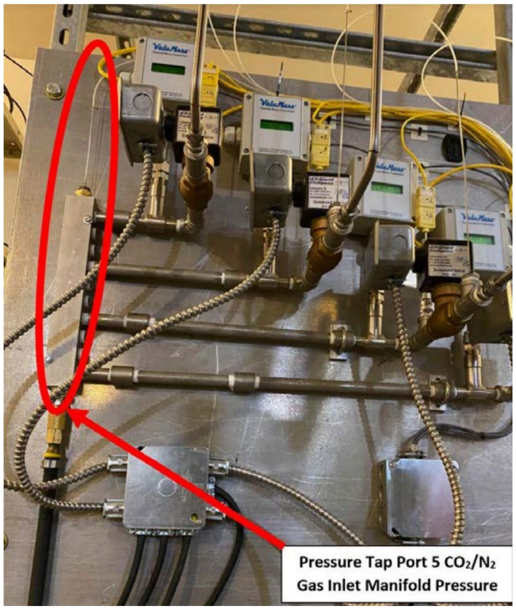


Figure 8. Inlet Pressure Manifold. Source: Reina [8].

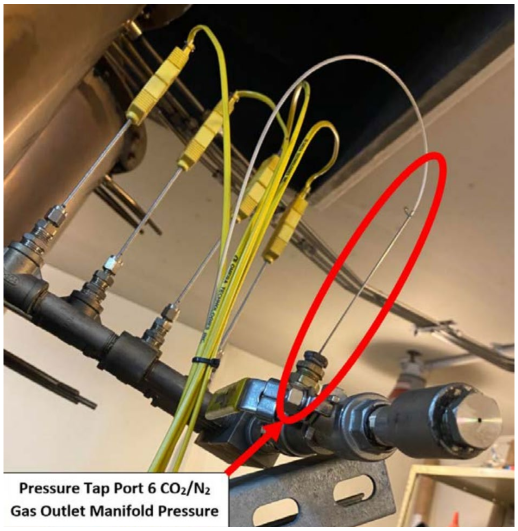


Figure 9. Outlet Pressure Manifold. Source: Reina [8].

2. Temperatures

Temperature measurements on the engine are measured via 30 K-type thermocouple sensors at various locations on the system. Eleven of the thirty temperature readings listed in Appendix E are utilized in heat exchanger performance calculations. Figures 10 through 13 show the location of the thermocouples along the exhaust duct work of the engine used for performance analysis of the heat exchangers.

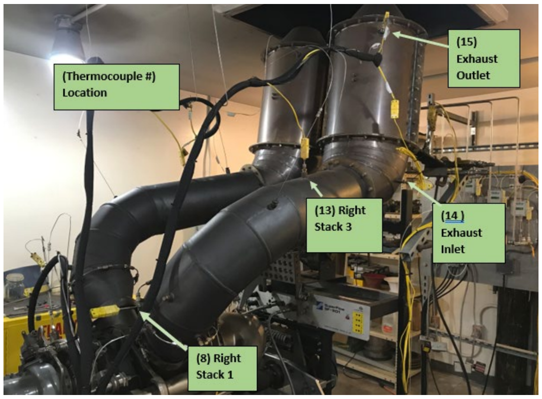


Figure 10. Right Stack Thermocouples

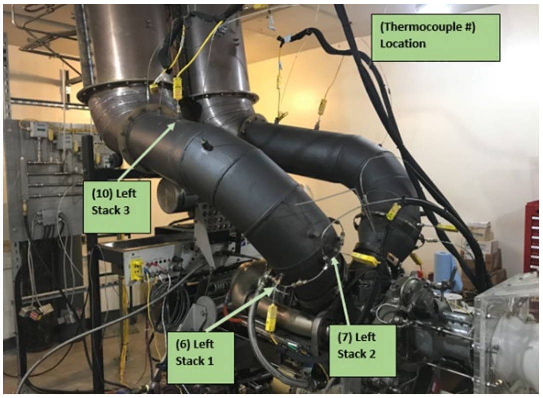


Figure 11. Left Stack Thermocouples

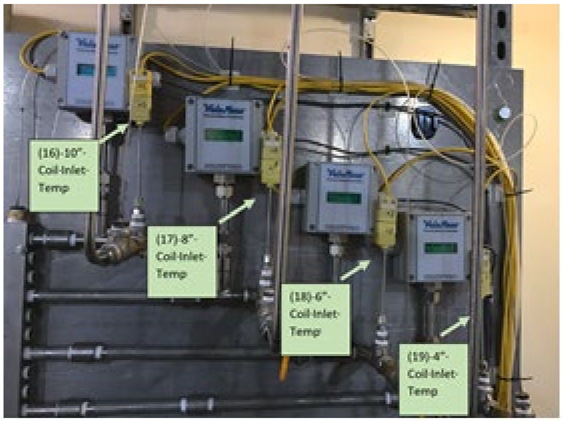


Figure 12. Coil Inlet Thermocouples

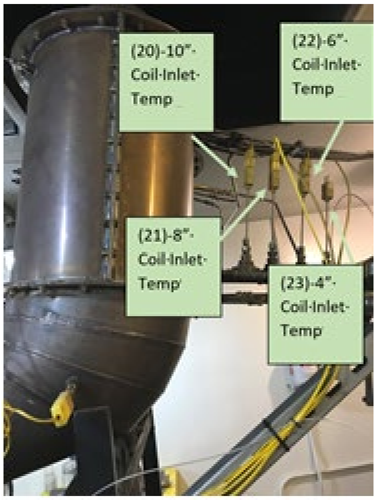


Figure 13. Coil Outlet Thermocouples

3. Flow

Gas flow rates through the heat exchanger are measured using four EPI flow meters as discussed in the previous section. Flow meters are located upstream of the heat exchanger inlet. Each meter monitors gas flow through each of the four coils and reports data in kilograms per hour. See Figure 14.

Figure 14. EPI Flow Meters (Model#: 400-INT-D41-DO24-S4003-PT-MW050-CO2)

4. Nozzles

Three different size nozzles were utilized at the exit of the heat exchanger. Nozzle diameter sizes were 1/16,” 1/8,” and 3/16.” The purpose of the nozzles was to establish possible choke flow condition. With choke flow conditions established, mass flow through the nozzle could be calculated via isentropic choke flow theory calculations. See Figures 15 and 16.

Figure 15. Fabricated 1/16” Exit Nozzle. Source: Reina [8].

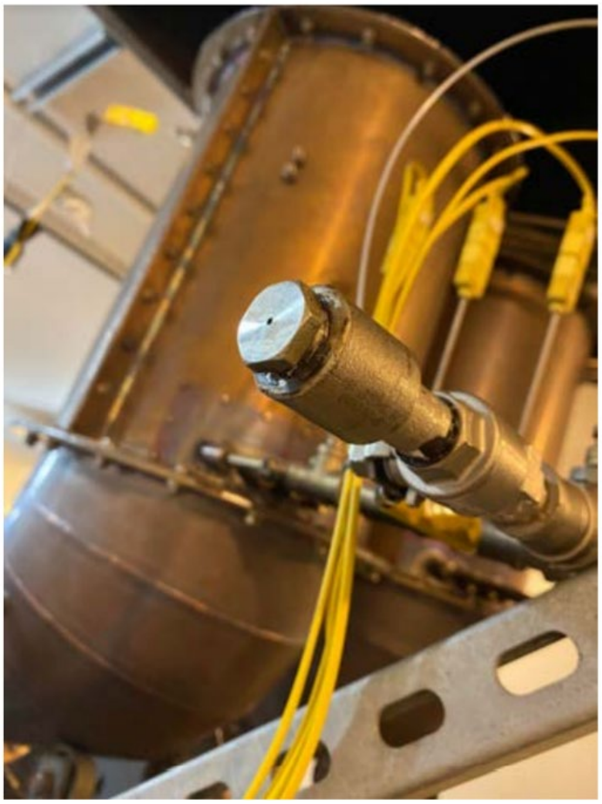


Figure 16. Exit Nozzle Location

C. TESTING AND RESULTS

Testing included monitoring different temperatures, pressures, and mass flow rates throughout heat exchanger at varying carbon dioxide supply pressures of 50, 75, and 100 PSI. All three nozzles were tested in four different configurations. The first configuration involved cold runs with each individual coil in operation, allowing mass flows to be individually calculated to be compared to actual flow recorded by the meters. The second configuration also involved cold runs with all four coils in operation to understand flow behavior. In this configuration it was observed to have fluctuating flow readings between multiple runs. It was suspected that originally installed solenoid valves were not fully opening between successive runs. Therefore, to ensure valve was fully open when directed, solenoid valves were replaced by manually operated ball valves. See Figure 17.

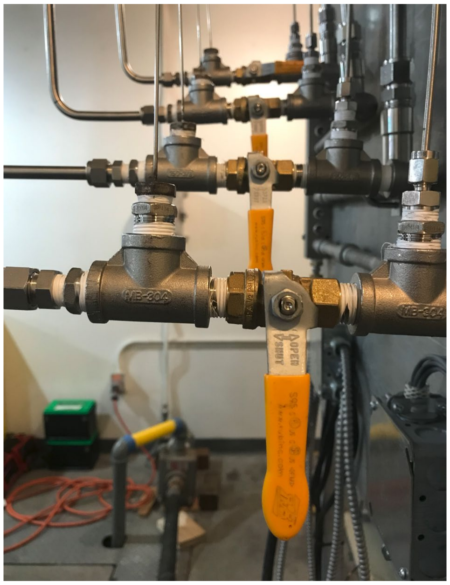


Figure 17. Ball Valve

The third configuration used hot runs with just the 4” coil in operation to gather baseline data on the 4” coils efficiency. The final configuration being hot runs with all four coils in operation, allowing baseline data to be populated and pressure maps of efficiencies and mass flow rates to be generated. See Appendix E, F, and G for associated data.

1. Mass Flow

Meter flow accuracy was determined via hot and cold runs of individual coils. Accuracy was verified by comparing calculated mass flow to actual flow meter measurements. Calculations were made via isentropic flow theory under choke flow conditions. By utilizing measured gas pressure into and out of the heat exchanger, the Mach number through a nozzle could be calculated [10].

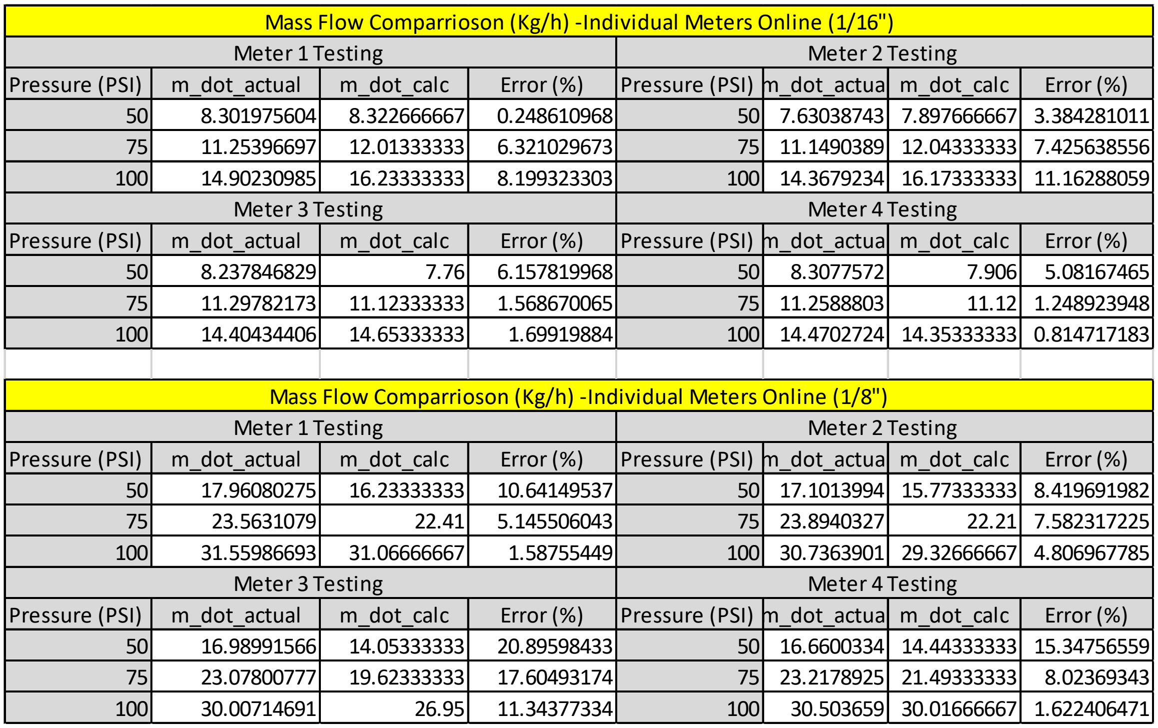
$$M = \sqrt{\left(\frac{2}{\gamma - 1}\right)\left(\left(\frac{p_o}{p}\right)^{\frac{\gamma-1}{\gamma}} - 1\right)}$$

A Mach number equal to or greater than 1 indicated a choked flow condition. Once nozzle had been determined to be choked, an associated mass flow could be calculated utilizing known inlet and outlet conditions of the nozzle as well as the nozzles cross sectional area [10].

$$\dot{m} = A * \left(\frac{p_o}{\sqrt{R * T_o}}\right)\sqrt{\gamma}\left(\frac{2}{\gamma + 1}\right)^{\frac{\gamma+1}{2(\gamma-1)}}$$

Individual meters calculated and recorded mass flow rates are shown in Table 2 and Table 3. With a 1/16” nozzle the error between recorded and calculated mass flow rates were observed to be between 0 and 11.2%. Whereas with a 1/8” nozzle the error is observed to be almost three times greater between 1.5 and 21%. The increase in error observed in the 1/8” nozzle results may be due to an increase pressure drop between inlet manifold and outlet manifold. It was observed that the pressure drop difference with a 1/8” nozzle was near three times larger than the pressure drop of a 1/16” nozzle. It was suspected that the large difference in pressure drop was due to static pressure being measured with a 1/16” nozzle, and stagnation pressure being measured with a 1/8” nozzle. In order to test this theory, the outlet manifold was increased in size as shown in Figure 18. The increase in size would help to ensure that static pressure was being measured vice stagnation pressure. The increase in reservoir size had a small change in pressure drop, but not significant enough to change mass flow rate calculations. See Appendix D for more in depth calculation.

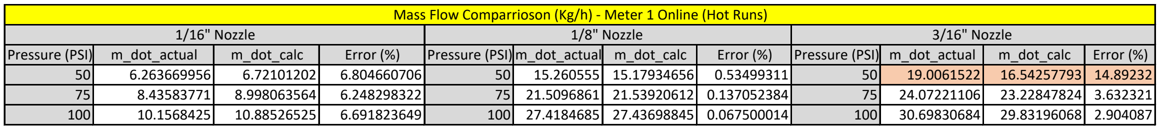
Table 2. Calculated vs. Measured Flow Rate – Individual Meters Online (Cold Runs)



Mass Flow Comparrioson (Kg/h) -Individual Meters Online (1/16")							
Meter 1 Testing				Meter 2 Testing			
Pressure (PSI)	m_dot_actual	m_dot_calc	Error (%)	Pressure (PSI)	m_dot_actua	m_dot_calc	Error (%)
50	8.301975604	8.322666667	0.248610968	50	7.63038743	7.897666667	3.384281011
75	11.25396697	12.01333333	6.321029673	75	11.1490389	12.04333333	7.425638556
100	14.90230985	16.23333333	8.199323303	100	14.3679234	16.17333333	11.16288059
Meter 3 Testing				Meter 4 Testing			
Pressure (PSI)	m_dot_actual	m_dot_calc	Error (%)	Pressure (PSI)	m_dot_actua	m_dot_calc	Error (%)
50	8.237846829	7.76	6.157819968	50	8.3077572	7.906	5.08167465
75	11.29782173	11.12333333	1.568670065	75	11.2588803	11.12	1.248923948
100	14.40434406	14.65333333	1.69919884	100	14.4702724	14.35333333	0.814717183

Mass Flow Comparrioson (Kg/h) -Individual Meters Online (1/8")							
Meter 1 Testing				Meter 2 Testing			
Pressure (PSI)	m_dot_actual	m_dot_calc	Error (%)	Pressure (PSI)	m_dot_actua	m_dot_calc	Error (%)
50	17.96080275	16.23333333	10.64149537	50	17.1013994	15.77333333	8.419691982
75	23.5631079	22.41	5.145506043	75	23.8940327	22.21	7.582317225
100	31.55986693	31.06666667	1.58755449	100	30.7363901	29.32666667	4.806967785
Meter 3 Testing				Meter 4 Testing			
Pressure (PSI)	m_dot_actual	m_dot_calc	Error (%)	Pressure (PSI)	m_dot_actua	m_dot_calc	Error (%)
50	16.98991566	14.05333333	20.89598433	50	16.6600334	14.44333333	15.34756559
75	23.07800777	19.62333333	17.60493174	75	23.2178925	21.49333333	8.02369343
100	30.00714691	26.95	11.34377334	100	30.503659	30.01666667	1.622406471

Table 3. Calculated vs. Measured Flow Rate – Meter 1 Online (Hot Runs)



Mass Flow Comparrioson (Kg/h) - Meter 1 Online (Hot Runs)											
1/16" Nozzle				1/8" Nozzle				3/16" Nozzle			
Pressure (PSI)	m_dot_actual	m_dot_calc	Error (%)	Pressure (PSI)	m_dot_actual	m_dot_calc	Error (%)	Pressure (PSI)	m_dot_actual	m_dot_calc	Error (%)
50	6.263669956	6.72101202	6.804660706	50	15.260555	15.17934656	0.53499311	50	19.0061522	16.54257793	14.89232
75	8.43583771	8.998063564	6.248298322	75	21.5096861	21.53920612	0.137052384	75	24.07221106	23.22847824	3.632321
100	10.1568425	10.88526525	6.691823649	100	27.4184685	27.43698845	0.067500014	100	30.69830684	29.83196068	2.904087

*3/16” Nozzle not choked at 50 PSI resulting in a large jump in error

Figure 18. Larger Outlet Manifold

2. Reynolds Number

Reynolds number is a dimensionless value that represents the ratio of inertia over viscous forces, utilized in determining if a boundary is laminar or turbulent [11]. For internal flow through a cylinder tube, a Reynolds number less than or equal to 2,300 corresponded to laminar flow and a Reynolds number of approximately 10,000 or greater corresponds to turbulent flow [11]. Everything in between these two values is in transitional flow. See Appendix F for calculation results. Though results show that internal coil flow with all four coils in operation was in the transitional region, flow was assumed to be laminar at a lower flow. In test runs where only meter one was in operation, Reynolds numbers were high enough that turbulent flow was well defined. Exhaust flow external of the coils, was greater than 10,000, thus turbulent flow.

3. Nusselt Number

For internal flows with all four coils in operation the assumption was made that flow was laminar and fully developed per previous Reynolds calculations. The assumption was also made that temperature was constant in both the axial and peripheral directions, due to helical shaped coils. Given these assumptions the Nusselt number of 3.66 is given for all coils when all four meters were in operation [11]. See Appendix F.

When only meter one was in operation the Nusselt number was based off the Dittus-Boelter equation, which under the assumption of a fully developed turbulent flow in a smooth circular tube the Nusselt number is defined per the following equations for heating [11]. See Appendix F.

$$N_{u_D} = 0.0243\, Re_D^{\frac{4}{5}} \mathrm{Pr}^{0.4}$$

On the hot side of the heat exchanger, the Nusselt number was calculated under the assumption of external cross flow over a circular cylinder. Additional assumptions made was that the exhaust leaving the engine was strictly air, therefore all constants were based on air properties. Utilizing the Hilpert empirical correlation, the Nusselt number for exhaust was found via the following equation [11].

$$N_{u_D} = 0.683 Re_D^{.466} \mathrm{Pr}^{1/3}$$

4. Overall Heat Transfer Coefficient

To predict energy balance within the heat exchanger the overall heat transfer coefficient and log mean temperature needed to be determined. The overall heat transfer coefficient is defined in terms of the total thermal resistance [11]. The heat exchanger is designed in which total thermal resistance consist of convection via carbon dioxide gas, conduction (R_w) through the cylindrical stainless steel coil walls, and convection via engine exhaust. Thus, overall heat transfer coefficient was calculated via the following equation assuming the tube walls are clean and unfinned [11].

$$\frac{1}{UA} = \frac{1}{h_{gas}A_i} + R_w + \frac{1}{h_{exh}A_o}$$

Per the equation A_i and A_o is referring to the inner and outer tubes area where A_i and A_o is calculated via the following Equations.

$$A_i = \pi D_i L \; and \; A_o = \pi D_o L$$

Heat coefficient of the exhaust (h_{exh}) and carbon dioxide gas (h_{gas}) was calculated via the general Nusselt equation, where k is the associated thermal conductivity and D is the associated diameter (inner diameter for carbon dioxide and outer diameter for exhaust). See Appendix F for overall heat transfer calculations.

$$Nu = \frac{hD}{\mathrm{k}}$$

5. Log Mean Temperature

Within the heat exchanger the temperature change from inlet to outlet changes logarithmically, thus log mean temperature difference is utilize when calculating heat transfer within the heat exchanger [11]. Log mean temperature difference relates the inlet and outlet temperature of both the hot and cold side of the heat exchanger to calculate the average temperature difference throughout the entire tube length [11]. Assuming a counterflow heat exchanger the log mean temperature difference was calculated using the following equation:

$$\Delta T_{lm} = \frac{\Delta T_1 - \Delta T_2}{\ln\left(\frac{\Delta T_1}{\Delta T_2}\right)}$$

$$\Delta T_1 = T_{hi} - T_{co}$$

$$\Delta T_2 = T_{ho} - T_{ci}$$

See Appendix F for log mean temperature difference calculations.

6. Heat Transfer

Two different heat transfer calculations were conducted. The first was the predicted heat transfer, which utilized the log mean temperature difference of the heat exchanger calculated via the following equation [11].

$$q_{\text{predicted}} = UA\Delta T_{lm}$$

The second heat transfer calculation utilized the general form of heat transfer equation, which utilizes the inlet and outlet gas temperatures through each coil.

$$q_{actual} = \dot{m}c_p(T_{co} - T_{ci})$$

Tables 4 and 5 provide a comparison between predicted and actual heat transfer. It can be observed that as the diameter of the coil get larger the error between predicted and actual gets larger as well. This could be because as exhaust travels through the heat exchanger, hotter gas is more centerline within the heat exchanger, therefore, leading to higher accuracy in actual heat transfer in the inner coils. See Appendix F for heat transfer calculations.

Table 4. Meter 1 Estimated vs. Actual Heat Transfer

Heat Transfer Comparrison (KW)								
Meter 1 Testing (1/16" Nozzle)			Meter 1 Testing (1/8" Nozzle)			Meter 1 Testing (3/16" Nozzle)		
Pressure (PSI)	q_actual	q_estimated	Pressure (PSI)	q_actual	q_estimated	Pressure (PSI)	q_actual	q_estimated
50	573.3912678	1777.002149	50	1458.30499	2867.045286	50	1609.3244	2947.070559
75	880.9162312	1935.162301	75	2120.06067	3579.206766	75	2242.3326	3798.759999
100	1082.003079	2179.393462	100	2625.32857	4376.299415	100	2751.4346	4747.597568

Table 5. All Meters Online- Estimated vs. Actual Heat Transfer

Heat Transfer Comparrison (KW)-All Meters Online (1/16")											
Meter 1 Testing			Meter 2 Testing			Meter 3 Testing			Meter 4 Testing		
Pressure (PSI)	q_actual	q_estimated	Pressure (PSI)	q_actual	q_estimated	Pressure (PSI)	q_actual	q_estimated	Pressure (PSI)	q_actual	q_estimated
50	136.5431641	209.5136612	50	118.463835	312.5990156	50	31.080946	573.5407671	50	35.00349098	700.2495801
75	197.1075761	206.4665521	75	190.419395	298.0526291	75	44.405993	582.2647113	75	48.08511587	711.2809434
100	257.1755407	205.778996	100	249.773275	289.9554351	100	59.946233	587.8045223	100	62.84906962	720.8861379

Heat Transfer Comparrison (KW)-All Meters Online (1/8")											
Meter 1 Testing			Meter 2 Testing			Meter 3 Testing			Meter 4 Testing		
Pressure (PSI)	q_actual	q_estimated	Pressure (PSI)	q_actual	q_estimated	Pressure (PSI)	q_actual	q_estimated	Pressure (PSI)	q_actual	q_estimated
50	320.6676048	207.617246	50	319.061811	297.8759321	50	65.011733	578.8558579	50	79.89631278	708.0096703
75	505.5064398	189.6186455	75	507.278374	273.6084371	75	105.1413	583.7178489	75	121.6463123	716.3258724
100	695.6430868	178.0592835	100	685.738474	261.2626301	100	146.75419	590.2148585	100	154.0165072	730.3839224

Heat Transfer Comparrison (KW)-All Meters Online (3/16")											
Meter 1 Testing			Meter 2 Testing			Meter 3 Testing			Meter 4 Testing		
Pressure (PSI)	q_actual	q_estimated	Pressure (PSI)	q_actual	q_estimated	Pressure (PSI)	q_actual	q_estimated	Pressure (PSI)	q_actual	q_estimated
50	365.5698745	203.051902	50	359.0964	292.7154115	50	66.602526	579.6654195	50	84.81195625	707.3382425
75	555.6243031	188.6360777	75	556.040378	272.4922584	75	108.65851	585.8755034	75	129.6547303	717.8458109
100	765.1622273	180.0220292	100	771.636766	261.4126753	100	150.67127	591.3202196	100	175.9962061	724.453489

7. Effectiveness

Via NTU method, effectiveness is defined as the ratio of actual heat transfer(q) over the maximum heat transfer experienced throughout the heat exchanger (q_{max}) [11].

$$\varepsilon = \frac{q}{q_{max}}$$

The higher the value calculated, the more effective the heat exchanger is. With this heat exchanger design there are 2 working fluids, the hot side, and the cold side. Hot side corresponding to exhaust gas leaving the engine which we assume to be air and the cold side corresponding to the gas internal of the tube, which was carbon dioxide. Assuming a counterflow heat exchanger of infinite length the max temperature difference would occur between hot inlet (T_{hi}) and cold inlet (T_{ci}). Therefore, the max heat transfer can be defined as the following [11].

$$q_{max} = c_{min}(T_{hi} - T_{ci})$$

By comparing heat capacity (c) for air and carbon dioxide at their operating temperatures, it can be determined that carbon dioxide has a lower heat capacity. Therefore, effectiveness can be defined as [11].

$$\varepsilon = \frac{q}{c_c(T_{hi} - T_{ci})}$$

where q is the actual heat transfer calculated. Tables 6 and 7 show the effectiveness (percentage) of each coil in different configurations. See Appendix F for effectiveness calculation results.

Table 6. Hot Run Effectiveness (Meter 1 Online)

Effectiveness Comparison (%) -Meter 1 Online			
Pressure	1/16" Nozzle	1/8" Nozzle	3/16" Nozzle
50	65.69423745	73.90577255	75.400328
75	75.48210455	75.46169918	74.41288594
100	76.81336427	73.13056609	70.80972051

Table 7. Hot Run Effectiveness (All Coils Online)

Effectiveness Comparrioson (%)-All Meters Online				
1/16" Nozzle				
Pressure	Meter 1	Meter 2	Meter 3	Meter 4
50	57.67882829	58.17663221	16.48807705	20.54959062
75	60.9572861	64.33266804	17.38860493	21.20340975
100	62.51650148	67.72730005	18.20621282	21.46936156

1/8" Nozzle				
Pressure	Meter 1	Meter 2	Meter 3	Meter 4
50	58.87942167	62.94821966	15.64255678	19.42304587
75	68.69931077	71.55355339	18.37702875	21.55067403
100	74.31300928	75.7184752	19.42938688	21.21113023

3/16" Nozzle				
Pressure	Meter 1	Meter 2	Meter 3	Meter 4
50	60.49000284	64.01015731	14.57011437	18.76984162
75	68.93518138	71.68378319	17.41968119	20.86542955
100	73.22779881	75.33531615	18.22436154	21.66372963

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V. OBJ 3: SERIES HEAT EXCHANGER

A. PREVIOUS THESIS WORK

Kaim designed two identical heat exchangers with four sets of coils operating in parallel as discussed in previous sections [4].

B. DESIGN MODIFICATIONS

All modifications were made to the left heat exchanger. Prior to modifications each set of coil operated in parallel, thus each coil had one inlet and one exit, and thus a total of four inlets into the heat exchanger and four outlet flows out of the heat exchanger as shown in Figure 19. The new series configuration connected all coils as to make a single long tube in series throughout the heat exchanger. Flow would enter the heat exchanger through the 10" coil and exit the heat exchanger through the nozzle via the 4" coil exit. New flow path entered the inlet of the original 10" coil and exited the bottom from the 10" coil. Flow then connected to the exit of the original 8" coil and exited the top of the original 8" coil inlet. Flow then connected to the inlet of the original 6" coil and exited the bottom from the original 6" coil. Finally flow connected to the original exit 4" coil and exited the inlet of the original 4" coil, out through the outlet manifold and through the nozzle. The total pipe length was approximated to be 17.698 m, which 5.3% of the total piping was outside the heat exchanger. In this configuration, flow was now monitored via meter four, inlet temperature via thermocouple 16 and outlet temperature via thermo couple 23. See Figure 19.

Figure 19. Parallel and Series Heat Exchanger Configuration

C. TESTING AND RESULTS

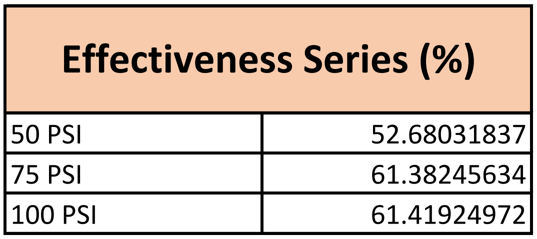
Hot runs at 50, 75, and a 100 PSI working fluid pressure was tested. Similar calculation discussed in objective II was conducted. See Table 8 for calculated vs. actual mass flow rates.

Table 8. Calculated vs. Mass Flow Rates (Left Heat Exchanger)

Calculated vs Actual Flow (Meter 4)		
Calculated Mass Flow Rate (Kg/h)	Recorded Flow Meter Mass Flow Rate (Kg/h)	Error (%)
14.798274	12.722	16.32458476
20.53235342	18.523	10.84602309
26.21534861	25.339	3.456461034

The change in temperature between outlet and inlet carbon dioxide was lower than the change in temperature of a single coil in parallel operations. Prior to testing it was predicted that carbon dioxide would be heated up more while in series operation due to multiple passes within the heat exchanger. What results actually showed was a lower change in temperature when compared to a single coil in parallel operations. This could be due to the amount of coil external to the heat exchanger that the gas passes through, which may be causing a cooling effect. Therefore, with a lower change in temperature, the effectiveness values are lower than expected. See Table 9.

Table 9. Effectiveness of Series Operated Heat Exchanger



Effectiveness Series (%)	
50 PSI	52.68031837
75 PSI	61.38245634
100 PSI	61.41924972

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VI. OBJ 4: COMPRESSOR VOLUTE DESIGN

A. PREVIOUS THESIS WORK

Buck designed an impeller housing around a commercially produced turbo charger compressor impeller [5]. See Figure 20. Kaim [4]. took Buck's impeller housing and designed a rounded tongue volute in which Buck's impeller would discharge to See Figure 21 and Figure 22. Kaim took the overall design and ran a CFD model at 100,000 RPM with the goal of determining the pressure ratio and efficiencies of the compressor. To do this Kaim utilized an iterative process in which backpressure was parameterized from 0.0 to 0.4 atm and with the results was able to identify mass flow rates that would populate the best efficiencies and pressure ratio.

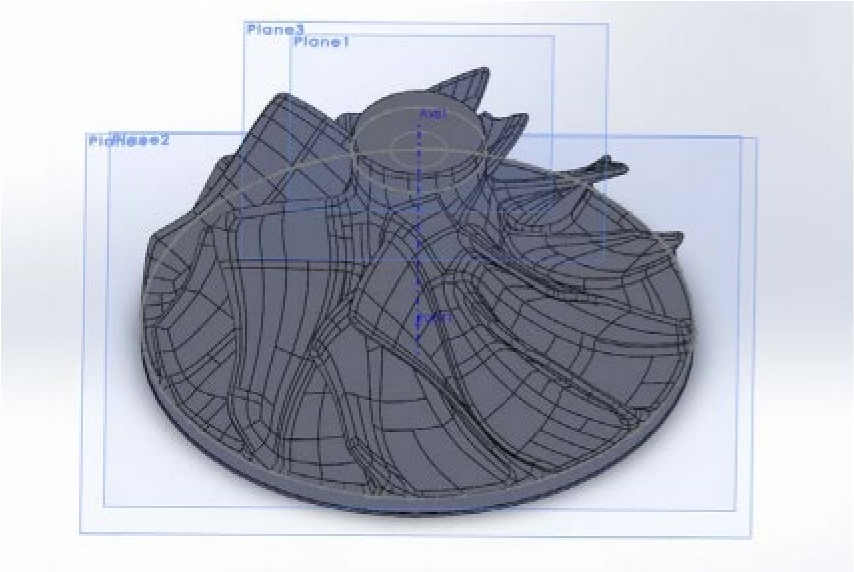

Figure 20. Impeller Model. Source: Buck [5].

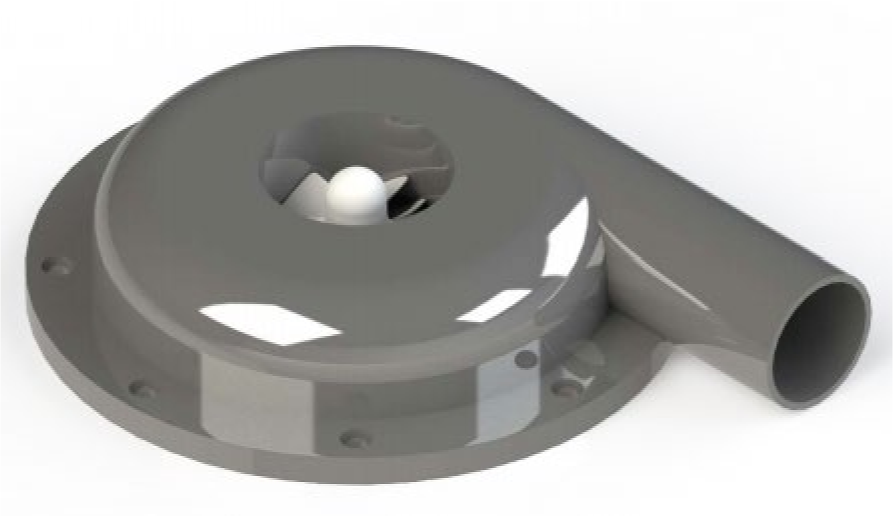

Figure 21. Volute Design. Source: Kaim [4].

Figure 22. 3D Printed Volute. Source: Kaim [4].

B. EXPANDING CFX MODEL DESIGN

The model of the centrifugal compressor was broken down into two separate domains, the impeller, and the volute. The goal of the analysis was to explore the effectiveness of the compressor at lower operating speeds. To accomplish this, compressor maps for 50,000 RPM and 75,000 RPM were generated and compared to the 100,000 RPM results gathered by Kaim. Compressor maps were generated by varying volute outlet relative pressure, starting at zero outlet pressure, and increased until stall conditions were observed.

C. MESH SETUP

The mesh setup was identical to the mesh utilized in Kaim's thesis [4]. The mesh utilized for the compressor was very coarse. To ensure a proper mesh was established and run time was minimized a few changes were made to the default settings. This resulted in 450783 total nodes and 1241609 elements. Setting changes are annotated in Table 10.

Table 10. Impeller Mesh Settings. Adapted from [4].

Curvature normal angle	2 degrees
Local minimum size	0.25mm
Number of layers	4
Growth Rate	1.2
Maximum thickness	1.0 mm
Global growth rate	1.4

D. SETUP BLOCK

The setup consists of two domains, the impeller, and the volute. Table 11 summarizes the settings for both domains. To ensure that the impeller always rotated in the same direction for all runs, the -abs (RPM) for angular velocity was specified.

Table 11. Domain Summary. Adapted from [4].

	Impeller	**Volute**
Material	Air Ideal Gas	Air Ideal Gas
Ref. Pressure	1 [atm]	1 [atm]
Buoyancy Model	Non Buoyant	Non Buoyant
Domain Motion	Rotating	Stationary
Angular Velocity	-abs(RPM)	-abs(RPM)
Heat Transfer	Total energy	Total energy
Turbulence	K-Epsilon	K-Epsilon
Wall Function	Scalable	Scalable
Mass and Momentum	Static Total Pressure-0atm	Static Pressure (0 atm-stalled condition)

Additionally, two expressions are defined, which are physical time scale and RPM. For a given RPM, all expressions were kept constant except for volute outlet relative pressure, which would vary starting at zero atmosphere and increased until stall conditions were observed. Table 12 shows the breakdown of each expression. Max iteration of each run was set to 1000 to allow convergence to occur, ideally achieving 5 orders of magnitude in convergence.

Table 12. Expressions within Setup Block

RPM	50,000/75,000/100,000
Physical Time Scale	1 deg/RPM

E. SOLUTION BLOCK

Table 13 shows all changes made to the default settings to achieve a quicker runtime. Adjusting the default settings took runtime down from 12 hours to about 9 hours per run. For the initial run at each angular velocity, initialization option was selected as “initial conditions.” All subsequent runs were selected as “current solution data (if possible).” Momentum and mass were monitored through all runs. See appendix I for CFX results.

Table 13. Changes within solution global run settings

Tab	Setting	Change
Run Definition	Partitions	8
Solver	Memory Alloc Factor	1.2
Interpolator	Memory Alloc Factor	1.2

F. RESULTS:

As speed of impeller increased, pressure ratios also increased. The goal was to determine what outlet back pressure of the compressor would result in a stalled condition. This was done by incrementally increasing outlet back pressure while keep all other parameters constant. Stalled conditions were identified by the large differences between mass flow in and mass flow out as well as the poor convergence in the momentum and mass residuals. See Appendix I. Once stalled conditions were found, the previous data point would be assumed most optimal operating condition of the compressor at that specific angular velocity. See Table 14 for maximum efficiencies and associated mass flow rate and power for each impeller speed. Figures 23, 24, and 25 compare results of varying angular velocities. Looking at Figure 23, the most optimal mass flows can be estimated by the mass flows along the given surge line (green line) for a specified RPM.

Table 14. Compressor Performance

Impeller Speed (RPM)	**Max Efficiency (%)**	**Mass Flow Rate (kg/s)**	**Power (kg m^2 s^-3)**
50,000	71.1512	0.0354151	326.4
75,000	73.1996	0.047088	1019.86
100,000	70.9981	0.063365	2443.22

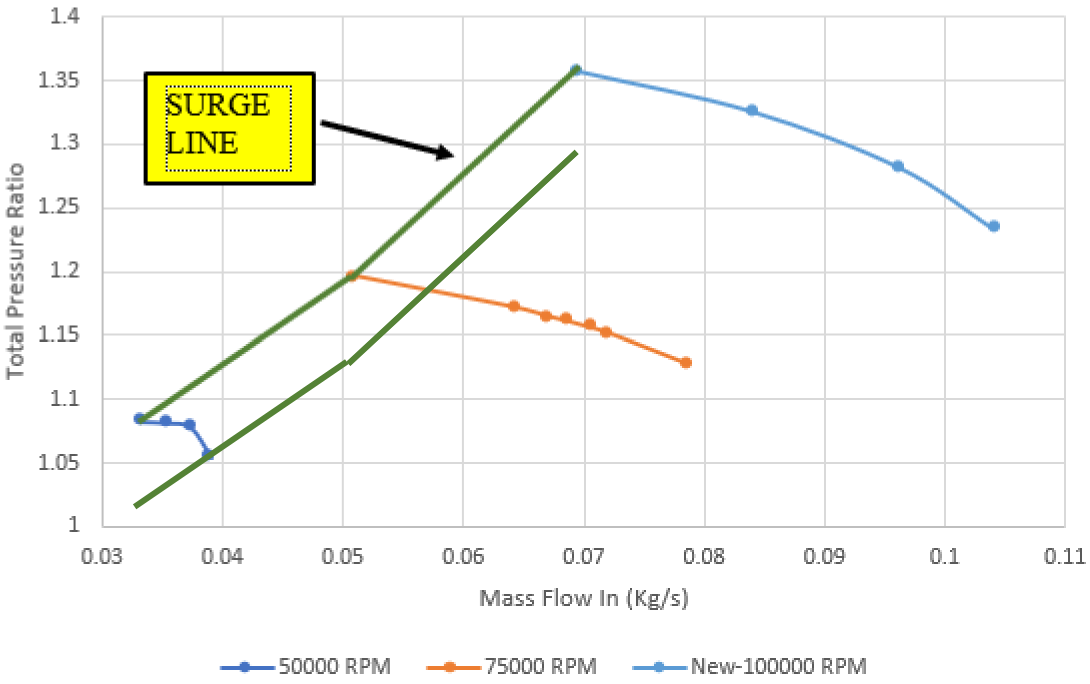

Figure 23. Total Pressure vs. Mass Flow Map

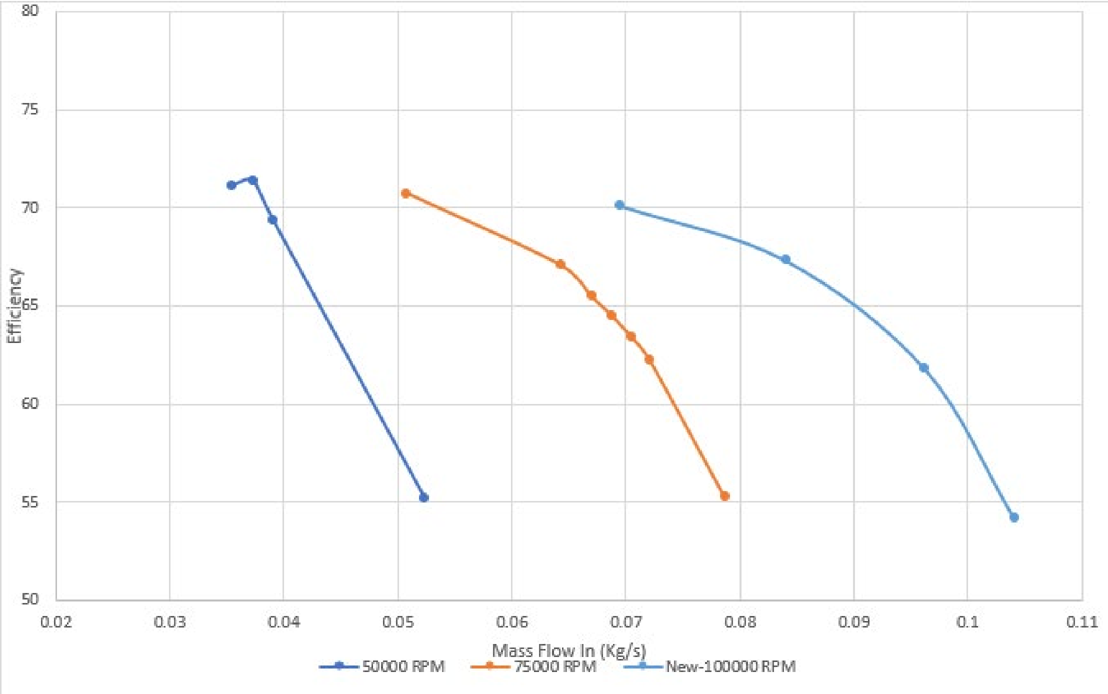

Figure 24. Efficiencies vs. Mass Flow Map

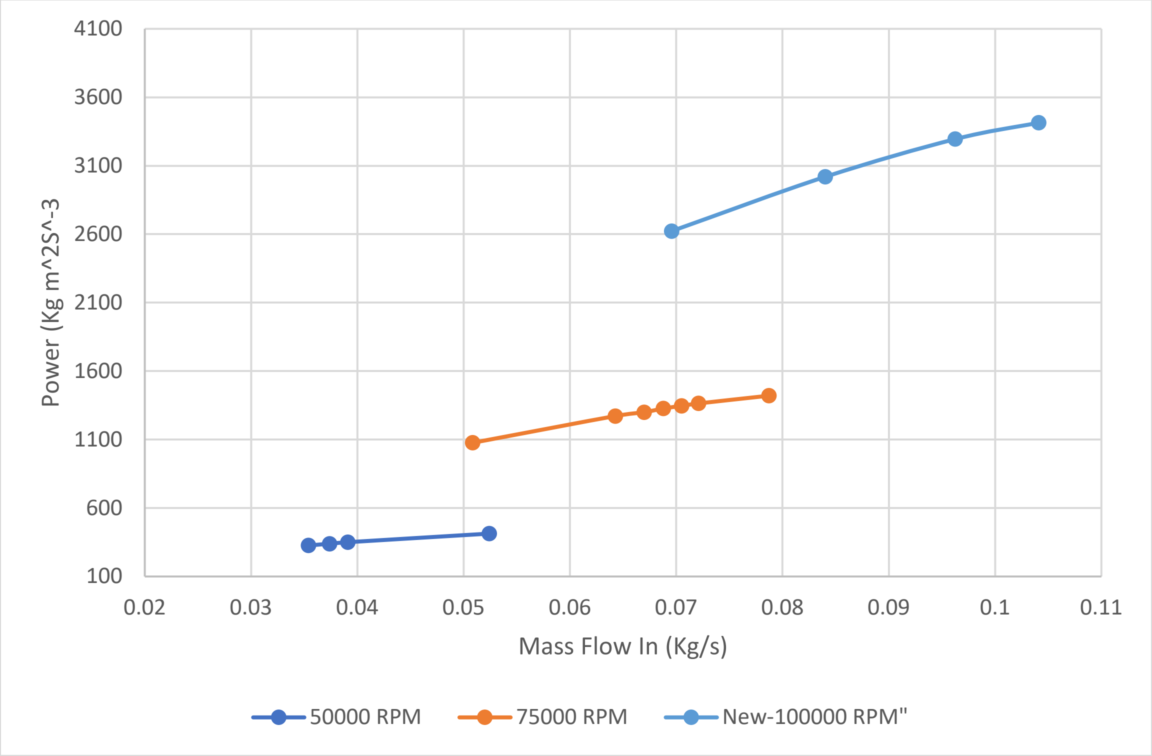

Figure 25. Power vs. Mass Flow Map

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VII. CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

A. CONCLUSIONS

The work outlined in this thesis adds the capabilities to further analyze both heat exchangers during hot operations. With a TCP/IP to Modbus gateway installed, remote communication with EPI flow meters during hot operations became possible. The new capability allowed flow data to be collected simultaneously from selected meters, which data was utilized to calculate the effectiveness of the right side heat exchangers. Calculations show that when coils were connected in parallel, inner coils with smaller diameter were significantly more effective then coils of larger diameters.

Additionally, the left heat exchanger was reconfigured in a series lineup to analyze the heat exchanger in a series configuration. Effectiveness of the left side heat exchanger was determined to be slightly less efficient than a single coil in parallel. There are many factors to explore on why this is the case and should be addressed in future work.

Finally, ANSY CFX was conducted on a designed compressor at 50,000, and 75,000 RPM. Pressure maps, total efficiency maps, and power maps were generated for each speed and compared. Results show that operating the compressor at a lower speed may be more achievable then originally tested 100,000 RPM compressor.

B. FUTURE WORK

Baseline data of the heat exchanger connected in a parallel has been collected but could be reverified via repeated hot runs. Focus should then be shifted to fully analyzing the heat exchanger in a series setup. To get a full grasp on heat transfer occurring within the series heat exchanger, thermocouples could be installed at each section the coil exits the heat exchanger to get accurate temperature readings. This will also help to provide an idea on how much heat is being loss due to coil piping outside of the heat exchanger.

An error code would occasionally pop-up during data gathering, forcing the DAQ system to be restarted, which may be due to a meter failing to respond back to the gateway. Error will prolong future data collection and should be addressed.

Now that ANSY CFX results have been generated at lower speeds, new motors should be selected to see if the proper speed capabilities can be met. Additionally, volute sizing can be investigated to minimize fluctuations in CFD solutions. There are multiple motors currently available at NPS listed in Table 15. A motor should be selected and tested to see if designed impeller can reach specific RPMs.

Table 15. Motors Available at Turbo Lab

HKII-2221-6 (Scorpion)	2	4400RPM/Volt	40,0000 RPM	525 Watts
HKIII-4035-560KV (Scorpion)-10V	5	560 KV RPM/Volt		4200 Watts
HK-5035-410KV (Scorpion)-10V	1	410 KV RPM/Volt		4662 Watts
HKIII-4525-520KV (Scorpion)	1	520KV RPM/Volt		4450 watts
SII-5535-190KV (Scorpion)	1	190 RPM/Volt		3900 Watts
P1524-B25 (Poseidon Boat Brushless Motor)	3	2550KV	Max RPM-50K	2000 Watts
P1521-C15 (Poseidon Car Brushless Motor)	1	1550KV	Max RPM-50K	2000 Watts
P1527-B15 (Poseidon Boat Brushless Motor)	1	1500KV	Max RPM-50K	2000 Watts

APPENDIX A: HEAT TRANSFER FORMULA AND CALCULATION

Mach Number	
$M = \sqrt{\left(\frac{2}{\gamma - 1}\right)\left(\left(\frac{p_o}{p}\right)^{\frac{\gamma-1}{\gamma}} - 1\right)}$	Equation 3.11 [10] P_o-Pressure Brick 3_05 P- Pressure bring 3_06
Mass Flow	
$\dot{m} = A * \left(\frac{p_o}{\sqrt{R * T_o}}\right)\sqrt{\gamma}\left(\frac{2}{\gamma + 1}\right)^{\frac{\gamma+1}{2(\gamma-1)}}$	Equation 3.14 [10] P_o- Pressure Brick 3_06 T_o- Outlet Temperature (16,17,18, or 19)
Effectiveness	
$\varepsilon = \frac{q}{q_{max}}$ $C_{min}((T_{h,i} - T_{c,i})$	Equation 11.19 [11] Equation 11.18 [11] $C_c = C_{min}$ $q = q_{act}$
Reynolds Number Gas	
$Re_D = \frac{\rho U_\infty D}{\mu}$	Equation 6.23 – [11]
Nusselt of Gas	
$Nu_D = 3.66 \qquad (Laminar)$ $Nu_D = 0.0243\, Re_D^{\frac{4}{5}} \mathrm{Pr}^{0.4}$	Equation 8.53 [11] Equation 8.60 [11]
Heat Transfer Coefficient	
$h_{gas} = \frac{Nu_D k}{D_i}$	Equation 8.53 [11]
Log Mean Temperature Difference	

$\Delta T_{lm} = \frac{\Delta T1 - \Delta T2}{\ln\left(\frac{\Delta T_1}{\Delta T_2}\right)}$ $\Delta T_1 = T_{h,i} - T_{c,o}$ $\Delta T_2 = T_{h,o} - T_{c,i}$	Equation 11.15 [11] Equation11.17 [11]
Reynolds Number Exhaust	
$\rho_\infty = \frac{p_\infty}{RT}$ $\dot{m}_{exh} = \rho_\infty U_\infty A$ $Re_{Exh} = \frac{\rho U_\infty D_o}{\mu}$	Equation 3.4 [11] Equation 6.23 [11]
Nusselt Number and Heat Transfer Coefficient of Exhaust	
$\overline{Nu_d} = \frac{\bar{h}D}{k} = C\ Re_D^m\ \mathrm{Pr}^{1/3}$ $\overline{h_{exh}} = \frac{\overline{Nu_d}k}{D}$	Equation 7.52 [11] Equation 7.69 [11]
Overall Heat Transfer Coefficient	
$\frac{1}{UA} = \frac{1}{h_{gas}A_i} + R_w + \frac{1}{h_{exh}A_o}$	Equation 11.1a [11]
Heat Transfer	
$q_{calc} = UA\Delta T_{lm}$ $q_{act} = \dot{m}\ C_p(T_o - T_i)$ $q_{max} = C_c(T_{H_i} - T_{C_i})$	Equation 11.14 [11]

APPENDIX B: INSTRUMENTATION SETUP

This section describes the proper configuration of establishing TCIP/IP to Modbus RTU communication.

A. IOLAN SDG8 P GATEWAY DEVICE

The SDG 8 P server device connects the EPI flow meters via RS485 interface to the user workstation via ethernet connection. See Figure 26.

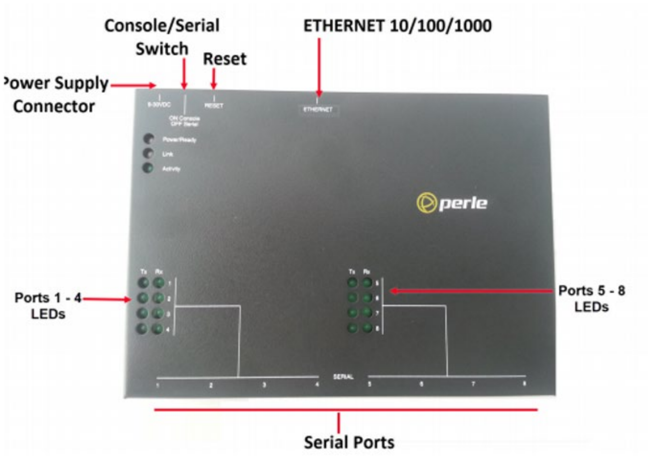


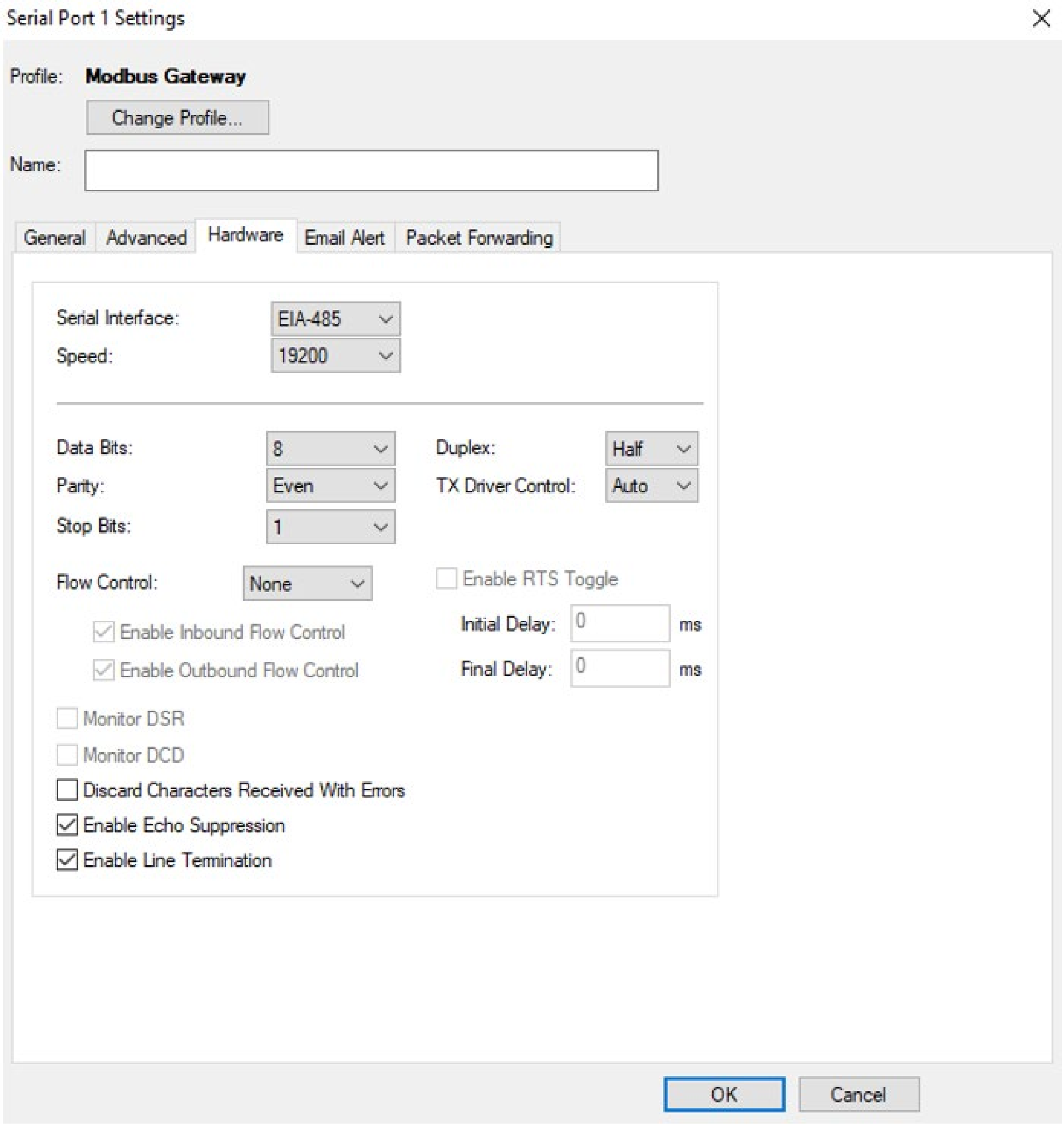
Figure 26. SDG 8 P Gateway Device

1. Software Setup

The Perle device manager is a software specific product utilize to configure the SDG8. An IP address of 195.30.5.150 was assigned to the SDG8. To access the device manager software, the IP address and password (superhero) was required. Within the software each serial port was configured with settings per Table 16. Figure 27 and Figure 28 provides an example of meter 1 setup. Settings are selected based on specified values from the EPICommunicator manual [12]. Each port was assigned its own “UID Range” which values are specified in section B.

Table 16. SDG 8 Software Configuration

Profile	Modbus Gateway
Serial Interface	EIA-485
Speed	19200
Data Bits	8
Duplex	Half
Parity	Even
Stop Bits	1
Enable Echo Suppression	Selected
Enable Line Termination	Selected
UID	See Section B
Modbus/RTU	Selected



Serial Port 1 Settings

Profile: **Modbus Gateway**

Name:

Serial Interface: EIA-485
Speed: 19200

Data Bits: 8
Parity: Even
Stop Bits: 1

Duplex: Half
TX Driver Control: Auto

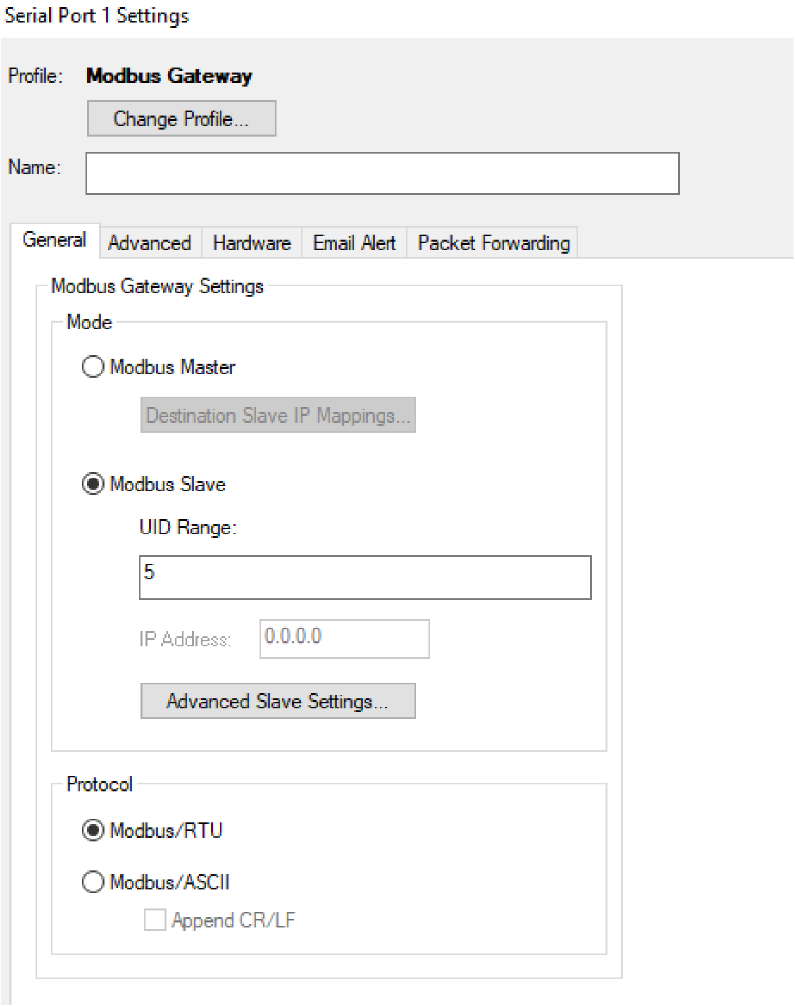
Flow Control: None

☑ Enable Inbound Flow Control
☑ Enable Outbound Flow Control

☐ Enable RTS Toggle
Initial Delay: 0 ms
Final Delay: 0 ms

☐ Monitor DSR
☐ Monitor DCD
☐ Discard Characters Received With Errors
☑ Enable Echo Suppression
☑ Enable Line Termination

Figure 27. Iolan SDG 8 P Hardware Setting



Serial Port 1 Settings

Profile: **Modbus Gateway**

Name:

Modbus Gateway Settings

Mode

○ Modbus Master

● Modbus Slave

UID Range: 5

IP Address: 0.0.0.0

Protocol

● Modbus/RTU

○ Modbus/ASCII

☐ Append CR/LF

Figure 28. Meter 1 General Settings

B. EPI FLOW METERS

Each flow meter communicated with the SDG8 via RS485 interface simultaneously reporting flow rates in Kg/h. Prior to establishing communications each meter was configured via RS232 interface directly to the PC.

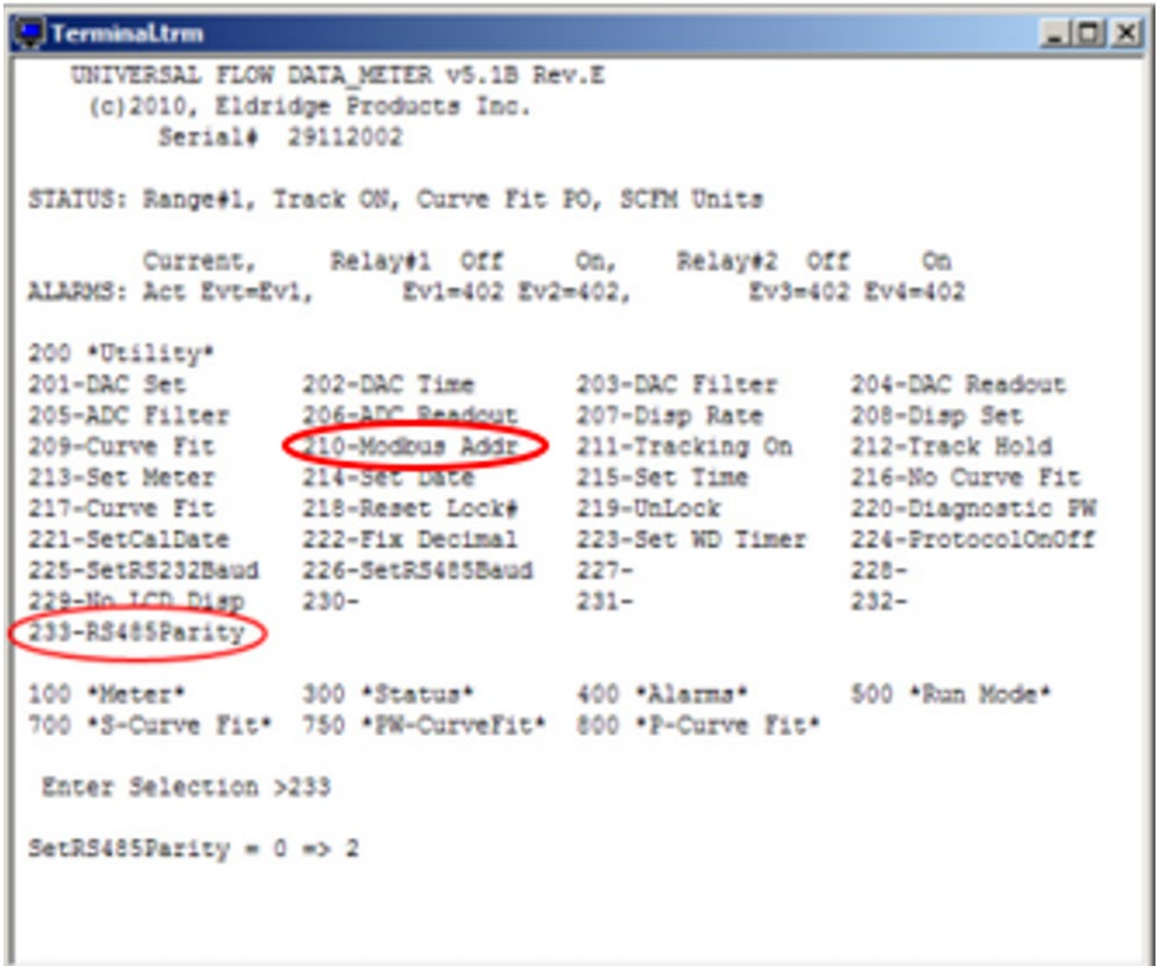
1. Software Setup

Configurations are made via EPIcom V.233 software, Figure 29, with a RS232 connection to each meter individually. Password to enter EPIcom is 9001. Once in the EPI software, flow meters one through four were assigned Modbus addresses as indicated in

Table 17 and corresponds to the respective ports of the SDG8. Selection 210 within the software was selected to set the proper configuration. See Figure 29.

Table 17. Assigned Modbus Address

Meter Number	UID Modbus Address	SDG8 Port Number
1	5	1
2	10	2
3	15	3
4	20	4
No Meter	25	5
No Meter	30	6
No Meter	35	7
No Meter	40	8



```
   UNIVERSAL FLOW DATA_METER v5.1B Rev.E
    (c)2010, Eldridge Products Inc.
        Serial#  29112002

STATUS: Range#1, Track ON, Curve Fit PO, SCFM Units

        Current,     Relay#1  Off     On,    Relay#2  Off     On
ALARMS: Act Evt=Evl,      Ev1=402 Ev2=402,        Ev3=402 Ev4=402

200 *Utility*
201-DAC Set         202-DAC Time        203-DAC Filter      204-DAC Readout
205-ADC Filter      206-ADC Readout     207-Disp Rate       208-Disp Set
209-Curve Fit       210-Modbus Addr     211-Tracking On     212-Track Hold
213-Set Meter       214-Set Date        215-Set Time        216-No Curve Fit
217-Curve Fit       218-Reset Lock#     219-UnLock          220-Diagnostic PW
221-SetCalDate      222-Fix Decimal     223-Set WD Timer    224-ProtocolOnOff
225-SetRS232Baud    226-SetRS485Baud    227-                228-
229-No LCD Disp     230-                231-                232-
233-RS485Parity

100 *Meter*         300 *Status*        400 *Alarms*        500 *Run Mode*
700 *S-Curve Fit*   750 *PW-CurveFit*   800 *P-Curve Fit*

 Enter Selection >233

SetRS485Parity = 0 => 2
```

Figure 29. EPIcom V.233 software

2. Wire Setup

When an EPI meter is being configured a RS232 wire is connected from PC directly to meter. When an EPI meter is being utilized to gather data, the RS232 wire was removed and RS485 wire was connected. Figures 30 and 31 provide wire setup in each configuration. Table 18 provides associated RS232 connections made from PC to EPI meter and Table 19 provides associated connections from SDG8 to EPI meter.

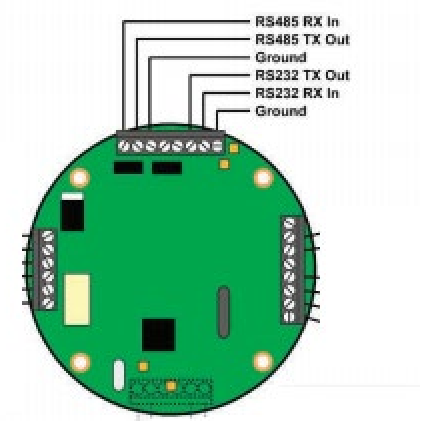


Figure 30. EPI Meter wire connection

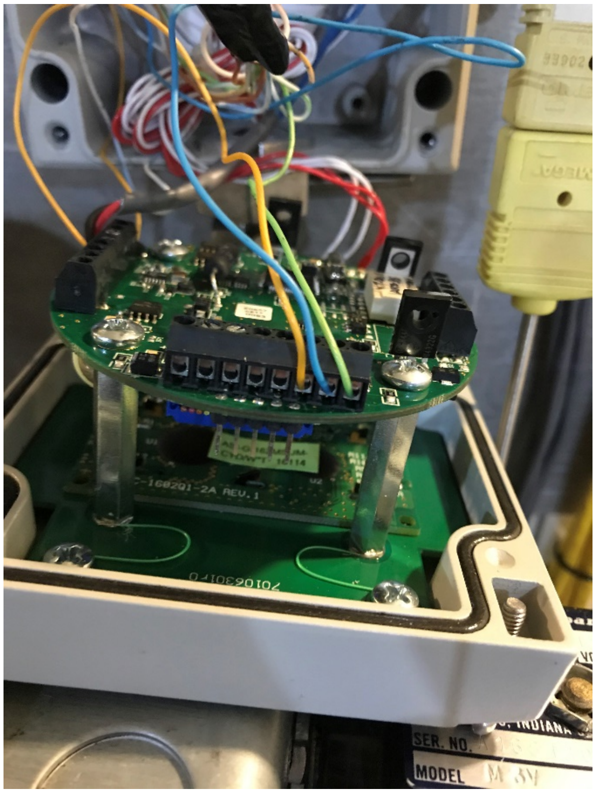


Figure 31. EPI Meter Wire Configuration

Table 18. RS232 wire connection from PC to EPI Meter (Setup Mode)

Pinout (From PC)	EPI Meter
1	
2	RS232 RX in
3	RS232 TX Out
4	
5	Ground
6	
7	
8	
9	

Table 19. RS485 wire connection from SDG 8 to EPI Meter (Operation Mode)

Pinout	EIA-485 Half Duplex (SDG8)	EPI Meter
1		
2	TxD +/RxD+	RS485 Rx in
3		
4	TxD +/RxD+	RS485 TX out
5		
6	GND	Ground
7		

APPENDIX C: DATA ACQUISITION SCRIPT AND UTILIZATION

A. MODBUS EXPLORER APPLICATION

The Modbus Explorer application is utilized to graphically monitor a single meter. Steady flow is assumed when oscillation in flow readings is observed. An example of oscillation in flow can be seen in Figure 32. Due to the ability of the application to only monitor a single meter at a time, steady flow is assumed in all four meters when the meter being monitored achieves steady flow.

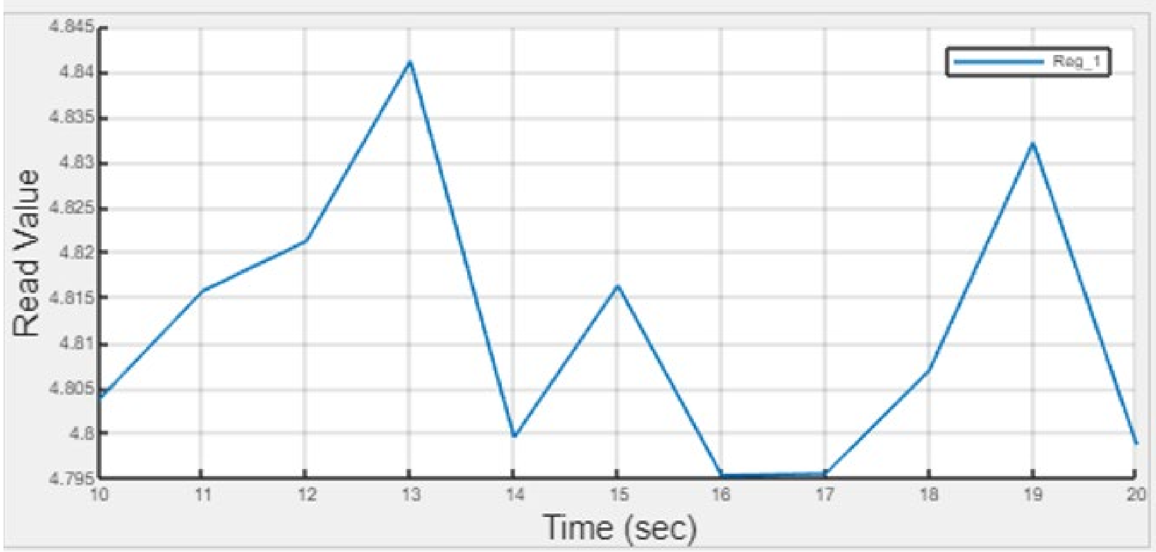
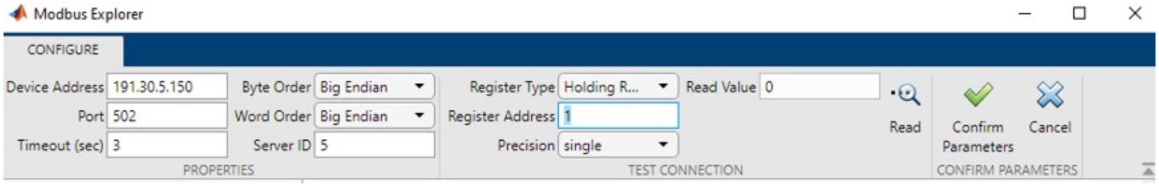


Figure 32. Flow Oscillation via ModBus Explorer Application

1. Configuration

Figure 33 shows the settings entered into the Modbus Explorer application to properly monitor flow through meter 1 and is further amplified by Table 20. Any meter can be monitored, simply by changing the server ID to match the ID number assigned in Appendix B.



Device Address 191.30.5.150
Port 502
Timeout (sec) 3
Byte Order Big Endian
Word Order Big Endian
Server ID 5
Register Type Holding R...
Register Address 1
Precision single
Read Value 0

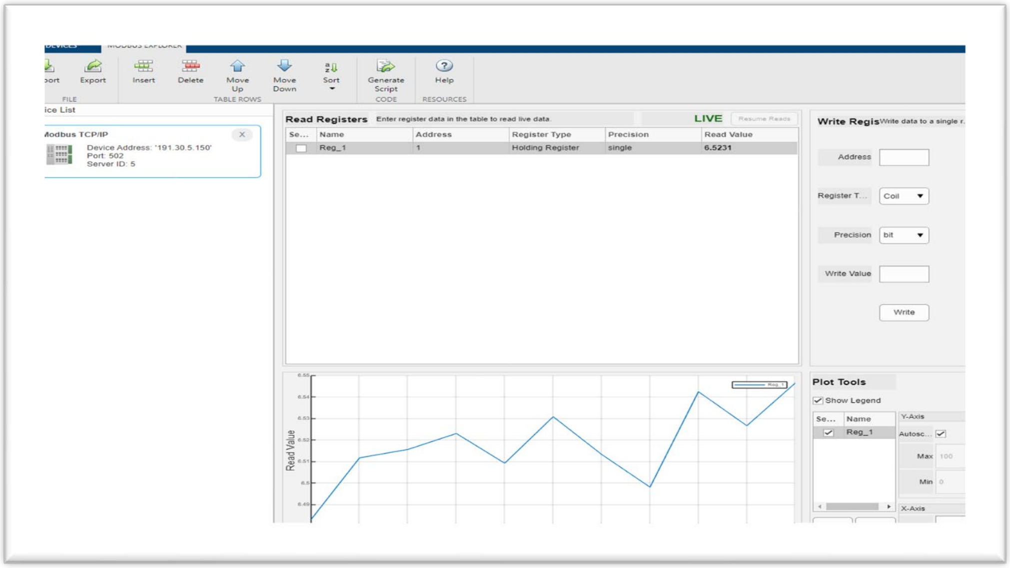
Figure 33. ModBus Explorer Application Setup

Table 20. Modbus Explorer Configuration

Device address	Assigned during initial setup of SDG8
Port	Set to 502 by default for Modbus communication
Timeout	Max amount of time ModBusExplorer will wait for a response before it times out
Byte Order	Set to Big Endian per Modbus standard
Word Order	Set to Big Endian which is specific to SDG8 device
Server ID	Set per Appendix A
Register Type	Holding register, specific to EPI meter commands
Register address	Address associated with flow per EPI manual [12].

B. UTILIZING DAQ SYSTEM

Prior to running the DAQ script, pressure bricks must be initialized as discussed in Kaim’s thesis [4]. Once the DAQ system is in run, MATLAB will prompt user to enter current barometric pressure. After barometric pressure is entered, the Modbus Explorer application will open. Once settings per Figure 33 are established the user must select the “Read” button. If setting have been entered properly, flow values will be displayed in the read value box. Once read value displays values, the “confirm parameters” is selected, and the designated meter will begin to monitor. See Figure 34.



Modbus TCP/IP
Device Address: '191.30.5.150'
Port: 502
Server ID: 5

Read Registers Enter register data in the table to read live data.

Se...	Name	Address	Register Type	Precision	Read Value
☐	Reg_1	1	Holding Register	single	6.5231

Write Regis Write data to a single r.
Address:
Register T...: Coil
Precision: bit
Write Value:

☑ Show Legend

Se...	Name
☑	Reg_1

Y-Axis
Autosc... ☑
Max 100
Min 0
X-Axis

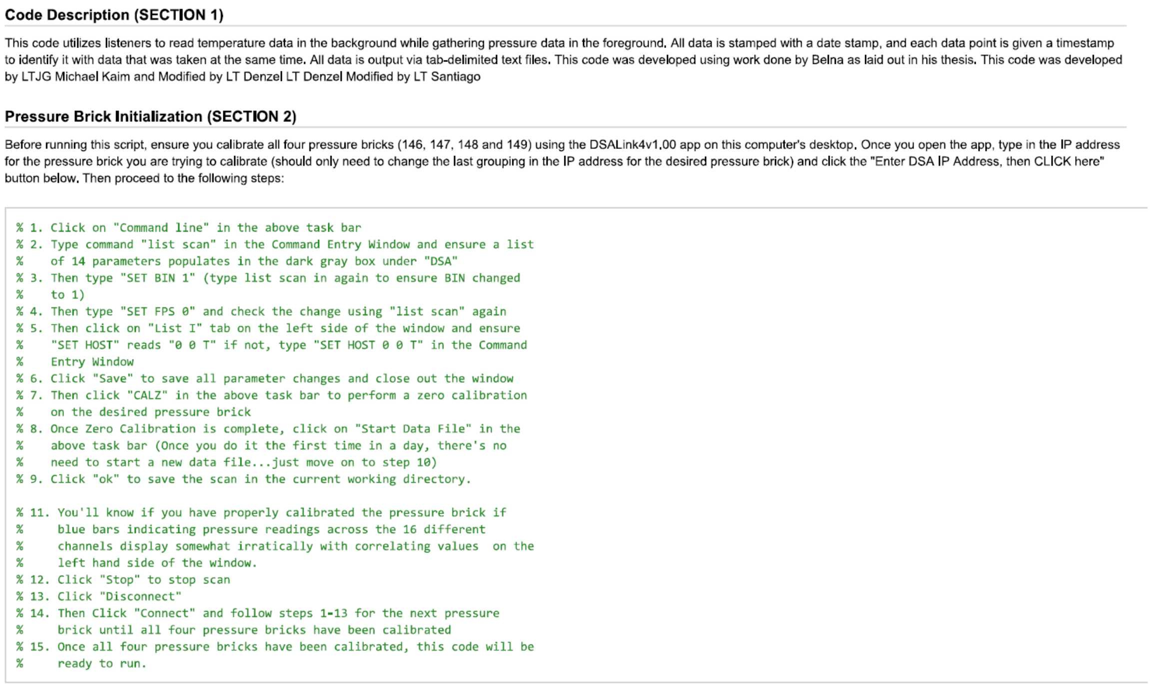
Figure 34. Live Flow Monitoring

Once proper oscillation is observed, user will return to the command window and hit "enter" to continue with data gathering. Once data gathering is complete the command window prompts user to enter the gas test pressure, gas being tested, and the size of nozzle being utilized. This information will be used to populate column labels for the associated excel file being populated by the DAQ program. Once information is entered, MATLAB will display "Run Complete."

C. CURRENT MATLAB SCRIPT

Data Acquisition Script

Contents



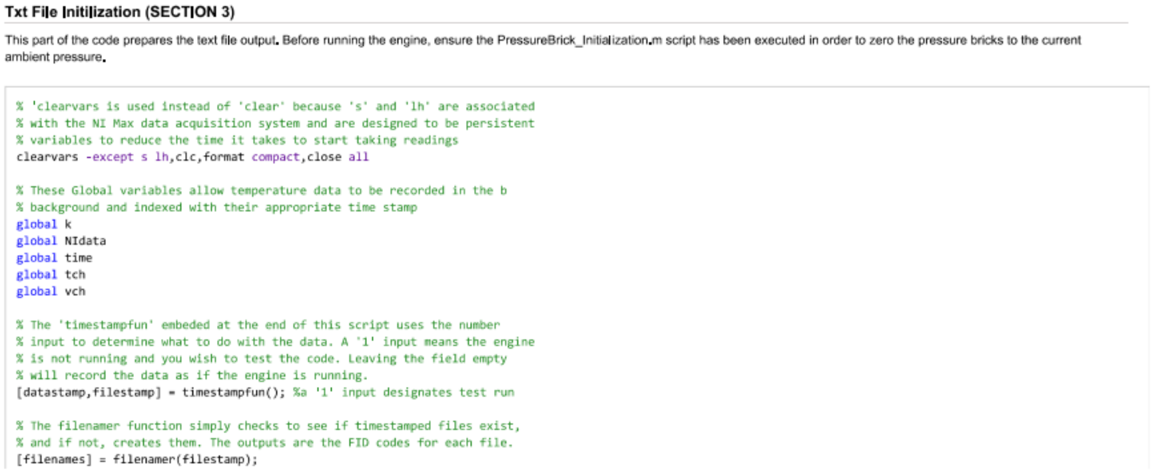
Code Description (SECTION 1)

This code utilizes listeners to read temperature data in the background while gathering pressure data in the foreground. All data is stamped with a date stamp, and each data point is given a timestamp to identify it with data that was taken at the same time. All data is output via tab-delimited text files. This code was developed using work done by Belna as laid out in his thesis. This code was developed by LTJG Michael Kaim and Modified by LT Denzel LT Denzel Modified by LT Santiago

Pressure Brick Initialization (SECTION 2)

Before running this script, ensure you calibrate all four pressure bricks (146, 147, 148 and 149) using the DSALink4v1.00 app on this computer's desktop. Once you open the app, type in the IP address for the pressure brick you are trying to calibrate (should only need to change the last grouping in the IP address for the desired pressure brick) and click the "Enter DSA IP Address, then CLICK here" button below. Then proceed to the following steps:

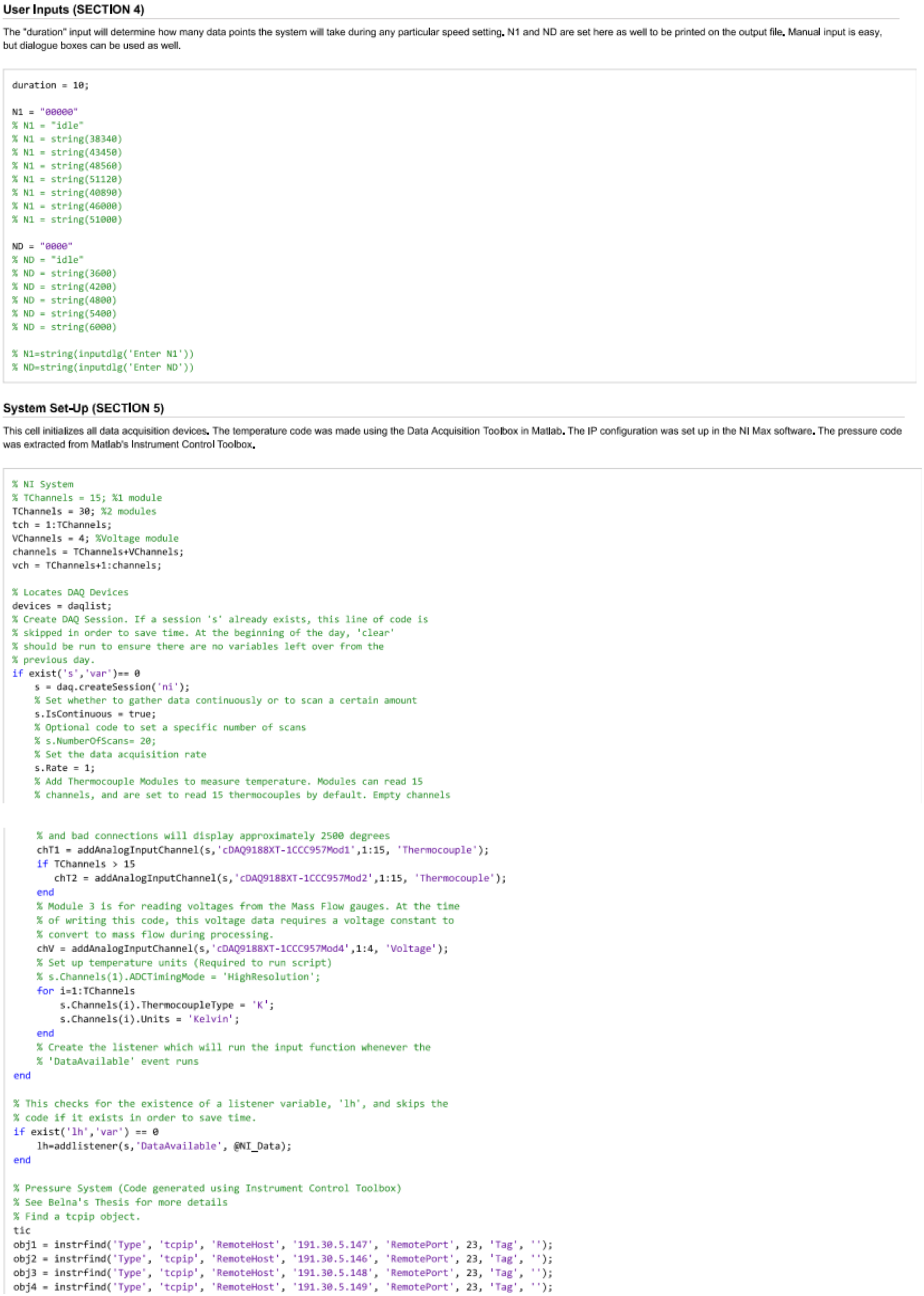
```
% 1. Click on "Command line" in the above task bar
% 2. Type command "list scan" in the Command Entry Window and ensure a list
%    of 14 parameters populates in the dark gray box under "DSA"
% 3. Then type "SET BIN 1" (type list scan in again to ensure BIN changed
%    to 1)
% 4. Then type "SET FPS 0" and check the change using "list scan" again
% 5. Then click on "List I" tab on the left side of the window and ensure
%    "SET HOST" reads "0 0 T" if not, type "SET HOST 0 0 T" in the Command
%    Entry Window
% 6. Click "Save" to save all parameter changes and close out the window
% 7. Then click "CALZ" in the above task bar to perform a zero calibration
%    on the desired pressure brick
% 8. Once Zero Calibration is complete, click on "Start Data File" in the
%    above task bar (Once you do it the first time in a day, there's no
%    need to start a new data file...just move on to step 10)
% 9. Click "ok" to save the scan in the current working directory.

% 11. You'll know if you have properly calibrated the pressure brick if
%     blue bars indicating pressure readings across the 16 different
%     channels display somewhat irratically with correlating values  on the
%     left hand side of the window.
% 12. Click "Stop" to stop scan
% 13. Click "Disconnect"
% 14. Then Click "Connect" and follow steps 1-13 for the next pressure
%     brick until all four pressure bricks have been calibrated
% 15. Once all four pressure bricks have been calibrated, this code will be
%     ready to run.
```



Txt File Initilization (SECTION 3)

This part of the code prepares the text file output. Before running the engine, ensure the PressureBrick_Initialization.m script has been executed in order to zero the pressure bricks to the current ambient pressure.

```
% 'clearvars is used instead of 'clear' because 's' and 'lh' are associated
% with the NI Max data acquisition system and are designed to be persistent
% variables to reduce the time it takes to start taking readings
clearvars -except s lh,clc,format compact,close all

% These Global variables allow temperature data to be recorded in the b
% background and indexed with their appropriate time stamp
global k
global NIdata
global time
global tch
global vch

% The 'timestampfun' embeded at the end of this script uses the number
% input to determine what to do with the data. A '1' input means the engine
% is not running and you wish to test the code. Leaving the field empty
% will record the data as if the engine is running.
[datastamp,filestamp] = timestampfun(); %a '1' input designates test run

% The filenamer function simply checks to see if timestamped files exist,
% and if not, creates them. The outputs are the FID codes for each file.
[filenames] = filenamer(filestamp);
```



User Inputs (SECTION 4)

The "duration" input will determine how many data points the system will take during any particular speed setting. N1 and ND are set here as well to be printed on the output file. Manual input is easy, but dialogue boxes can be used as well.

```
duration = 10;

N1 = "00000"
% N1 = "idle"
% N1 = string(38340)
% N1 = string(43450)
% N1 = string(48560)
% N1 = string(51120)
% N1 = string(40890)
% N1 = string(46000)
% N1 = string(51000)

ND = "0000"
% ND = "idle"
% ND = string(3600)
% ND = string(4200)
% ND = string(4800)
% ND = string(5400)
% ND = string(6000)

% N1=string(inputdlg('Enter N1'))
% ND=string(inputdlg('Enter ND'))
```

System Set-Up (SECTION 5)

This cell initializes all data acquisition devices. The temperature code was made using the Data Acquisition Toolbox in Matlab. The IP configuration was set up in the NI Max software. The pressure code was extracted from Matlab's Instrument Control Toolbox.

```
% NI System
% TChannels = 15; %1 module
TChannels = 30; %2 modules
tch = 1:TChannels;
VChannels = 4; %Voltage module
channels = TChannels+VChannels;
vch = TChannels+1:channels;

% Locates DAQ Devices
devices = daqlist;
% Create DAQ Session. If a session 's' already exists, this line of code is
% skipped in order to save time. At the beginning of the day, 'clear'
% should be run to ensure there are no variables left over from the
% previous day.
if exist('s','var')== 0
    s = daq.createSession('ni');
    % Set whether to gather data continuously or to scan a certain amount
    s.IsContinuous = true;
    % Optional code to set a specific number of scans
    % s.NumberOfScans= 20;
    % Set the data acquisition rate
    s.Rate = 1;
    % Add Thermocouple Modules to measure temperature. Modules can read 15
    % channels, and are set to read 15 thermocouples by default. Empty channels
```

```
    % and bad connections will display approximately 2500 degrees
    chT1 = addAnalogInputChannel(s,'cDAQ9188XT-1CCC957Mod1',1:15, 'Thermocouple');
    if TChannels > 15
       chT2 = addAnalogInputChannel(s,'cDAQ9188XT-1CCC957Mod2',1:15, 'Thermocouple');
    end
    % Module 3 is for reading voltages from the Mass Flow gauges. At the time
    % of writing this code, this voltage data requires a voltage constant to
    % convert to mass flow during processing.
    chV = addAnalogInputChannel(s,'cDAQ9188XT-1CCC957Mod4',1:4, 'Voltage');
    % Set up temperature units (Required to run script)
    % s.Channels(1).ADCTimingMode = 'HighResolution';
    for i=1:TChannels
        s.Channels(i).ThermocoupleType = 'K';
        s.Channels(i).Units = 'Kelvin';
    end
    % Create the listener which will run the input function whenever the
    % 'DataAvailable' event runs
end

% This checks for the existence of a listener variable, 'lh', and skips the
% code if it exists in order to save time.
if exist('lh','var') == 0
    lh=addlistener(s,'DataAvailable', @NI_Data);
end

% Pressure System (Code generated using Instrument Control Toolbox)
% See Belna's Thesis for more details
% Find a tcpip object.
tic
obj1 = instrfind('Type', 'tcpip', 'RemoteHost', '191.30.5.147', 'RemotePort', 23, 'Tag', '');
obj2 = instrfind('Type', 'tcpip', 'RemoteHost', '191.30.5.146', 'RemotePort', 23, 'Tag', '');
obj3 = instrfind('Type', 'tcpip', 'RemoteHost', '191.30.5.148', 'RemotePort', 23, 'Tag', '');
obj4 = instrfind('Type', 'tcpip', 'RemoteHost', '191.30.5.149', 'RemotePort', 23, 'Tag', '');
```

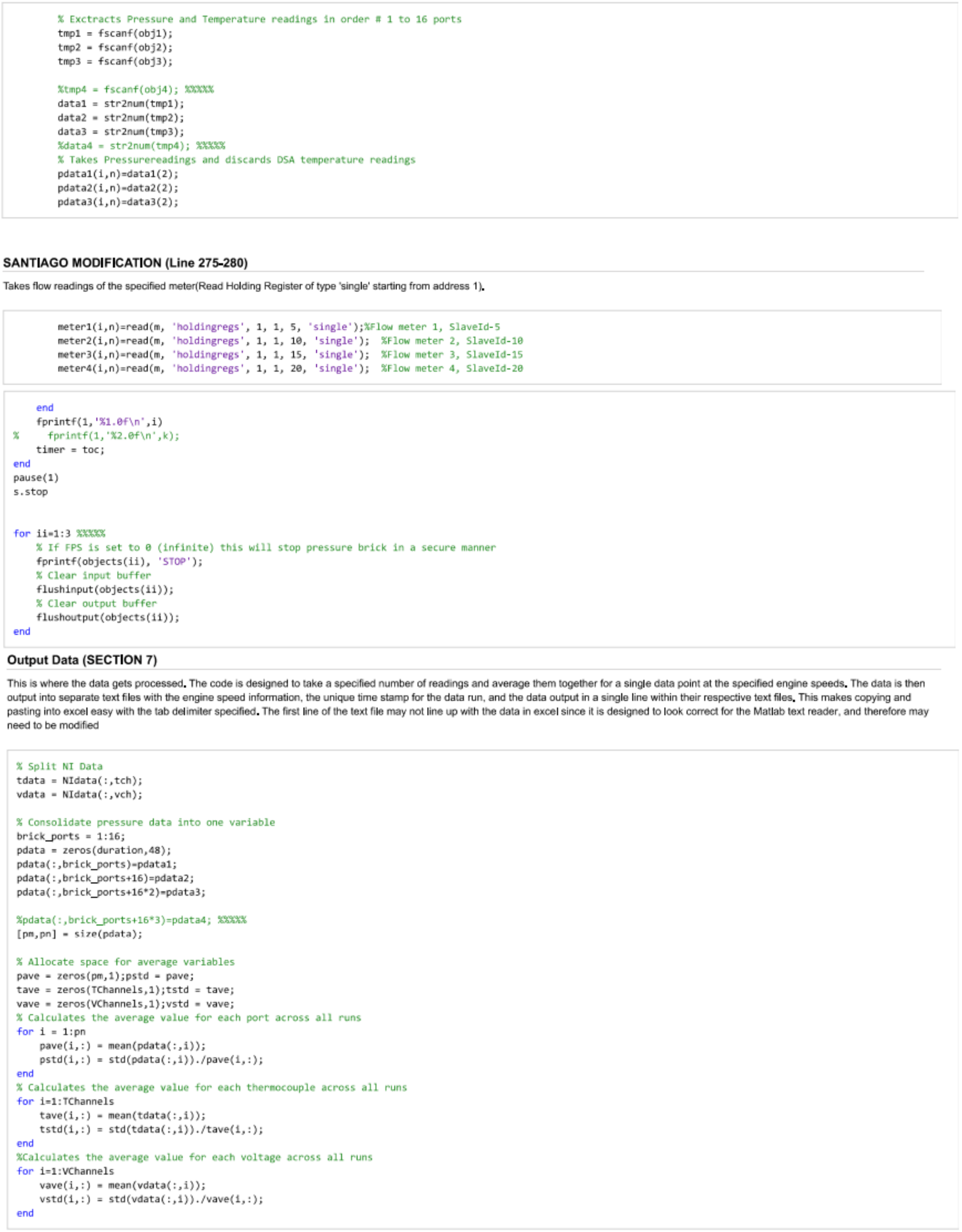
```
% Create the tcpip object if it does not exist, otherwise use the object that was found.
if isempty(obj1)
    obj1 = tcpip('191.30.5.147', 23);
else
    fclose(obj1); obj1 = obj1(1);
end
if isempty(obj2)
    obj2 = tcpip('191.30.5.146', 23);
else
    fclose(obj2); obj2 = obj2(1);
end
if isempty(obj3)
    obj3 = tcpip('191.30.5.148', 23);
else
    fclose(obj3); obj3 = obj3(1);
end
%if isempty(obj4) %%%%%
    %obj4 = tcpip('191.30.5.149', 23); %%%%%
%else
    %fclose(obj4); obj4 = obj4(1); %%%%
%end
% Opens the previously specified objects and sets the parameters for each
% pressure brick
objects = [obj1;obj2;obj3]; %%%%%% [obj1;obj2;obj3;obj4]
for ii=1:3 %%%%%
    fopen(objects(ii));
    % Communicating with instrument object.
    fprintf(objects(ii), 'SET PERIOD 500');
    fprintf(objects(ii), 'SET AVG 32');
    % Set Frames Per Scan
    fprintf(objects(ii), 'SET FPS 1');
    % Set units to Pascals
    fprintf(objects(ii), 'SET UNITSCAN PA');
    % Set Engineering Units format
    fprintf(objects(ii), 'SET EU 1');
    % Set to ASCII data format
    fprintf(objects(ii), 'SET BIN 0');
    % Other Parameters
    fprintf(objects(ii), 'SET PERIOD 500');
    fprintf(objects(ii), 'SET AVG 32');
    fprintf(objects(ii), 'SET FORMAT 0');
    fprintf(objects(ii), 'SET TIME 0');
    % Set Buffer to clear when full and continue sending data
    fprintf(objects(ii), 'SET QPKTS 0');
end
```

Data Gathering (SECTION 6)

The Temperature gathering code runs in the background after the s.startBackground() code is executed. From there, the pressure readings start within the for loop. The code is designed to take the specified number of readings from the pressure bricks while continuously gathering real-time temperature data at the specified rate. Once the pressure data is collected, the Temperature process is stopped so that the readings are taken during the same interval.

```
pdata1 = zeros(duration,16);
pdata2 = pdata1;
pdata3 = pdata1;
%pdata4 = pdata1; %%%%%
NIdata = zeros(1,channels);
```

```
time = 0;
k = 0;
s.startBackground();
% Takes the requested number of data points from the pressure bricks while
% running the thermocouple readings in the background
timer=0;
for i=1:duration
%     if i>1
        pause(1-timer)
%     end
    tic
    % Sends Scan Command to DSA Pressure Brick
    fprintf(obj1, 'SCAN');
    fprintf(obj2, 'SCAN');
    fprintf(obj3, 'SCAN');
    %fprintf(obj4, 'SCAN'); %%%%%
    % Discards first variable from packet which lists frame number,
    % if set to FPS = 1 all frames will be 0
    frame = fscanf(obj1);
    frame = fscanf(obj2);
    frame = fscanf(obj3);
    %frame = fscanf(obj4); %%%%%
    for n=1:16
```



```
        % Exctracts Pressure and Temperature readings in order # 1 to 16 ports
        tmp1 = fscanf(obj1);
        tmp2 = fscanf(obj2);
        tmp3 = fscanf(obj3);

        %tmp4 = fscanf(obj4); %%%%%
        data1 = str2num(tmp1);
        data2 = str2num(tmp2);
        data3 = str2num(tmp3);
        %data4 = str2num(tmp4); %%%%%
        % Takes Pressurereadings and discards DSA temperature readings
        pdata1(i,n)=data1(2);
        pdata2(i,n)=data2(2);
        pdata3(i,n)=data3(2);
```

SANTIAGO MODIFICATION (Line 275-280)

Takes flow readings of the specified meter(Read Holding Register of type 'single' starting from address 1).

```
        meter1(i,n)=read(m, 'holdingregs', 1, 1, 5, 'single');%Flow meter 1, SlaveId-5
        meter2(i,n)=read(m, 'holdingregs', 1, 1, 10, 'single');  %Flow meter 2, SlaveId-10
        meter3(i,n)=read(m, 'holdingregs', 1, 1, 15, 'single');  %Flow meter 3, SlaveId-15
        meter4(i,n)=read(m, 'holdingregs', 1, 1, 20, 'single');  %Flow meter 4, SlaveId-20
```

```
    end
    fprintf(1,'%1.0f\n',i)
%     fprintf(1,'%2.0f\n',k);
    timer = toc;
end
pause(1)
s.stop


for ii=1:3 %%%%%
    % If FPS is set to 0 (infinite) this will stop pressure brick in a secure manner
    fprintf(objects(ii), 'STOP');
    % Clear input buffer
    flushinput(objects(ii));
    % Clear output buffer
    flushoutput(objects(ii));
end
```

Output Data (SECTION 7)

This is where the data gets processed. The code is designed to take a specified number of readings and average them together for a single data point at the specified engine speeds. The data is then output into separate text files with the engine speed information, the unique time stamp for the data run, and the data output in a single line within their respective text files. This makes copying and pasting into excel easy with the tab delimiter specified. The first line of the text file may not line up with the data in excel since it is designed to look correct for the Matlab text reader, and therefore may need to be modified

```
% Split NI Data
tdata = NIdata(:,tch);
vdata = NIdata(:,vch);

% Consolidate pressure data into one variable
brick_ports = 1:16;
pdata = zeros(duration,48);
pdata(:,brick_ports)=pdata1;
pdata(:,brick_ports+16)=pdata2;
pdata(:,brick_ports+16*2)=pdata3;

%pdata(:,brick_ports+16*3)=pdata4; %%%%%
[pm,pn] = size(pdata);

% Allocate space for average variables
pave = zeros(pm,1);pstd = pave;
tave = zeros(TChannels,1);tstd = tave;
vave = zeros(VChannels,1);vstd = vave;
% Calculates the average value for each port across all runs
for i = 1:pn
    pave(i,:) = mean(pdata(:,i));
    pstd(i,:) = std(pdata(:,i))./pave(i,:);
end
% Calculates the average value for each thermocouple across all runs
for i=1:TChannels
    tave(i,:) = mean(tdata(:,i));
    tstd(i,:) = std(tdata(:,i))./tave(i,:);
end
%Calculates the average value for each voltage across all runs
for i=1:VChannels
    vave(i,:) = mean(vdata(:,i));
    vstd(i,:) = std(vdata(:,i))./vave(i,:);
end
```

SANTIAGO MODIFICATIONS (LINE 345-385)

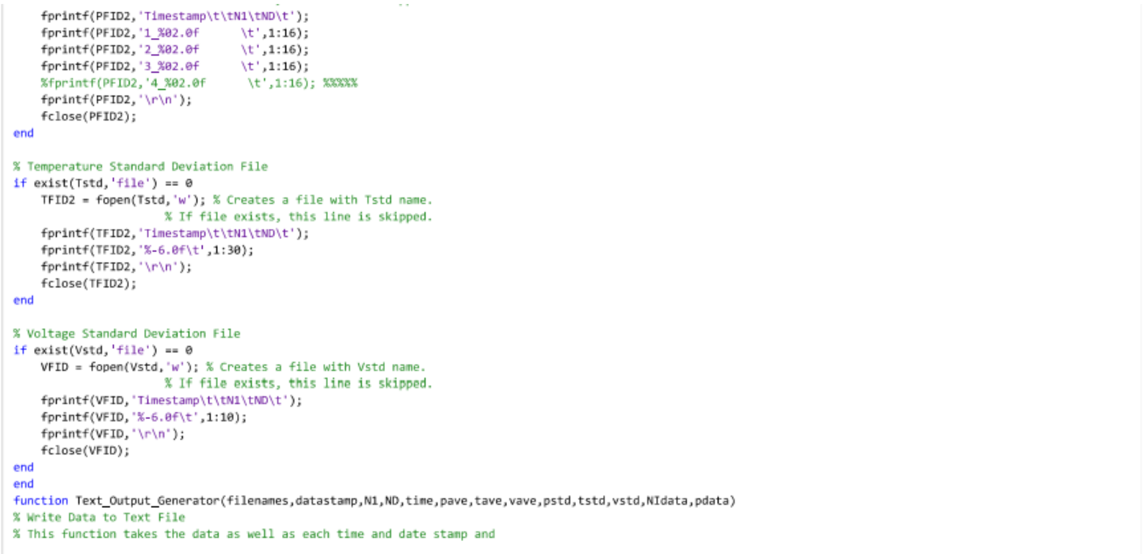
```
%This section calculates the average flow of each individual meter and
%populates an excel file based on user input.

Flow1=mean(meter1); %Calculates the average of 10 runs for meter 1
Flow2=mean(meter2); %Calculates the average of 10 runs for meter 2
Flow3=mean(meter3); %Calculates the average of 10 runs for meter 3
Flow4=mean(meter4); %Calculates the average of 10 runs for meter 4

Flow1Actual=Flow1(1,6);
Flow2Actual=Flow2(1,6);
Flow3Actual=Flow3(1,6);
Flow4Actual=Flow4(1,6);

prompt1 = 'Enter gas test pressure (50/75/100)'; %Creates Prompt
prompt2 = 'Enter gas(CO2/N2)'; %Creates Prompt
prompt3 = 'Enter nozzle size (1/8,3/16, 1/16)'; %Creates Prompt
prompt4='Enter run number (1,2,3...)'; %Creates Prompt

GasPres=input(prompt1,'s') %Request gas pressure input
GasType=input(prompt2,'s') %Request type input
NozSize=input(prompt3,'s') %Request nozzle size input
RunNum=input(prompt4,'s')  %Request run number Input
Run=str2num(RunNum);
datastamps=str2num(filestamp)

%Creates file and location to store file
filename = sprintf('%d_MassFlowData',datastamps);
folder = (['D:\Santiago\A.Santiago Data Acquisition and Sequence\Data Acquisition Code (Santiago Modified)\Test Data\' filestamp])
fullFileName = fullfile(folder, filename);

%Sets up column labels so that information is easily identifiable in excel
count='a';
Col=char(count + Run)
num='1'
A ={'Device'; 'Meter 1'; 'Meter 2'; 'Meter 3'; 'Meter 4'}
B = {sprintf('%s#_%s_%s_Nozzle', GasPres,GasType,NozSize); Flow1Actual; Flow2Actual; Flow3Actual; Flow4Actual};
```

Functions (SECTION 8)

This part of the code is reserved for the local functions. Local Functions must be specified at the end of the code after everything else.

```
function [datastamp,filestamp] = timestampfun(test)
% This function creates a time and date stamp for the data output files. If
% a script test run is designated, the filestamp variable is replaced with
% 'test' to output the data to a continuous testing data file. For actual
% data acquisition runs, the filestamp is the current date in YYYYMMDD
% format. The datastamp variable is the date but also includes the time at
% which the run was initiated.
% [datastamp,filestamp] = timestampfun(test)
%       where 'test' is a 1 for a script test run. Leave this field empty
%       for actual data acquisition.
if nargin == 0
    test=0;
end
% Calculate current date and time for timestamp
now = datetime('now');
y = num2str(year(now));
m = month(now);
if m<10
    m = (['0' num2str(m)]);
else
    m = num2str(m);
end
d = day(now);
if d<10
    d = (['0' num2str(d)]);
else
    d = num2str(d);
end
hr = hour(now);
if hr<10
    hr = (['0' num2str(hr)]);
else
    hr = num2str(hr);
end
min = minute(now);
if min<10
    min = (['0' num2str(min)]);
else
    min = num2str(min);
end
sec = round(second(now));
if sec<10
    sec = (['0' num2str(sec)]);
else
    sec = num2str(sec);
end
```

```
datastamp = [y m d '_' hr min '_' sec]
if test == 1
    filestamp = 'test'
else
    filestamp = [y m d]
end
end
function [filenames] = filenamer(filestamp)
% Description
% This function generates the filenames for each of the output text files.
% It uses the filestamp from the previous function to ensure each file is
% dated with the YYYYMMDD date format. The output 'filenames' is a cell
% array which is an input to the text file output function. No user input
% is necessary

% File Name Generator
mkdir(['Test Data\' filestamp])
Pfile = ['Test Data\' filestamp '\' filestamp '_PressureData' '.txt'];
Tfile = ['Test Data\' filestamp '\' filestamp '_TemperatureData' '.txt'];
Vfile = ['Test Data\' filestamp '\' filestamp '_VoltageData' '.txt'];
NIdatafile = ['Test Data\' filestamp '\' filestamp '_NIdata' '.txt'];
Pdatafile = ['Test Data\' filestamp '\' filestamp '_pdata' '.txt'];
Pstd = ['Test Data\' filestamp '\' filestamp '_PressureStdDev' '.txt'];
Tstd = ['Test Data\' filestamp '\' filestamp '_TemperatureStdDev' '.txt'];
Vstd = ['Test Data\' filestamp '\' filestamp '_VoltageStdDev' '.txt'];
filenames = {Pfile; Tfile; Vfile; NIdatafile; Pdatafile; Pstd; Tstd; Vstd};

save('names.mat','Pfile','Tfile','Vfile','NIdatafile','Pdatafile','Pstd','Tstd','Vstd')

% File Generator
% If the file exists, this portion of the code is skipped. This would
% indicate a file with today's date is already created, and will simple by
% ammended.

% Pressure File
if exist(Pfile,'file') == 0
    P_atm = string(inputdlg('Enter Atmospheric Pressure (with units)'));
%     P_atm = "29.90 inHg"
    PFID = fopen(Pfile,'w'); % Creates a file with Pfile name.
                      % If file exists, this line is skipped.
    fprintf(PFID,'Atmospheric Pressure:\t%s\r',P_atm);
    fprintf(PFID,'Timestamp\t\tN1\tND\t');
%     fprintf(PFID,'%-8.2f\t',[1.01:.01:1.16,2.01:.01:2.16,3.01:.01:3.16]);
    fprintf(PFID,'1_%02.0f      \t',1:16);
    fprintf(PFID,'2_%02.0f      \t',1:16);
    fprintf(PFID,'3_%02.0f      \t',1:16);
    %fprintf(PFID,'4_%02.0f      \t',1:16);%%%%%
    fprintf(PFID,'\r\n');
    fclose(PFID);
end

% Temperature File
if exist(Tfile,'file') == 0
    TFID = fopen(Tfile,'w'); % Creates a file with Tfile name.
                      % If file exists, this line is skipped.
    fprintf(TFID,'Timestamp\t\tN1\tND\t');
    fprintf(TFID,'%-8.0f\t',1:32);
    fprintf(TFID,'\r\n');
    fclose(TFID);
end

% Voltage File
if exist(Vfile,'file') == 0
    VFID = fopen(Vfile,'w'); % Creates a file with Vfile name.
                      % If file exists, this line is skipped.
    fprintf(VFID,'Timestamp\t\tN1\tND\t');
    fprintf(VFID,'%-8.0f\t',1:10);
    fprintf(VFID,'\r\n');
    fclose(VFID);
end

% Raw NI Max Data File
if exist(NIdatafile,'file') == 0
    TFID = fopen(NIdatafile,'w'); % Creates a file with Tdatafile name.
                      % If file exists, this line is skipped.
    fclose(TFID);
end

% Raw Pressure Data File
if exist(Pdatafile,'file') == 0
    PFID = fopen(Pdatafile,'w'); % Creates a file with Pdatafile name.
                      % If file exists, this line is skipped.
    fclose(PFID);
end

% Pressure Standard Deviation File
if exist(Pstd,'file') == 0
    PFID2 = fopen(Pstd,'w'); % Creates a file with Pstd name.
                      % If file exists, this line is skipped.
```



```
    fprintf(PFID2,'Timestamp\t\tN1\tND\t');
    fprintf(PFID2,'1_%02.0f      \t',1:16);
    fprintf(PFID2,'2_%02.0f      \t',1:16);
    fprintf(PFID2,'3_%02.0f      \t',1:16);
    %fprintf(PFID2,'4_%02.0f      \t',1:16); %%%%%
    fprintf(PFID2,'\r\n');
    fclose(PFID2);
end

% Temperature Standard Deviation File
if exist(Tstd,'file') == 0
    TFID2 = fopen(Tstd,'w'); % Creates a file with Tstd name.
                             % If file exists, this line is skipped.
    fprintf(TFID2,'Timestamp\t\tN1\tND\t');
    fprintf(TFID2,'%-6.0f\t',1:30);
    fprintf(TFID2,'\r\n');
    fclose(TFID2);
end

% Voltage Standard Deviation File
if exist(Vstd,'file') == 0
    VFID = fopen(Vstd,'w'); % Creates a file with Vstd name.
                             % If file exists, this line is skipped.
    fprintf(VFID,'Timestamp\t\tN1\tND\t');
    fprintf(VFID,'%-6.0f\t',1:10);
    fprintf(VFID,'\r\n');
    fclose(VFID);
end
end
function Text_Output_Generator(filenames,datastamp,N1,ND,time,pave,tave,vave,pstd,tstd,vstd,NIdata,pdata)
% Write Data to Text File
% This function takes the data as well as each time and date stamp and
```

```
% outputs them in separate text files for processing. The text files are
% tab-delimited and formatted to be viewed in MATLAB. For MATLAB data
% processing, the files need to be formatted further by removing excess
% tab delimiters. For excel, the data needs to be imported with the import
% function or can be copied and pasted directly into excel.

% Pressure Data
Pname = (['Pdata_' datastamp]);
PFID = fopen(string(filenames(1)),'a');
fprintf(PFID,'%s\t',Pname);
fprintf(PFID,'%s\t%s\t',[N1 ND]);
fprintf(PFID,'%08.2f\t',pave);
fprintf(PFID,'\r\n');
fclose(PFID);
% Temperature Data
Tname = (['Tdata_' datastamp]);
TFID = fopen(string(filenames(2)),'a');
fprintf(TFID,'%s\t',Tname);
fprintf(TFID,'%s\t%s\t',[N1 ND]);
fprintf(TFID,'%-010.4f\t',tave);
fprintf(TFID,'\r\n');
fclose(TFID);
% Voltage Data
Vname = (['Vdata_' datastamp]);
VFID = fopen(string(filenames(3)),'a');
fprintf(VFID,'%s\t',Vname);
fprintf(VFID,'%s\t%s\t',[N1 ND]);
fprintf(VFID,'%-010.4f\t',vave);
fprintf(VFID,'\r\n');
fclose(VFID);
% Raw NI Values
Tname = (['Trawdata_' datastamp]);
[m,n] = size(NIdata);
TFID = fopen(string(filenames(4)),'a');
fprintf(TFID,'%s\t',Tname);
fprintf(TFID,'N1: %s\tND: %s\t\ntime\t',[N1 ND]);
fprintf(TFID,'%-10.0f\t',1:n);
fprintf(TFID,'\n');
for i=1:m
    fprintf(TFID,'%2.2f\t',time(i));
    fprintf(TFID,'%-06.4f\t',NIdata(i,1:n));
    fprintf(TFID,'\r');
end
fprintf(TFID,'\n');
fclose(TFID);

% Raw Pressure Values
Pname = (['Prawdata_' datastamp]);
[m,n] = size(pdata);
PFID = fopen(string(filenames(5)),'a');
fprintf(PFID,'%s\t',Pname);
fprintf(PFID,'N1: %s\tND: %s\t\n',[N1 ND]);
%     fprintf(PFID,'%-6.4f\t',[1.01:.01:1.16,2.01:.01:2.16,3.01:.01:3.16]);
fprintf(PFID,'1_%02.0f      \t',1:16);
fprintf(PFID,'2_%02.0f      \t',1:16);
fprintf(PFID,'3_%02.0f      \t',1:16);
%fprintf(PFID,'4_%02.0f      \t',1:16); %%%%%
fprintf(PFID,'\n');
for i=1:m
    fprintf(PFID,'%010.2f\t',pdata(i,1:n));
    fprintf(PFID,'\r');
end
fprintf(PFID,'\n');
fclose(PFID);
```

```
% Pressure Standard Deviation
Pname = (['Pstd_' datastamp]);
PFID = fopen(string(filenames(6)),'a');
fprintf(PFID,'%s\t',Pname);
fprintf(PFID,'%s\t%s\t',[N1 ND]);
fprintf(PFID,'%08.4G%%\t',pstd.*100);
fprintf(PFID,'\r\n');
fclose(PFID);
% Temperature Standard Deviation
Tname = (['Tstd_' datastamp]);
TFID = fopen(string(filenames(7)),'a');
fprintf(TFID,'%s\t',Tname);
fprintf(TFID,'%s\t%s\t',[N1 ND]);
fprintf(TFID,'%-2.4f%%\t',tstd.*100);
fprintf(TFID,'\r\n');
fclose(TFID);
% Voltage Standard Deviation
Vname = (['Vstd_' datastamp]);
VFID = fopen(string(filenames(8)),'a');
fprintf(VFID,'%s\t',Vname);
fprintf(VFID,'%s\t%s\t',[N1 ND]);
fprintf(VFID,'%-2.2f%%\t',vstd.*100);
fprintf(VFID,'\r\n');
fclose(VFID);
end
```

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APPENDIX D: CARBON DIOXIDE COLD RUN TESTING CALCULATIONS

A. CALCULATED VS. MEASURED MASS FLOW RATES- INDIVIDUAL METER TESTING

1. 1/16" Nozzle Calculations

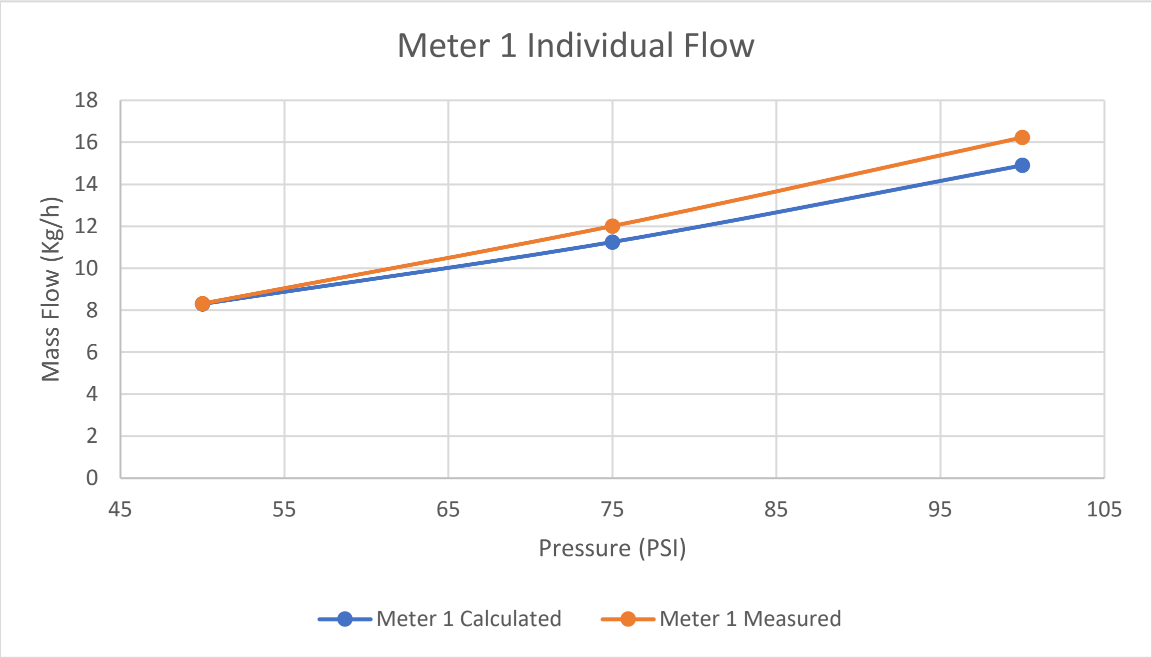
Meter 1											
Total Pressure (Pa)	Recorded Pressure Brick Port 6 Gage Values (Pa)	Recorded Pressure Brick Atmospheric Values (Pa)	Diameter exit (in)	Diameter exit (m)	Area exit (m^2)	Mach Number (M)	Choked Flow? (M > 1)	Calculated Mass Flow Rate (Kg/s)	Calculated Mass Flow Rate (Kg/h)	Recorded Flow Meter Mass Flow Rate (Kg/h)	Error (%)
344738 (50 psi)	309818.62	411444.14	1/16	0.0015875	1.97933E-06	1.60	Yes	0.002306104	8.301975604	8.322666667	0.248610968
517107 (75 psi)	456158.29	557783.81	1/16	0.0015875	1.97933E-06	1.79	Yes	0.003126102	11.25396697	12.01333333	6.321029673
689476 (100 psi)	637210.93	738836.45	1/16	0.0015875	1.97933E-06	1.97	Yes	0.004139531	14.90230985	16.23333333	8.199323303

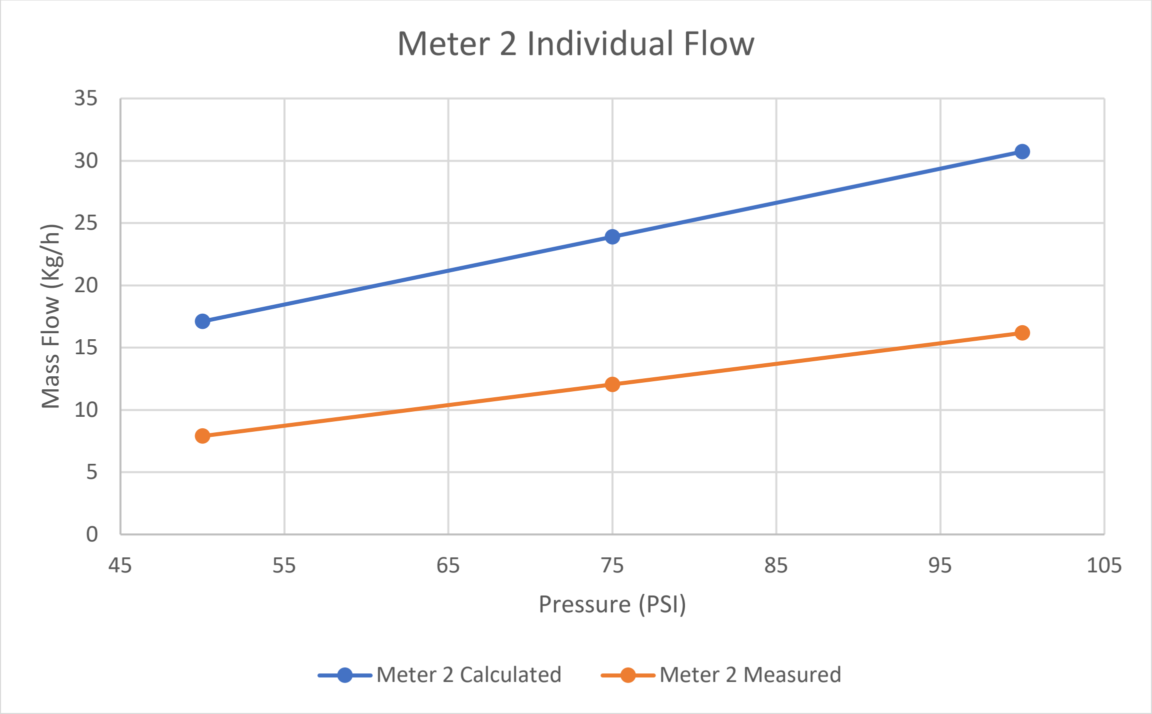
Meter 2											
Total Pressure (Pa)	Recorded Pressure Brick Port 6 Gage Values (Pa)	Recorded Pressure Brick Atmospheric Values (Pa)	Diameter exit (in)	Diameter exit (m)	Area exit (m^2)	Mach Number (M)	Choked Flow? (M > 1)	Calculated Mass Flow Rate (Kg/s)	Calculated Mass Flow Rate (Kg/h)	Recorded Flow Meter Mass Flow Rate (Kg/h)	Error (%)
344738 (50 psi)	276854.98	378480.5	1/16	0.0015875	1.97933E-06	1.54	Yes	0.002119552	7.630387433	7.897666667	3.384281011
517107 (75 psi)	451423.63	553049.15	1/16	0.0015875	1.97933E-06	1.79	Yes	0.003096955	11.14903893	12.04333333	7.425638556
689476 (100 psi)	609996.41	711621.93	1/16	0.0015875	1.97933E-06	1.95	Yes	0.00399109	14.36792345	16.17333333	11.16288059

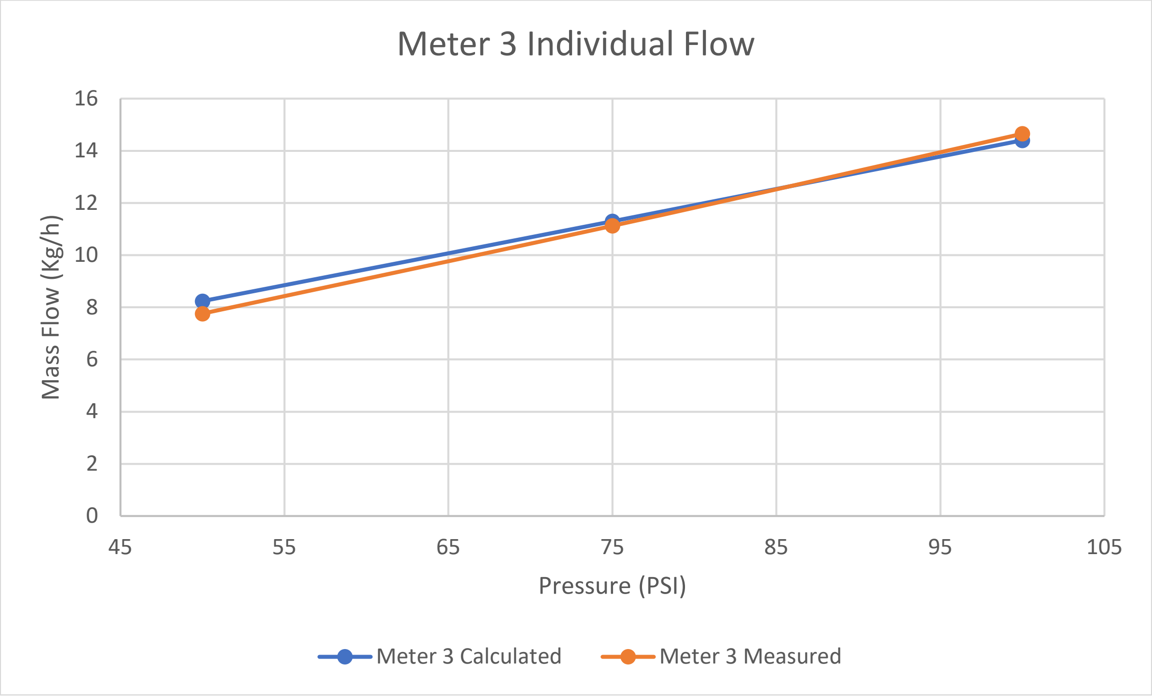
Meter 3											
Total Pressure (Pa)	Recorded Pressure Brick Port 6 Gage Values (Pa)	Recorded Pressure Brick Atmospheric Values (Pa)	Diameter exit (in)	Diameter exit (m)	Area exit (m^2)	Mach Number (M)	Choked Flow? (M > 1)	Calculated Mass Flow Rate (Kg/s)	Calculated Mass Flow Rate (Kg/h)	Recorded Flow Meter Mass Flow Rate (Kg/h)	Error (%)
344738 (50 psi)	305825.75	407451.27	1/16	0.0015875	1.97933E-06	1.59	Yes	0.002288291	8.237846829	7.76	6.157819968
517107 (75 psi)	457439.09	559064.61	1/16	0.0015875	1.97933E-06	1.80	Yes	0.003138284	11.29782173	11.12333333	1.568670065
689476 (100 psi)	611790.49	713416.01	1/16	0.0015875	1.97933E-06	1.95	Yes	0.004001207	14.40434406	14.65333333	1.69919884

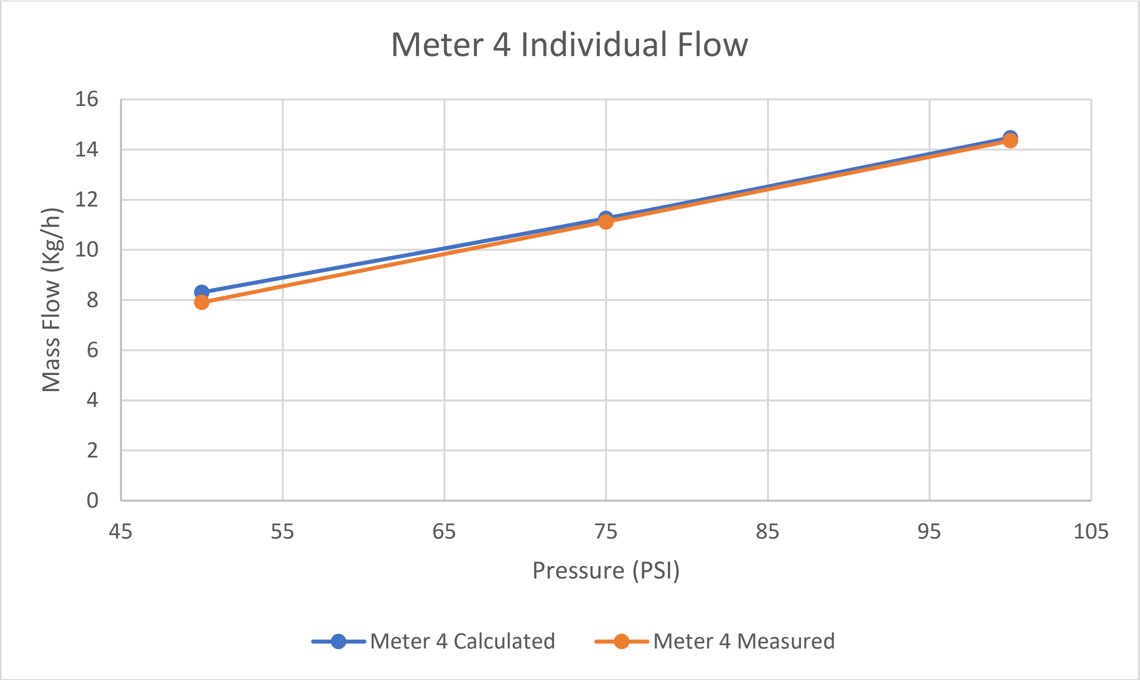
Meter 4											
Total Pressure (Pa)	Recorded Pressure Brick Port 6 Gage Values (Pa)	Recorded Pressure Brick Atmospheric Values (Pa)	Diameter exit (in)	Diameter exit (m)	Area exit (m^2)	Mach Number (M)	Choked Flow? (M > 1)	Calculated Mass Flow Rate (Kg/s)	Calculated Mass Flow Rate (Kg/h)	Recorded Flow Meter Mass Flow Rate (Kg/h)	Error (%)
344738 (50 psi)	310135.45	411760.97	1/16	0.0015875	1.97933E-06	1.60	Yes	0.00230771	8.307757198	7.906	5.08167465
517107 (75 psi)	456514.18	558139.7	1/16	0.0015875	1.97933E-06	1.79	Yes	0.003127467	11.25888034	11.12	1.248923948
689476 (100 psi)	616325.51	717951.03	1/16	0.0015875	1.97933E-06	1.95	Yes	0.00401952	14.47027241	14.35333333	0.814717183

2. 1/16" Nozzle Calculated vs. Actual Plots




Meter 2 Individual Flow
35
30
25
20
15
10
5
0
Mass Flow (Kg/h)
45
55
65
75
85
95
105
Pressure (PSI)
Meter 2 Calculated
Meter 2 Measured


Meter 3 Individual Flow
16
14
12
10
8
6
4
2
0
Mass Flow (Kg/h)
45
55
65
75
85
95
105
Pressure (PSI)
Meter 3 Calculated
Meter 3 Measured



3. 1/8" Nozzle Calculations

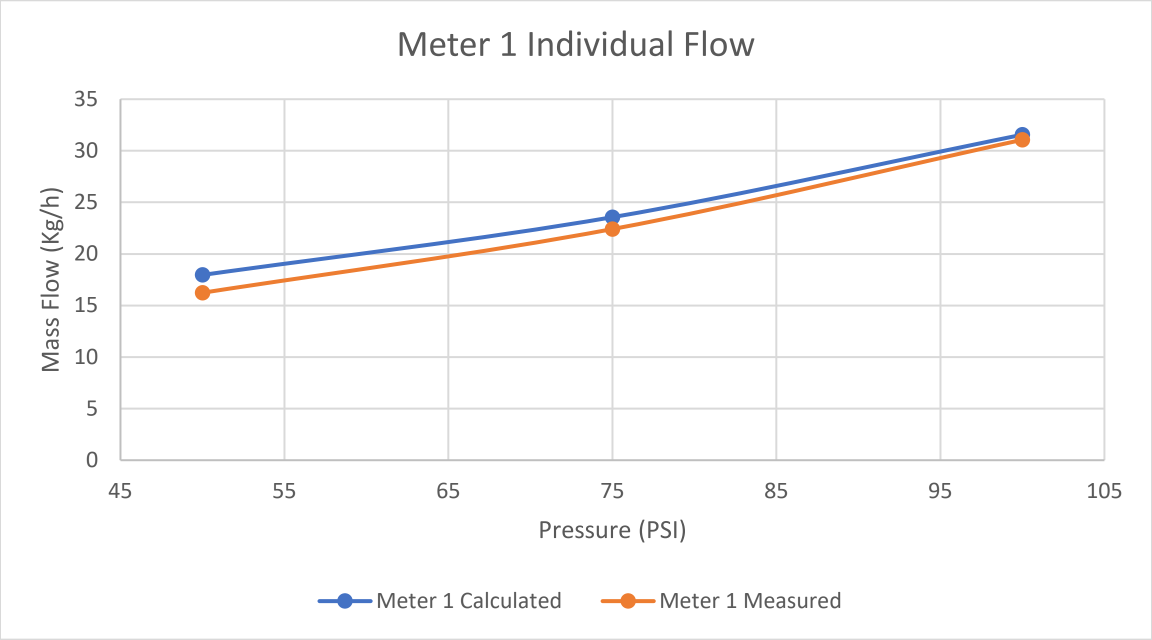
Meter 1											
Total Pressure (Pa)	Recorded Pressure Brick Port 6 Gage Values (Pa)	Recorded Pressure Brick Atmospheric Values (Pa)	Diameter exit (in)	Diameter exit (m)	Area exit (m^2)	Mach Number (M)	Choked Flow? (M > 1)	Calculated Mass Flow Rate (Kg/s)	Calculated Mass Flow Rate (Kg/h)	Recorded Flow Meter Mass Flow Rate (Kg/h)	Error (%)
344738 (50 psi)	121656.11	223146.18	1/8	0.003175	7.9173E-06	1.16	Yes	0.004989112	17.96080275	16.23333333	10.64149537
517107 (75 psi)	189568.91	291058.98	1/8	0.003175	7.9173E-06	1.36	Yes	0.006545308	23.5631079	22.41	5.145506043
689476 (100 psi)	288322.78	389812.85	1/8	0.003175	7.9173E-06	1.56	Yes	0.00876663	31.55986693	31.06666667	1.58755449

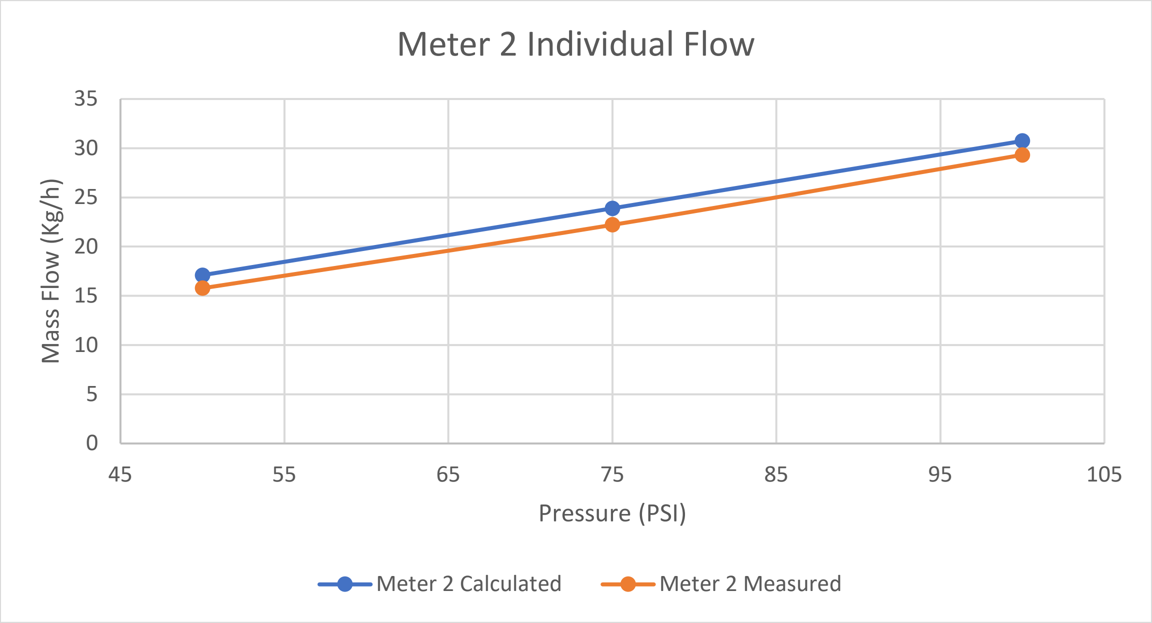
Meter 2											
Total Pressure (Pa)	Recorded Pressure Brick Port 6 Gage Values (Pa)	Recorded Pressure Brick Atmospheric Values (Pa)	Diameter exit (in)	Diameter exit (m)	Area exit (m^2)	Mach Number (M)	Choked Flow? (M > 1)	Calculated Mass Flow Rate (Kg/s)	Calculated Mass Flow Rate (Kg/h)	Recorded Flow Meter Mass Flow Rate (Kg/h)	Error (%)
344738 (50 psi)	109738.49	211228.56	1/8	0.003175	7.9173E-06	1.11	Yes	0.004750389	17.10139942	15.77333333	8.419691982
517107 (75 psi)	193646.79	295136.86	1/8	0.003175	7.9173E-06	1.37	Yes	0.006637231	23.89403266	22.21	7.582317225
689476 (100 psi)	278162.95	379653.02	1/8	0.003175	7.9173E-06	1.54	Yes	0.008537886	30.73639009	29.32666667	4.806967785

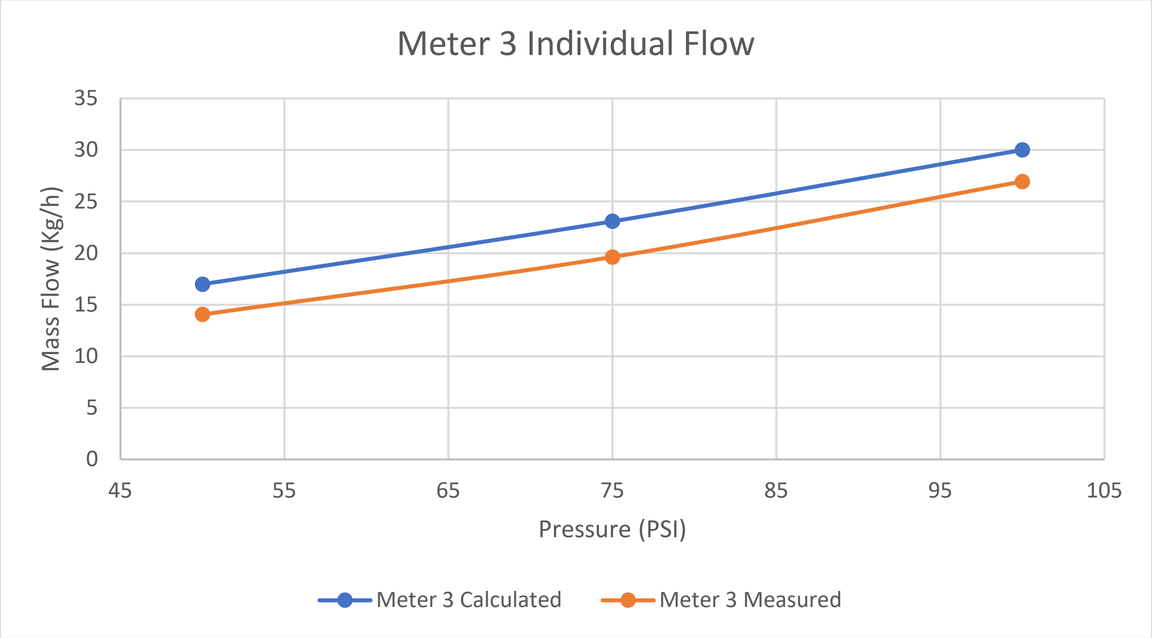
Meter 3											
Total Pressure (Pa)	Recorded Pressure Brick Port 6 Gage Values (Pa)	Recorded Pressure Brick Atmospheric Values (Pa)	Diameter exit (in)	Diameter exit (m)	Area exit (m^2)	Mach Number (M)	Choked Flow? (M > 1)	Calculated Mass Flow Rate (Kg/s)	Calculated Mass Flow Rate (Kg/h)	Recorded Flow Meter Mass Flow Rate (Kg/h)	Error (%)
344738 (50 psi)	108362.47	209852.54	1/8	0.003175	7.9173E-06	1.11	Yes	0.004719421	16.98991566	14.05333333	20.89598433
517107 (75 psi)	183529.63	285019.7	1/8	0.003175	7.9173E-06	1.34	Yes	0.006410558	23.07800777	19.62333333	17.60493174
689476 (100 psi)	269202.82	370692.89	1/8	0.003175	7.9173E-06	1.53	Yes	0.008335319	30.00714691	26.95	11.34377334

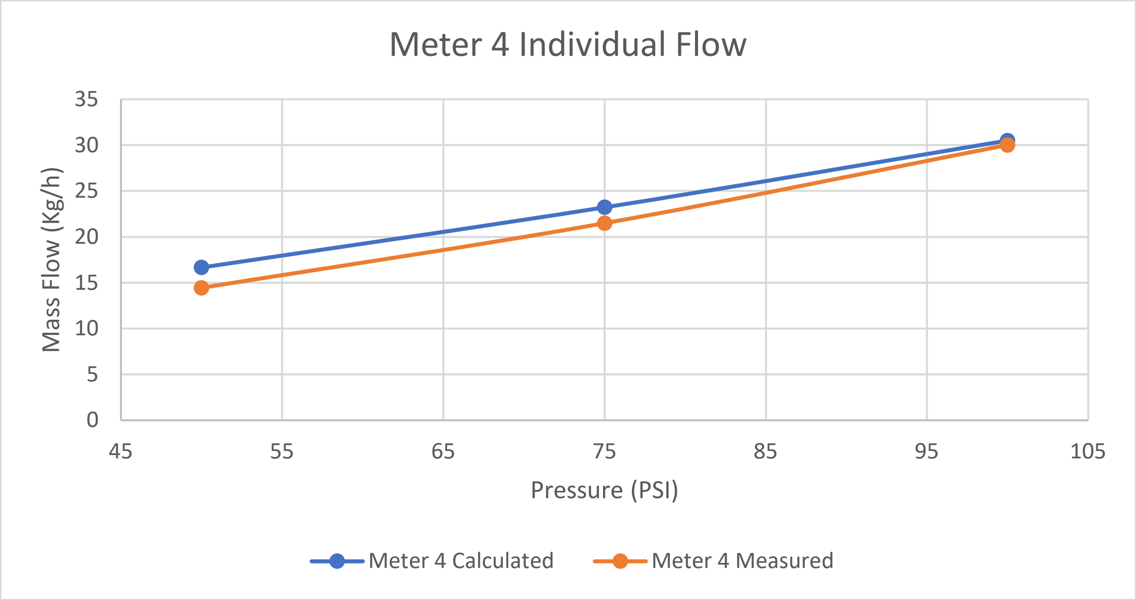
Meter 4											
Total Pressure (Pa)	Recorded Pressure Brick Port 6 Gage Values (Pa)	Recorded Pressure Brick Atmospheric Values (Pa)	Diameter exit (in)	Diameter exit (m)	Area exit (m^2)	Mach Number (M)	Choked Flow? (M > 1)	Calculated Mass Flow Rate (Kg/s)	Calculated Mass Flow Rate (Kg/h)	Recorded Flow Meter Mass Flow Rate (Kg/h)	Error (%)
344738 (50 psi)	104352.34	205842.41	1/8	0.003175	7.9173E-06	1.09	Yes	0.004627787	16.66003339	14.44333333	15.34756559
517107 (75 psi)	185395.49	286885.56	1/8	0.003175	7.9173E-06	1.35	Yes	0.006449415	23.21789251	21.49333333	8.02369343
689476 (100 psi)	275560.13	377050.2	1/8	0.003175	7.9173E-06	1.54	Yes	0.008473239	30.50365901	30.01666667	1.622406471

4. 1/8" Nozzle Calculated vs. Actual Plots






Meter 3 Individual Flow
Mass Flow (Kg/h)
35
30
25
20
15
10
5
0
45
55
65
75
85
95
105
Pressure (PSI)
Meter 3 Calculated
Meter 3 Measured


Meter 4 Individual Flow
Mass Flow (Kg/h)
35
30
25
20
15
10
5
0
45
55
65
75
85
95
105
Pressure (PSI)
Meter 4 Calculated
Meter 4 Measured

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APPENDIX E: THERMOCOUPLE AND PRESSURE BRICK PORT LOCATIONS

A. THERMOCOUPLE INSTRUMENTATION

Thermocouple Number (DAQ)	Location	Labeled At the WorkStation
1	Compressor Inlet 1	Compressor Inlet 1
2	Compressor Inlet 2	Compressor Inlet 2
3	Compressor Outlet Left	Compressor Outlet Left
4	Compressor Outlet Right	Compressor Outlet Right
5	T5	T5
6	Left Stack 1	Left Stack 1
7	Left Stack 2	Left Stack 2
8	Right Stack 1	Right Stack 1
9	Not Assigned	Not Assigned
10	Left Stack 3	Left Stack 3
11	Not Assigned	Not Assigned
12	Not Assigned	Not Assigned
13	Right Stack 3	18
14	Exhaust Inlet	19
15	Exhaust Outlet	20
16	10" Coil (IN)	31
17	8" Coil (IN)	32
18	6" Coil (IN)	33
19	4" Coil (IN)	34
20	10" Coil (OUT)	35
21	8" Coil (OUT)	36
22	6" Coil (OUT)	37
23	4" Coil (OUT)	38

B. PRESSURE BRICK INSTRUMENTATION

Port	(Pressure Brick 1) 10” H_2O	(Pressure Brick 2) 2.5 PSID	(Pressure Brick 3) 100 PSID
1	Compressor Inlet Static	Compressor Inlet Static	Compressor Inlet Static
2	Compressor Inlet Total	Compressor Inlet Total	Compressor Inlet Total
3	**Not Assigned**	**Not Assigned**	Compressor Outlet Left
4	**Not Assigned**	**Not Assigned**	Compressor Outlet Right
5	**Not Assigned**	**Not Assigned**	Gas (CO_2/N_2) Manifold Inlet
6	**Not Assigned**	**Not Assigned**	Gas (CO_2/N_2) ManifoldOutlet
7	Left Stack 1	Left Stack 1	Left Stack 1
8	Right Stack 1	Right Stack 1	Right Stack 1
9	Left Stack 0	Left Stack 0	Left Stack 0
10	Right Stack 0	Right Stack 0	Right Stack 0
11	Left Stack 2	Left Stack 2	Left Stack 2
12	Right Stack 2	Right Stack 2	Right Stack 2
13	Left Stack 3	Left Stack 3	4” Coil Inlet
14	Right Stack 3	Right Stack 3	6” Coil Inlet
15	Left Stack 4	Left Stack 4	8” Coil Inlet
16	Right Stack 4	Right Stack 4	10” Coil Inlet

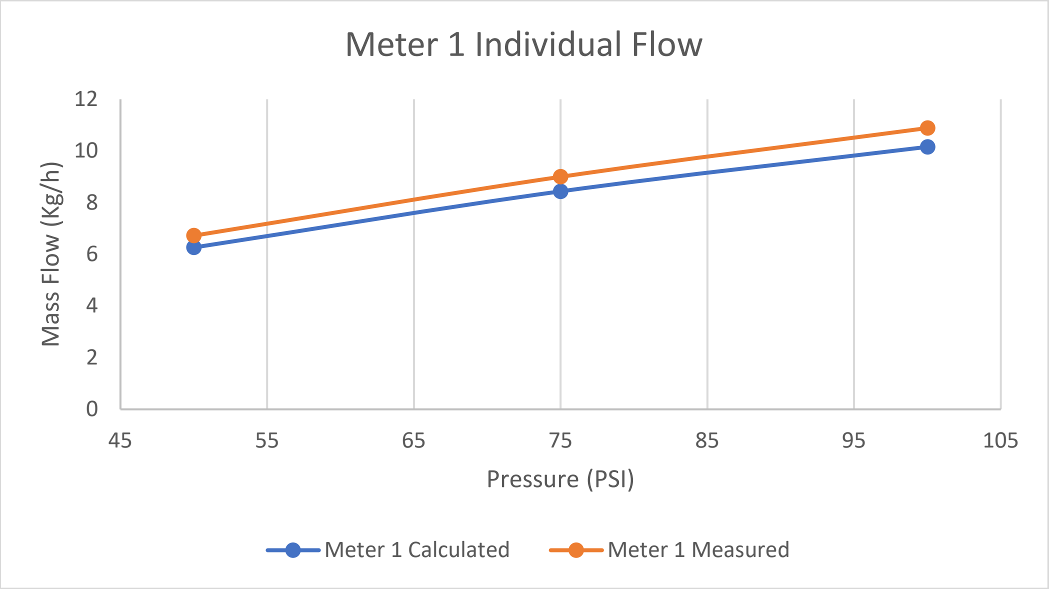
APPENDIX F: CARBON DIOXIDE HOT RUN TESTING CALCULATIONS

A. CALCULATED VS. MEASURED MASS FLOW RATES- METER 1 TESTING

1. 1/16” Nozzle Calculations

Meter 1											
Total Pressure (Pa)	Recorded Pressure Brick Port 6 Gage Values (Pa)	Recorded Pressure Brick Atmospheric Values (Pa)	Diameter exit (in)	Diameter exit (m)	Area exit (m^2)	Mach Number (M)	Choked Flow? (M > 1)	Calculated Mass Flow Rate (Kg/s)	Calculated Mass Flow Rate (Kg/h)	Recorded Flow Meter Mass Flow Rate (Kg/h)	Error (%)
344738 (50 psi)	354246.67	455872.19	1/16	0.0015875	1.97933E-06	1.66	Yes	0.001739908	6.263669956	6.721	6.804660706
517107 (75 psi)	536966.81	638592.33	1/16	0.0015875	1.97933E-06	1.88	Yes	0.002343288	8.43583771	8.998	6.248298322
689476 (100 psi)	670952.73	772578.25	1/16	0.0015875	1.97933E-06	2.00	Yes	0.002821345	10.1568425	10.885	6.691823649

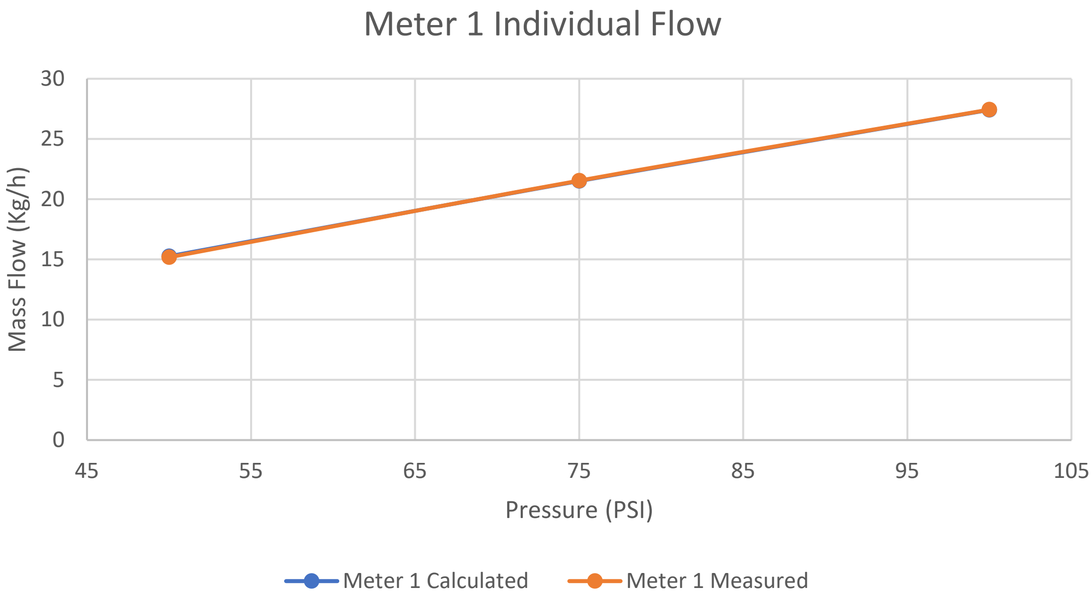
2. 1/16” Nozzle Calculated vs. Actual Plots



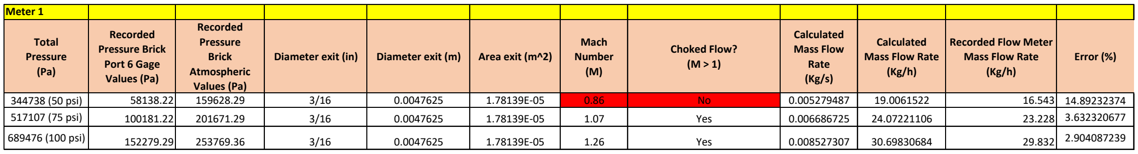
3. 1/8” Nozzle Calculations

Meter 1											
Total Pressure (Pa)	Recorded Pressure Brick Port 6 Gage Values (Pa)	Recorded Pressure Brick Atmospheric Values (Pa)	Diameter exit (in)	Diameter exit (m)	Area exit (m^2)	Mach Number (M)	Choked Flow? (M > 1)	Calculated Mass Flow Rate (Kg/s)	Calculated Mass Flow Rate (Kg/h)	Recorded Flow Meter Mass Flow Rate (Kg/h)	Error (%)
344738 (50 psi)	185884.1	287306.44	1/8	0.003175	7.9173E-06	1.35	Yes	0.004239043	15.26055502	15.179	0.53499311
517107 (75 psi)	306606.58	408028.92	1/8	0.003175	7.9173E-06	1.59	Yes	0.005974913	21.50968613	21.539	0.137052384
689476 (100 psi)	414324.45	515746.79	1/8	0.003175	7.9173E-06	1.74	Yes	0.007616241	27.41846848	27.437	0.067500014

4. 1/8” Nozzle Calculated vs. Actual Plots

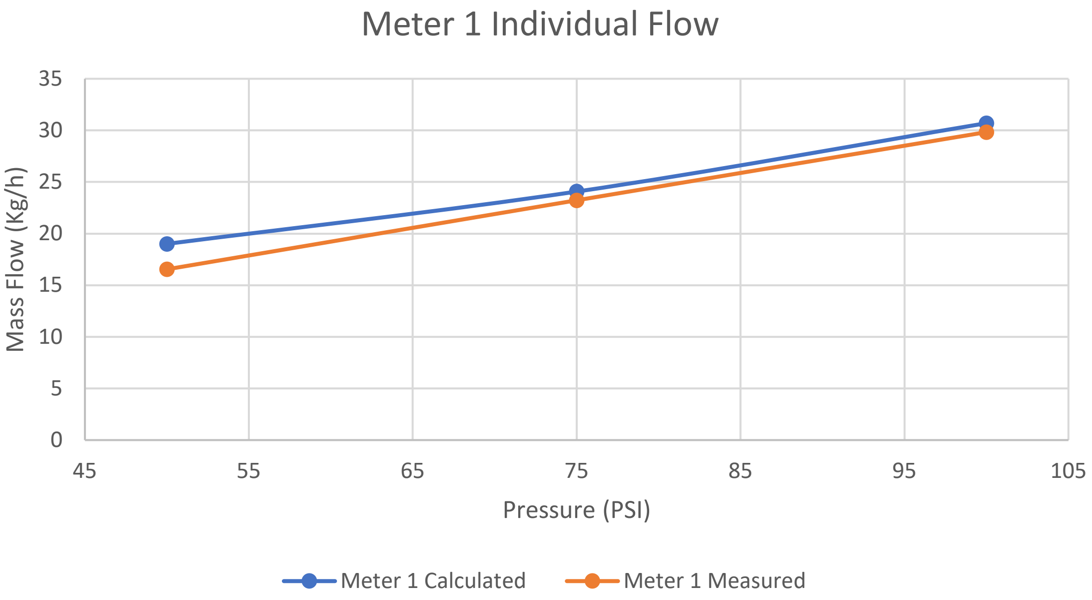


5. 3/16” Nozzle Calculations



Meter 1											
Total Pressure (Pa)	Recorded Pressure Brick Port 6 Gage Values (Pa)	Recorded Pressure Brick Atmospheric Values (Pa)	Diameter exit (in)	Diameter exit (m)	Area exit (m^2)	Mach Number (M)	Choked Flow? (M > 1)	Calculated Mass Flow Rate (Kg/s)	Calculated Mass Flow Rate (Kg/h)	Recorded Flow Meter Mass Flow Rate (Kg/h)	Error (%)
344738 (50 psi)	58138.22	159628.29	3/16	0.0047625	1.78139E-05	0.86	No	0.005279487	19.0061522	16.543	14.89232374
517107 (75 psi)	100181.22	201671.29	3/16	0.0047625	1.78139E-05	1.07	Yes	0.006686725	24.07221106	23.228	3.632320677
689476 (100 psi)	152279.29	253769.36	3/16	0.0047625	1.78139E-05	1.26	Yes	0.008527307	30.69830684	29.832	2.904087239

6. 3/16” Nozzle Calculated vs. Actual Plots



B. EFFICIENCY CALCULATION - METER 1 TESTING

1. 1/16” Nozzle Calculations

METER 1

Pressure (psi)	**Mass Flow Rate (kg/s)**	**4in Coil Tube Diameter (m) *(3/8 inch diam. tubing)***	**4in Coil Tube Length (m) *(6 foot tubing)***	**Area (m^2)**	**Calculated Velocity (m/s)**	**Dynamic Viscosity (N-s/m^2)**	**Calculated Reynolds No. (-)**	**Turbulent Condition ? (Re > 10000)**	**Pr**	**Nu Laminar Flow**	**Nu Turbulent**	**Nu Approx.**	**Thermal Conductivity (W/mK)**	**Heat Transfer Coefficient**	**Delta T_o**	**Delta T_i**	**Delta T_lm**	**q**	**Effectiveness NTU**
50	0.00187	0.00953	2.39400	0.00007	17.28618	0.00002	11442.51894	YES	0.73400	3.66000	35.87762	35.87762	0.02920	109.98702	485.55490	174.70930	304.10395	573.39127	0.65694
75	0.00250	0.00953	2.39400	0.00007	23.33356	0.00002	15056.85916	YES	0.72700	3.66000	44.51733	44.51733	0.02990	139.74469	486.56290	124.70520	265.79556	880.91623	0.75482
100	0.00302	0.00953	2.39400	0.00007	28.28951	0.00002	18044.03379	YES	0.72700	3.66000	51.45274	51.45274	0.03030	163.67643	485.57970	117.66580	259.55216	1082.00308	0.76813
Overall Heat Transfer Coef	***Patm (Pa)***	***Dexh***	***A_exh***	***m_dot_exh***	***Pho_inf***	***U_inf***	***Di***	***Do***	***Re_Exh***	***Nu***	***hexh***	***Rconv Gas***	***Rcond Steel***	***Rconv Exhaust***	***Rtot***	***UA***	***13. Heat Transfer***	***qmax***	**Effectiveness q/qmax**
50	101625.52	0.35600	0.09954	0.70850	0.44654	15.94006	0.00762	0.00953	1832.37027	20.19297	1214.75843	0.15865	0.00100	0.01149	0.17113	5.84340	1777.00215	872.81821	0.65694
75	101625.52	0.35600	0.09954	0.70850	0.44520	15.98809	0.00762	0.00953	1832.37027	20.19297	1214.75843	0.12486	0.00100	0.01149	0.13735	7.28064	1935.16230	1167.05309	0.75482
100	101625.52	0.35600	0.09954	0.70850	0.44520	15.98809	0.00762	0.00953	1832.37027	20.19297	1214.75843	0.10661	0.00100	0.01149	0.11909	8.39675	2179.39346	1408.61306	0.76813

2. 1/8” Nozzle Calculations

METER 1																				
Pressure (psi)	**Mass Flow Rate (kg/s)**	**4in Coil Tube Diameter (m) *(3/8 inch diam. tubing)***	**4in Coil Tube Length (m) *(6 foot tubing)***	**Area (m^2)**	**Calculated Velocity (m/s)**	**Dynamic Viscosity (N-s/m^2)**	**Calculated Reynolds No. (-)**	**Turbulent Condition? (Re > 10000)**	**Pr**	**Nu Laminar Flow**	**Nu Turbulent**	**Nu Approx.**	**Thermal Conductivity (W/mK)**	**Heat Transfer Coefficient**	**Delta T_o**	**Delta T_i**	**Delta T_lm**	**q**	**Effectiveness NTU**
50	0.00422	0.009525	2.394	7.12557E-05	39.0407	2.181E-05	25842.83	YES	0.734	3.66	68.8459339	68.8459	0.0292	211.05525	487.2114	133.0213	272.834	1458.3	0.73905773
75	0.00598	0.009525	2.394	7.12557E-05	55.855	2.219E-05	36042.51	YES	0.727	3.66	89.49393811	89.4939	0.0299	280.9311	488.1665	125.5152	267.0029	2120.06	0.75461699
100	0.00762	0.009525	2.394	7.12557E-05	71.3055	0.0000224	45481.11	YES	0.727	3.66	107.796943	107.797	0.0303	342.91311	488.9749	137.869	277.3333	2625.33	0.73130566
Overall Heat Transfer Coef	***Patm (Pa***	***Dexh***	***A_exh***	***m_dot_exh***	***Pho_inf***	***U_inf***	***Di***	***Do***	***Re_Exh***	***Nu***	***hexh***	***Rconv Gas***	***Rcond Steel***	***Rconv Exhaust***	***Rtot***	***UA***	***13. Heat Transfer***	***qmax***	**Effectiveness q/qmax**
50	101422	0.356	0.0995	0.7085	0.44375	16.040448	0.00762	0.009525	1832	20.19297	1214.75843	0.08268	0.00099562	0.0114914	0.095162	10.50839	2867.045	1973.19	0.73905773
75	101422	0.356	0.0995	0.7085	0.44242	16.08834	0.00762	0.009525	1832	20.19297	1214.75843	0.06211	0.00099562	0.0114914	0.074598	13.40512	3579.207	2809.45	0.75461699
100	101422	0.356	0.0995	0.7085	0.44242	16.08834	0.00762	0.009525	1832	20.19297	1214.75843	0.05088	0.00099562	0.0114914	0.063372	15.77993	4376.299	3589.92	0.73130566

3. 3/16” Nozzle Calculations

METER 1																			
Pressure (psi)	**Mass Flow Rate (kg/s)**	**4in Coil Tube Diameter (m) *(3/8 inch diam. tubing)***	**4in Coil Tube Length (m) *(6 foot tubing)***	**Area (m^2)**	**Calculated Velocity (m/s)**	**Dynamic Viscosity (N-s/m^2)**	**Calculated Reynolds No. (-)**	**Turbulent Condition? (Re > 10000)**	**Pr**	**Nu Laminar Flow**	**Nu Turbulent**	**Nu Approx.**	**Thermal Conductivity (W/mK)**	**Heat Transfer Coefficient**	**Delta T_o**	**Delta T_i**	**Delta T_lm**	**q**	**Effectiveness NTU**
50	0.0046	0.009525	2.394	7.12557E-05	42.54687	2.181E-05	28163.73	YES	0.734	3.66	73.749382	73.749	0.0292	226.08734	482.5195	124.4676	264.2496	1609.32	0.75400328
75	0.00645	0.009525	2.394	7.12557E-05	60.23553	2.219E-05	38869.24	YES	0.727	3.66	95.066274	95.066	0.0299	298.42326	484.3518	130.1704	269.5512	2242.33	0.74412886
100	0.00829	0.009525	2.394	7.12557E-05	77.52972	0.0000224	49451.15	YES	0.727	3.66	115.26109	115.26	0.0303	366.65733	486.267	149.1017	285.2186	2751.43	0.70809721
Overall Heat Transfer Coef	***Patm (Pa***	***Dexh***	***A_exh***	***m_dot_exh***	***Pho_inf***	***U_inf***	***Di***	***Do***	***Re_Exh***	***Nu***	***hexh***	***Rconv Gas***	***Rcond Steel***	***Rconv Exhaust***	***Rtot***	***UA***	***13. Heat Transfer***	***qmax***	**Effectiveness q/qmax**
50	100779	0.356	0.0995	0.7085	0.443121	16.063035	0.00762	0.009525	1832	20.193	1214.7584	0.0772	0.00099562	0.0114914	0.089665	11.1526	2947.071	2134.37	0.75400328
75	100779	0.356	0.0995	0.7085	0.442093	16.100383	0.00762	0.009525	1832	20.193	1214.7584	0.0585	0.00099562	0.0114914	0.070958	14.09291	3798.76	3013.37	0.74412886
100	100779	0.356	0.0995	0.7085	0.442093	16.100383	0.00762	0.009525	1832	20.193	1214.7584	0.0476	0.00099562	0.0114914	0.060076	16.64547	4747.598	3885.67	0.70809721

C. EFFICIENCY CALCULATION – ALL METERS ONLINE

1. 1/16” Nozzle Calculations

2. Run 1

METER 4																			
Pressure (psi)	**Mass Flow Rate (kg/s)**	**10in Coil Tube Diameter (m) *(3/8 inch diam. tubing)***	**10in Coil Tube Length (m) *(6 foot tubing)***	**Area (m^2)**	**Calculated Velocity (m/s)**	**Dynamic Viscosity (N-s/m^2)**	**Calculated Reynolds No. (-)**	**Turbulent Condition? (Re > 10000)**	**Pr**	**Nu Laminar Flow**	**Nu Turbulent**	**Nu Approx.**	**Thermal Conductivity (W/mK)**	**Heat Transfer Coefficient**	**Delta T_o**	**Delta T_i**	**Delta T_lm**	**q**	**Effectiveness NTU**
50	0.00037	0.009525	5.985	7.12557E-05	3.38872	2.181E-05	2243.15	NO	0.734	3.66	32.2112	3.66	0.0292	11.2201575	480.4426	399.3286	438.6363	35.9545	0.211347656
75	0.00049	0.009525	5.985	7.12557E-05	4.598259	2.219E-05	2967.2	NO	0.727	3.66	32.0879	3.66	0.0299	11.4891339	479.3417	391.9634	434.1882	51.1951	0.22411801
100	0.00062	0.009525	5.985	7.12557E-05	5.831863	0.0000224	3719.765	NO	0.727	3.66	32.0879	3.66	0.0303	11.6428346	478.6659	392.3287	434.0672	64.9981	0.224521934
Overall Heat Transfer Coef	***Patm (Pa***	***Dexh***	***A_exh***	***m_dot_exh***	***Pho_inf***	***U_inf***	***Di***	***Do***	***Re_Exh***	***Nu***	***hexh***	***Rconv Gas***	***Rcond Steel***	***Rconv Exhaust***	***Rtot***	***UA***	***13. Heat Transfer***	***qmax***	***Effectiveness q/qmax***
50	101626	0.356	0.0995	0.7085	0.445913	15.962449	0.00762	0.009525	1832	20.19297	1214.76	0.6221	0.00039825	0.00459654	0.627054	1.594758	699.5186	170.12	0.211347656
75	101626	0.356	0.0995	0.7085	0.446193	15.952433	0.00762	0.009525	1832	20.19297	1214.76	0.6075	0.00039825	0.00459654	0.612491	1.632677	708.8888	228.429	0.22411801
100	101626	0.356	0.0995	0.7085	0.446193	15.952433	0.00762	0.009525	1832	20.19297	1214.76	0.5995	0.00039825	0.00459654	0.604471	1.654338	718.0938	289.495	0.224521934

METER 3																			
Pressure (psi)	**Mass Flow Rate (kg/s)**	**8in Coil Tube Diameter (m) *(3/8 inch diam. tubing)***	**8in Coil Tube Length (m) *(6 foot tubing)***	**Area (m^2)**	**Calculated Velocity (m/s)**	**Dynamic Viscosity (N-s/m^2)**	**Calculated Reynolds No. (-)**	**Turbulent Condition? (Re > 10000)**	**Pr**	**Nu Laminar Flow**	**Nu Turbulent**	**Nu Approx.**	**Thermal Conductivity (W/mK)**	**Heat Transfer Coefficient**	**Delta T_o**	**Delta T_i**	**Delta T_lm**	**q**	**Effectiveness NTU**
50	0.0004	0.009525	4.788	7.12557E-05	3.627848	2.181E-05	2470.519	NO	0.734	3.66	32.2112	3.66	0.0292	11.2201575	479.9736	421.4903	450.0988	31.2248	0.166807753
75	0.00054	0.009525	4.788	7.12557E-05	4.946578	2.219E-05	3280.295	NO	0.727	3.66	32.0879	3.66	0.0299	11.4891339	478.8633	413.5944	445.4322	45.545	0.180523945
100	0.0007	0.009525	4.788	7.12557E-05	6.448565	0.0000224	4206.076	NO	0.727	3.66	32.0879	3.66	0.0303	11.6428346	478.2696	411.4404	444.0171	60.8735	0.186108147
Overall Heat Transfer Coef	***Patm (Pa***	***Dexh***	***A_exh***	***m_dot_exh***	***Pho_inf***	***U_inf***	***Di***	***Do***	***Re_Exh***	***Nu***	***hexh***	***Rconv Gas***	***Rcond Steel***	***Rconv Exhaust***	***Rtot***	***UA***	***13. Heat Transfer***	***qmax***	***Effectiveness q/qmax***
50	101626	0.356	0.0995	0.7085	0.445913	15.962449	0.00762	0.009525	1832	20.19297	1214.76	0.7776	0.00049781	0.00574568	0.783818	1.275806	574.2389	187.19	0.166807753
75	101626	0.356	0.0995	0.7085	0.446193	15.952433	0.00762	0.009525	1832	20.19297	1214.76	0.7594	0.00049781	0.00574568	0.765614	1.306141	581.7973	252.294	0.180523945
100	101626	0.356	0.0995	0.7085	0.446193	15.952433	0.00762	0.009525	1832	20.19297	1214.76	0.7493	0.00049781	0.00574568	0.755589	1.32347	587.6435	327.087	0.186108147

METER 2																			
Pressure (psi)	**Mass Flow Rate (kg/s)**	**6in Coil Tube Diameter (m) *(3/8 inch diam. tubing)***	**6in Coil Tube Length (m) *(6 foot tubing)***	**Area (m^2)**	**Calculated Velocity (m/s)**	**Dynamic Viscosity (N-s/m^2)**	**Calculated Reynolds No. (-)**	**Turbulent Condition? (Re > 10000)**	**Pr**	**Nu Laminar Flow**	**Nu Turbulent**	**Nu Approx.**	**Thermal Conductivity (W/mK)**	**Heat Transfer Coefficient**	**Delta T_o**	**Delta T_i**	**Delta T_lm**	**q**	**Effectiveness NTU**
50	0.00043	0.009525	3.591	7.12557E-05	5.089833	2.181E-05	2652.988	NO	0.734	3.66	32.2112	3.66	0.0292	11.2201575	479.6891	210.8068	327.0294	117.136	0.583047547
75	0.00064	0.009525	3.591	7.12557E-05	7.816811	2.219E-05	3865.358	NO	0.727	3.66	32.0879	3.66	0.0299	11.4891339	478.496	179.2811	304.7948	191.472	0.644522351
100	0.0008	0.009525	3.591	7.12557E-05	9.889015	0.0000224	4749.171	NO	0.727	3.66	32.0879	3.66	0.0303	11.6428346	477.8441	156.8012	288.1102	254.455	0.689562019
Overall Heat Transfer Coef	***Patm (Pa***	***Dexh***	***A_exh***	***m_dot_exh***	***Pho_inf***	***U_inf***	***Di***	***Do***	***Re_Exh***	***Nu***	***hexh***	***Rconv Gas***	***Rcond Steel***	***Rconv Exhaust***	***Rtot***	***UA***	***13. Heat Transfer***	***qmax***	***Effectiveness q/qmax***
50	101626	0.356	0.0995	0.7085	0.445913	15.962449	0.00762	0.009525	1832	20.19297	1214.76	1.0368	0.00066375	0.0076609	1.045091	0.956855	312.9196	200.903	0.583047547
75	101626	0.356	0.0995	0.7085	0.446193	15.952433	0.00762	0.009525	1832	20.19297	1214.76	1.0125	0.00066375	0.0076609	1.020819	0.979606	298.5788	297.075	0.644522351
100	101626	0.356	0.0995	0.7085	0.446193	15.952433	0.00762	0.009525	1832	20.19297	1214.76	0.9991	0.00066375	0.0076609	1.007452	0.992603	285.979	369.01	0.689562019

METER 1																			
Pressure (psi)	**Mass Flow Rate (kg/s)**	**4in Coil Tube Diameter (m) *(3/8 inch diam. tubing)***	**4in Coil Tube Length (m) *(6 foot tubing)***	**Area (m^2)**	**Calculated Velocity (m/s)**	**Dynamic Viscosity (N-s/m^2)**	**Calculated Reynolds No. (-)**	**Turbulent Condition? (Re > 10000)**	**Pr**	**Nu Laminar Flow**	**Nu Turbulent**	**Nu Approx.**	**Thermal Conductivity (W/mK)**	**Heat Transfer Coefficient**	**Delta T_o**	**Delta T_i**	**Delta T_lm**	**q**	**Effectiveness NTU**
50	0.00051	0.009525	2.394	7.12557E-05	5.9945	2.181E-05	3133.693	NO	0.734	3.66	32.2112	3.66	0.0292	11.2201575	481.0074	202.2524	321.7519	142.81	0.600698183
75	0.0007	0.009525	2.394	7.12557E-05	8.380241	2.219E-05	4220.95	NO	0.727	3.66	32.0879	3.66	0.0299	11.4891339	480.1689	192.4523	314.6887	201.844	0.61984806
100	0.00089	0.009525	2.394	7.12557E-05	10.77256	0.0000224	5320.075	NO	0.727	3.66	32.0879	3.66	0.0303	11.6428346	480.5264	183.9264	308.8469	265.015	0.637761249
Overall Heat Transfer Coef	***Patm (Pa***	***Dexh***	***A_exh***	***m_dot_exh***	***Pho_inf***	***U_inf***	***Di***	***Do***	***Re_Exh***	***Nu***	***hexh***	***Rconv Gas***	***Rcond Steel***	***Rconv Exhaust***	***Rtot***	***UA***	***13. Heat Transfer***	***qmax***	***Effectiveness q/qmax***
50	101626	0.356	0.0995	0.7085	0.445443	15.979289	0.00762	0.009525	1832	20.19297	1214.76	1.5551	0.00099562	0.01149135	1.567636	0.637903	205.2466	237.74	0.600698183
75	101626	0.356	0.0995	0.7085	0.445302	15.984369	0.00762	0.009525	1832	20.19297	1214.76	1.5187	0.00099562	0.01149135	1.531228	0.653071	205.5139	325.635	0.61984806
100	101626	0.356	0.0995	0.7085	0.445302	15.984369	0.00762	0.009525	1832	20.19297	1214.76	1.4987	0.00099562	0.01149135	1.511179	0.661735	204.3748	415.54	0.637761249

3. Run 2

METER 4																			
Pressure (psi)	**Mass Flow Rate (kg/s)**	**10in Coil Tube Diameter (m) *(3/8 inch diam. tubing)***	**10in Coil Tube Length (m) *(6 foot tubing)***	**Area (m^2)**	**Calculated Velocity (m/s)**	**Dynamic Viscosity (N-s/m^2)**	**Calculated Reynolds No. (-)**	**Turbulent Condition? (Re > 10000)**	**Pr**	**Nu Laminar Flow**	**Nu Turbulent**	**Nu Approx.**	**Thermal Conductivity (W/mK)**	**Heat Transfer Coefficient**	**Delta T_o**	**Delta T_i**	**Delta T_lm**	**q**	**Effectiveness NTU**
50	0.00037	0.009525	5.985	7.12557E-05	3.4014261	2.181E-05	2251.56	NO	0.734	3.66	32.2112	3.66	0.0292	11.2201575	479.1926	401.2985	439.0946	35.0035	0.205495906
75	0.00049	0.009525	5.985	7.12557E-05	4.5833523	2.219E-05	2957.581	NO	0.727	3.66	32.0879	3.66	0.0299	11.4891339	477.326	396.4797	435.6533	48.0851	0.212034098
100	0.00063	0.009525	5.985	7.12557E-05	5.9098912	0.0000224	3769.534	NO	0.727	3.66	32.0879	3.66	0.0303	11.6428346	477.5789	396.4474	435.7551	62.8491	0.214693616
Overall Heat Transfer Coef	***Patm (Pa***	***Dexh***	***A_exh***	***m_dot_exh***	***Pho_inf***	***U_inf***	***Di***	***Do***	***Re_Exh***	***Nu***	***hexh***	***Rconv Gas***	***Rcond Steel***	***Rconv Exhaust***	***Rtot***	***UA***	***13. Heat Transfer***	***qmax***	**Effectiveness q/qmax**
50	101151	0.356	0.0995	0.7085	0.4438331	16.037264	0.00762	0.009525	1832	20.19297	1214.76	0.62206	0.000398248	0.00459654	0.627054	1.594758	700.2496	170.337	0.205495906
75	101151	0.356	0.0995	0.7085	0.4441118	16.027201	0.00762	0.009525	1832	20.19297	1214.76	0.607496	0.000398248	0.00459654	0.612491	1.632677	711.2809	226.78	0.212034098
100	101151	0.356	0.0995	0.7085	0.4441118	16.027201	0.00762	0.009525	1832	20.19297	1214.76	0.599477	0.000398248	0.00459654	0.604471	1.654338	720.8861	292.738	0.214693616

METER 3																			
Pressure (psi)	**Mass Flow Rate (kg/s)**	**8in Coil Tube Diameter (m) *(3/8 inch diam. tubing)***	**8in Coil Tube Length (m) *(6 foot tubing)***	**Area (m^2)**	**Calculated Velocity (m/s)**	**Dynamic Viscosity (N-s/m^2)**	**Calculated Reynolds No. (-)**	**Turbulent Condition? (Re > 10000)**	**Pr**	**Nu Laminar Flow**	**Nu Turbulent**	**Nu Approx.**	**Thermal Conductivity (W/mK)**	**Heat Transfer Coefficient**	**Delta T_o**	**Delta T_i**	**Delta T_lm**	**q**	**Effectiveness NTU**
50	0.00041	0.009525	4.788	7.12557E-05	3.6616895	2.181E-05	2493.564	NO	0.734	3.66	32.2112	3.66	0.0292	11.2201575	478.8196	421.5014	449.5516	31.0809	0.16488077
75	0.00055	0.009525	4.788	7.12557E-05	5.0222741	2.219E-05	3330.493	NO	0.727	3.66	32.0879	3.66	0.0299	11.4891339	477.326	415.6746	445.79	44.406	0.173886049
100	0.00071	0.009525	4.788	7.12557E-05	6.5049995	0.0000224	4242.885	NO	0.727	3.66	32.0879	3.66	0.0303	11.6428346	477.2175	412.6252	444.1388	59.9462	0.182062128
Overall Heat Transfer Coef	***Patm (Pa***	***Dexh***	***A_exh***	***m_dot_exh***	***Pho_inf***	***U_inf***	***Di***	***Do***	***Re_Exh***	***Nu***	***hexh***	***Rconv Gas***	***Rcond Steel***	***Rconv Exhaust***	***Rtot***	***UA***	***13. Heat Transfer***	***qmax***	**Effectiveness q/qmax**
50	101151	0.356	0.0995	0.7085	0.4438331	16.037264	0.00762	0.009525	1832	20.19297	1214.76	0.777575	0.000497811	0.00574568	0.783818	1.275806	573.5408	188.506	0.16488077
75	101151	0.356	0.0995	0.7085	0.4441118	16.027201	0.00762	0.009525	1832	20.19297	1214.76	0.759371	0.000497811	0.00574568	0.765614	1.306141	582.2647	255.374	0.173886049
100	101151	0.356	0.0995	0.7085	0.4441118	16.027201	0.00762	0.009525	1832	20.19297	1214.76	0.749346	0.000497811	0.00574568	0.755589	1.32347	587.8045	329.263	0.182062128

METER 2																			
Pressure (psi)	**Mass Flow Rate (kg/s)**	**6in Coil Tube Diameter (m) *(3/8 inch diam. tubing)***	**6in Coil Tube Length (m) *(6 foot tubing)***	**Area (m^2)**	**Calculated Velocity (m/s)**	**Dynamic Viscosity (N-s/m^2)**	**Calculated Reynolds No. (-)**	**Turbulent Condition? (Re > 10000)**	**Pr**	**Nu Laminar Flow**	**Nu Turbulent**	**Nu Approx.**	**Thermal Conductivity (W/mK)**	**Heat Transfer Coefficient**	**Delta T_o**	**Delta T_i**	**Delta T_lm**	**q**	**Effectiveness NTU**
50	0.00044	0.009525	3.591	7.12557E-05	5.1706493	2.181E-05	2695.112	NO	0.734	3.66	32.2112	3.66	0.0292	11.2201575	478.5369	210.9727	326.6943	118.464	0.581766322
75	0.00064	0.009525	3.591	7.12557E-05	7.8122909	2.219E-05	3863.123	NO	0.727	3.66	32.0879	3.66	0.0299	11.4891339	476.9469	179.3316	304.2577	190.419	0.64332668
100	0.0008	0.009525	3.591	7.12557E-05	9.9035747	0.0000224	4756.163	NO	0.727	3.66	32.0879	3.66	0.0303	11.6428346	476.8047	162.6729	292.1163	249.773	0.677273001
Overall Heat Transfer Coef	***Patm (Pa***	***Dexh***	***A_exh***	***m_dot_exh***	***Pho_inf***	***U_inf***	***Di***	***Do***	***Re_Exh***	***Nu***	***hexh***	***Rconv Gas***	***Rcond Steel***	***Rconv Exhaust***	***Rtot***	***UA***	***13. Heat Transfer***	***qmax***	**Effectiveness q/qmax**
50	101151	0.356	0.0995	0.7085	0.4438331	16.037264	0.00762	0.009525	1832	20.19297	1214.76	1.036766	0.000663747	0.0076609	1.045091	0.956855	312.599	203.628	0.581766322
75	101151	0.356	0.0995	0.7085	0.4441118	16.027201	0.00762	0.009525	1832	20.19297	1214.76	1.012494	0.000663747	0.0076609	1.020819	0.979606	298.0526	295.992	0.64332668
100	101151	0.356	0.0995	0.7085	0.4441118	16.027201	0.00762	0.009525	1832	20.19297	1214.76	0.999128	0.000663747	0.0076609	1.007452	0.992603	289.9554	368.793	0.677273001

METER 1																			
Pressure (psi)	**Mass Flow Rate (kg/s)**	**4in Coil Tube Diameter (m) *(3/8 inch diam. tubing)***	**4in Coil Tube Length (m) *(6 foot tubing)***	**Area (m^2)**	**Calculated Velocity (m/s)**	**Dynamic Viscosity (N-s/m^2)**	**Calculated Reynolds No. (-)**	**Turbulent Condition? (Re > 10000)**	**Pr**	**Nu Laminar Flow**	**Nu Turbulent**	**Nu Approx.**	**Thermal Conductivity (W/mK)**	**Heat Transfer Coefficient**	**Delta T_o**	**Delta T_i**	**Delta T_lm**	**q**	**Effectiveness NTU**
50	0.00051	0.009525	2.394	7.12557E-05	5.9924073	2.181E-05	3132.599	NO	0.734	3.66	32.2112	3.66	0.0292	11.2201575	478.6395	213.5272	328.4412	136.543	0.576788283
75	0.0007	0.009525	2.394	7.12557E-05	8.3783921	2.219E-05	4220.019	NO	0.727	3.66	32.0879	3.66	0.0299	11.4891339	476.9726	196.3127	316.1474	197.108	0.609572861
100	0.00089	0.009525	2.394	7.12557E-05	10.742878	0.0000224	5305.416	NO	0.727	3.66	32.0879	3.66	0.0303	11.6428346	476.7932	188.934	310.9688	257.176	0.625165015
Overall Heat Transfer Coef	***Patm (Pa***	***Dexh***	***A_exh***	***m_dot_exh***	***Pho_inf***	***U_inf***	***Di***	***Do***	***Re_Exh***	***Nu***	***hexh***	***Rconv Gas***	***Rcond Steel***	***Rconv Exhaust***	***Rtot***	***UA***	***13. Heat Transfer***	***qmax***	**Effectiveness q/qmax**
50	101151	0.356	0.0995	0.7085	0.4438331	16.037264	0.00762	0.009525	1832	20.19297	1214.76	1.555149	0.000995621	0.01149135	1.567636	0.637903	209.5137	236.73	0.576788283
75	101151	0.356	0.0995	0.7085	0.4441118	16.027201	0.00762	0.009525	1832	20.19297	1214.76	1.518741	0.000995621	0.01149135	1.531228	0.653071	206.4666	323.354	0.609572861
100	101151	0.356	0.0995	0.7085	0.4441118	16.027201	0.00762	0.009525	1832	20.19297	1214.76	1.498692	0.000995621	0.01149135	1.511179	0.661735	205.779	411.372	0.625165015

4. 1/8” Nozzle Calculations

METER 4

Pressure (psi)	**Mass Flow Rate (kg/s)**	**10in Coil Tube Diameter (m) *(3/8 inch diam. tubing)***	**10in Coil Tube Length (m) *(6 foot tubing)***	**Area (m^2)**	**Calculated Velocity (m/s)**	**Dynamic Viscosity (N-s/m^2)**	**Calculated Reynolds No. (-)**	**Turbulent Condition? (Re > 10000)**	**Pr**	**Nu Laminar Flow**	**Nu Turbulent**	**Nu Approx.**	**Thermal Conductivity (W/mK)**	**Heat Transfer Coefficient**	**Delta T_o**	**Delta T_i**	**Delta T_lm**	**q**	**Effectiveness NTU**
50	0.00088	0.009525	5.985	7.12557E-05	8.1195637	2.181E-05	5374.713	NO	0.734	3.66	32.2112	3.66	0.0292	11.220157	477.8317	411.7293	443.9606	79.8963	0.194230459
75	0.0012	0.009525	5.985	7.12557E-05	11.216419	2.219E-05	7237.816	NO	0.727	3.66	32.0879	3.66	0.0299	11.489134	478.2429	401.4809	438.7433	121.646	0.21550674
100	0.00154	0.009525	5.985	7.12557E-05	14.362481	0.0000224	9160.891	NO	0.727	3.66	32.0879	3.66	0.0303	11.642835	479.0462	405.9617	441.4962	154.017	0.212111302
Overall Heat Transfer Coef	***Patm (Pa***	***Dexh***	***A_exh***	***m_dot_exh***	***Pho_inf***	***U_inf***	***Di***	***Do***	***Re_Exh***	***Nu***	***hexh***	***Rconv Gas***	***Rcond Steel***	***Rconv Exhaust***	***Rtot***	***UA***	***13. Heat Transfer***	***qmax***	**Effectiveness q/qmax**
50	101151	0.356	0.0995	0.7085	0.4466987	15.934385	0.00762	0.00953	1832	20.193	1214.76	0.6221	0.00039825	0.0045965	0.627054	1.594758	708.0097	411.348	0.194230459
75	101151	0.356	0.0995	0.7085	0.4456023	15.97359	0.00762	0.00953	1832	20.193	1214.76	0.6075	0.00039825	0.0045965	0.612491	1.632677	716.3259	564.466	0.21550674
100	101151	0.356	0.0995	0.7085	0.4456023	15.97359	0.00762	0.00953	1832	20.193	1214.76	0.5995	0.00039825	0.0045965	0.604471	1.654338	730.3839	726.112	0.212111302

METER 3

Pressure (psi)	**Mass Flow Rate (kg/s)**	**8in Coil Tube Diameter (m) *(3/8 inch diam. tubing)***	**8in Coil Tube Length (m) *(6 foot tubing)***	**Area (m^2)**	**Calculated Velocity (m/s)**	**Dynamic Viscosity (N-s/m^2)**	**Calculated Reynolds No. (-)**	**Turbulent Condition? (Re > 10000)**	**Pr**	**Nu Laminar Flow**	**Nu Turbulent**	**Nu Approx.**	**Thermal Conductivity (W/mK)**	**Heat Transfer Coefficient**	**Delta T_o**	**Delta T_i**	**Delta T_lm**	**q**	**Effectiveness NTU**
50	0.00089	0.009525	4.788	7.12557E-05	7.9796986	2.181E-05	5434.073	NO	0.734	3.66	32.2112	3.66	0.0292	11.220157	477.484	430.7534	453.7177	65.0117	0.156425568
75	0.00122	0.009525	4.788	7.12557E-05	11.07217	2.219E-05	7342.447	NO	0.727	3.66	32.0879	3.66	0.0299	11.489134	477.8032	417.3638	446.9026	105.141	0.183770287
100	0.0016	0.009525	4.788	7.12557E-05	14.62178	0.0000224	9537.054	NO	0.727	3.66	32.0879	3.66	0.0303	11.642835	478.6328	414.8091	445.96	146.754	0.194293869
Overall Heat Transfer Coef	***Patm (Pa***	***Dexh***	***A_exh***	***m_dot_exh***	***Pho_inf***	***U_inf***	***Di***	***Do***	***Re_Exh***	***Nu***	***hexh***	***Rconv Gas***	***Rcond Steel***	***Rconv Exhaust***	***Rtot***	***UA***	***13. Heat Transfer***	***qmax***	**Effectiveness q/qmax**
50	101151	0.356	0.0995	0.7085	0.4466987	15.934385	0.00762	0.00953	1832	20.193	1214.76	0.7776	0.00049781	0.0057457	0.783818	1.275806	578.8559	415.608	0.156425568
75	101151	0.356	0.0995	0.7085	0.4456023	15.97359	0.00762	0.00953	1832	20.193	1214.76	0.7594	0.00049781	0.0057457	0.765614	1.306141	583.7178	572.134	0.183770287
100	101151	0.356	0.0995	0.7085	0.4456023	15.97359	0.00762	0.00953	1832	20.193	1214.76	0.7493	0.00049781	0.0057457	0.755589	1.32347	590.2149	755.321	0.194293869

METER 2

Pressure (psi)	**Mass Flow Rate (kg/s)**	**6in Coil Tube Diameter (m) *(3/8 inch diam. tubing)***	**6in Coil Tube Length (m) *(6 foot tubing)***	**Area (m^2)**	**Calculated Velocity (m/s)**	**Dynamic Viscosity (N-s/m^2)**	**Calculated Reynolds No. (-)**	**Turbulent Condition? (Re > 10000)**	**Pr**	**Nu Laminar Flow**	**Nu Turbulent**	**Nu Approx.**	**Thermal Conductivity (W/mK)**	**Heat Transfer Coefficient**	**Delta T_o**	**Delta T_i**	**Delta T_lm**	**q**	**Effectiveness NTU**
50	0.00108	0.009525	3.591	7.12557E-05	12.718658	2.181E-05	6629.382	NO	0.734	3.66	32.2112	3.66	0.0292	11.220157	477.3192	189.136	311.3074	319.062	0.629482197
75	0.00151	0.009525	3.591	7.12557E-05	18.407804	2.219E-05	9102.531	NO	0.727	3.66	32.0879	3.66	0.0299	11.489134	477.5628	145.3872	279.3046	507.278	0.715535534
100	0.00192	0.009525	3.591	7.12557E-05	23.827215	0.0000224	11442.95	YES	0.727	3.66	35.7414	3.66	0.0303	11.642835	478.279	124.9249	263.2097	685.738	0.757184752
Overall Heat Transfer Coef	***Patm (Pa***	***Dexh***	***A_exh***	***m_dot_exh***	***Pho_inf***	***U_inf***	***Di***	***Do***	***Re_Exh***	***Nu***	***hexh***	***Rconv Gas***	***Rcond Steel***	***Rconv Exhaust***	***Rtot***	***UA***	***13. Heat Transfer***	***qmax***	**Effectiveness q/qmax**
50	101151	0.356	0.0995	0.7085	0.4466987	15.934385	0.00762	0.00953	1832	20.193	1214.76	1.0368	0.00066375	0.0076609	1.045091	0.956855	297.8759	506.864	0.629482197
75	101151	0.356	0.0995	0.7085	0.4456023	15.97359	0.00762	0.00953	1832	20.193	1214.76	1.0125	0.00066375	0.0076609	1.020819	0.979606	273.6084	708.949	0.715535534
100	101151	0.356	0.0995	0.7085	0.4456023	15.97359	0.00762	0.00953	1832	20.193	1214.76	0.9991	0.00066375	0.0076609	1.007452	0.992603	261.2626	905.642	0.757184752

METER 1

Pressure (psi)	**Mass Flow Rate (kg/s)**	**4in Coil Tube Diameter (m) *(3/8 inch diam. tubing)***	**4in Coil Tube Length (m) *(6 foot tubing)***	**Area (m^2)**	**Calculated Velocity (m/s)**	**Dynamic Viscosity (N-s/m^2)**	**Calculated Reynolds No. (-)**	**Turbulent Condition? (Re > 10000)**	**Pr**	**Nu Laminar Flow**	**Nu Turbulent**	**Nu Approx.**	**Thermal Conductivity (W/mK)**	**Heat Transfer Coefficient**	**Delta T_o**	**Delta T_i**	**Delta T_lm**	**q**	**Effectiveness NTU**
50	0.00116	0.009525	2.394	7.12557E-05	13.627637	2.181E-05	7124.002	NO	0.734	3.66	32.2112	3.66	0.0292	11.220157	477.2595	209.8812	325.4683	320.668	0.588794217
75	0.00157	0.009525	2.394	7.12557E-05	18.759393	2.219E-05	9448.711	NO	0.727	3.66	32.0879	3.66	0.0299	11.489134	477.5025	159.9561	290.3494	505.506	0.686993108
100	0.00198	0.009525	2.394	7.12557E-05	23.951907	0.0000224	11828.75	YES	0.727	3.66	36.7023	3.66	0.0303	11.642835	478.2365	132.1449	269.0794	695.643	0.743130093
Overall Heat Transfer Coef	***Patm (Pa***	***Dexh***	***A_exh***	***m_dot_exh***	***Pho_inf***	***U_inf***	***Di***	***Do***	***Re_Exh***	***Nu***	***hexh***	***Rconv Gas***	***Rcond Steel***	***Rconv Exhaust***	***Rtot***	***UA***	***13. Heat Transfer***	***qmax***	**Effectiveness q/qmax**
50	101151	0.356	0.0995	0.7085	0.4466987	15.934385	0.00762	0.00953	1832	20.193	1214.76	1.5551	0.00099562	0.0114914	1.567636	0.637903	207.6172	544.617	0.588794217
75	101151	0.356	0.0995	0.7085	0.4456023	15.97359	0.00762	0.00953	1832	20.193	1214.76	1.5187	0.00099562	0.0114914	1.531228	0.653071	189.6186	735.825	0.686993108
100	101151	0.356	0.0995	0.7085	0.4456023	15.97359	0.00762	0.00953	1832	20.193	1214.76	1.4987	0.00099562	0.0114914	1.511179	0.661735	178.0593	936.099	0.743130093

5. 3/16” Nozzle Calculations

METER 4

Pressure (psi)	Mass Flow Rate (kg/s)	10in Coil Tube Diameter (m) *(3/8 inch diam. tubing)*	10in Coil Tube Length (m) *(6 foot tubing)*	Area (m^2)	Calculated Velocity (m/s)	Dynamic Viscosity (N-s/m^2)	Calculated Reynolds No. (-)	Turbulent Condition? (Re > 10000)	Pr	Nu Laminar Flow	Nu Turbulent	Nu Approx.	Thermal Conductivity (W/mK)	Heat Transfer Coefficient	Delta T_o	Delta T_i	Delta T_lm	q	Effectiveness NTU
50	0.00097	0.009525	5.985	7.13E-05	8.93602	2.2E-05	5915.16274	NO	0.734	3.66	32.2112	3.66	0.0292	11.220157	474.1456	414.2799	443.5396	84.812	0.187698416
75	0.00132	0.009525	5.985	7.13E-05	12.35095	2.2E-05	7969.91767	NO	0.727	3.66	32.0879	3.66	0.0299	11.489134	476.415	404.8728	439.6742	129.655	0.208654296
100	0.00172	0.009525	5.985	7.13E-05	16.12232	2.2E-05	10283.3794	YES	0.727	3.66	32.8133	3.66	0.0303	11.642835	475.5633	402.3014	437.9114	175.996	0.216637296
Overall Heat Transfer Coef	*Patm (Pa*	*Dexh*	*A_exh*	*m_dot_ex*	*Pho_inf*	*U_inf*	*Di*	*Do*	*Re_Exh*	*Nu*	*hexh*	*Rconv Gas*	*Rcond Steel*	*Rconv Exhaust*	*Rtot*	*UA*	*13. Heat Transfer*	*qmax*	**Effectiveness q/qmax**
50	100779	0.356	0.0995	0.7085	0.446535	15.9402	0.00762	0.009525	1832	20.193	1214.76	0.6221	0.00039825	0.0045965	0.627054	1.594758	707.3382	451.852	0.187698416
75	100779	0.356	0.0995	0.7085	0.444961	15.9966	0.00762	0.009525	1832	20.193	1214.76	0.6075	0.00039825	0.0045965	0.612491	1.632677	717.8458	621.385	0.208654296
100	100779	0.356	0.0995	0.7085	0.444961	15.9966	0.00762	0.009525	1832	20.193	1214.76	0.5995	0.00039825	0.0045965	0.604471	1.654338	724.4535	812.4	0.216637296

METER 3

Pressure (psi)	Mass Flow Rate (kg/s)	8in Coil Tube Diameter (m) *(3/8 inch diam. tubing)*	8in Coil Tube Length (m) *(6 foot tubing)*	Area (m^2)	Calculated Velocity (m/s)	Dynamic Viscosity (N-s/m^2)	Calculated Reynolds No. (-)	Turbulent Condition? (Re > 10000)	Pr	Nu Laminar Flow	Nu Turbulent	Nu Approx.	Thermal Conductivity (W/mK)	Heat Transfer Coefficient	Delta T_o	Delta T_i	Delta T_lm	q	Effectiveness NTU
50	0.00098	0.009525	4.788	7.13E-05	8.792942	2.2E-05	5987.88139	NO	0.734	3.66	32.2112	3.66	0.0292	11.220157	473.8225	435.4228	454.3522	66.6025	0.145701144
75	0.00133	0.009525	4.788	7.13E-05	12.07392	2.2E-05	8006.75332	NO	0.727	3.66	32.0879	3.66	0.0299	11.489134	476.0145	422.1714	448.5545	108.659	0.174196812
100	0.00176	0.009525	4.788	7.13E-05	16.05819	2.2E-05	10473.952	YES	0.727	3.66	32.0879	3.66	0.0303	11.642835	475.1299	419.6101	446.7952	150.671	0.182243615
Overall Heat Transfer Coef	*Patm (Pa*	*Dexh*	*A_exh*	*m_dot_ex*	*Pho_inf*	*U_inf*	*Di*	*Do*	*Re_Exh*	*Nu*	*hexh*	*Rconv Gas*	*Rcond Steel*	*Rconv Exhaust*	*Rtot*	*UA*	*13. Heat Transfer*	*qmax*	**Effectiveness q/qmax**
50	100779	0.356	0.0995	0.7085	0.446535	15.9402	0.00762	0.009525	1832	20.193	1214.76	0.7776	0.00049781	0.0057457	0.783818	1.275806	579.6654	457.117	0.145701144
75	100779	0.356	0.0995	0.7085	0.444961	15.9966	0.00762	0.009525	1832	20.193	1214.76	0.7594	0.00049781	0.0057457	0.765614	1.306141	585.8755	623.769	0.174196812
100	100779	0.356	0.0995	0.7085	0.444961	15.9966	0.00762	0.009525	1832	20.193	1214.76	0.7493	0.00049781	0.0057457	0.755589	1.32347	591.3202	826.757	0.182243615

METER 2

Pressure (psi)	Mass Flow Rate (kg/s)	6in Coil Tube Diameter (m) *(3/8 inch diam. tubing)*	6in Coil Tube Length (m) *(6 foot tubing)*	Area (m^2)	Calculated Velocity (m/s)	Dynamic Viscosity (N-s/m^2)	Calculated Reynolds No. (-)	Turbulent Condition? (Re > 10000)	Pr	Nu Laminar Flow	Nu Turbulent	Nu Approx.	Thermal Conductivity (W/mK)	Heat Transfer Coefficient	Delta T_o	Delta T_i	Delta T_lm	q	Effectiveness NTU
50	0.0012	0.009525	3.591	7.13E-05	14.10246	2.2E-05	7350.66687	NO	0.734	3.66	32.2112	3.66	0.0292	11.220157	473.6827	183.3843	305.9142	359.096	0.640101573
75	0.00165	0.009525	3.591	7.13E-05	20.14313	2.2E-05	9960.6357	NO	0.727	3.66	32.0879	3.66	0.0299	11.489134	475.8159	144.7034	278.1652	556.04	0.716837832
100	0.00218	0.009525	3.591	7.13E-05	27.03293	2.2E-05	12982.4865	YES	0.727	3.66	32.0879	3.66	0.0303	11.642835	474.8805	126.4988	263.3608	771.637	0.753353161
Overall Heat Transfer Coef	*Patm (Pa*	*Dexh*	*A_exh*	*m_dot_ex*	*Pho_inf*	*U_inf*	*Di*	*Do*	*Re_Exh*	*Nu*	*hexh*	*Rconv Gas*	*Rcond Steel*	*Rconv Exhaust*	*Rtot*	*UA*	*13. Heat Transfer*	*qmax*	**Effectiveness q/qmax**
50	100779	0.356	0.0995	0.7085	0.446535	15.9402	0.00762	0.009525	1832	20.193	1214.76	1.0368	0.00066375	0.0076609	1.045091	0.956855	292.7154	560.999	0.640101573
75	100779	0.356	0.0995	0.7085	0.444961	15.9966	0.00762	0.009525	1832	20.193	1214.76	1.0125	0.00066375	0.0076609	1.020819	0.979606	272.4923	775.685	0.716837832
100	100779	0.356	0.0995	0.7085	0.444961	15.9966	0.00762	0.009525	1832	20.193	1214.76	0.9991	0.00066375	0.0076609	1.007452	0.992603	261.4127	1024.27	0.753353161

METER 1

Pressure (psi)	Mass Flow Rate (kg/s)	4in Coil Tube Diameter (m) *(3/8 inch diam. tubing)*	4in Coil Tube Length (m) *(6 foot tubing)*	Area (m^2)	Calculated Velocity (m/s)	Dynamic Viscosity (N-s/m^2)	Calculated Reynolds No. (-)	Turbulent Condition? (Re > 10000)	Pr	Nu Laminar Flow	Nu Turbulent	Nu Approx.	Thermal Conductivity (W/mK)	Heat Transfer Coefficient	Delta T_o	Delta T_i	Delta T_lm	q	Effectiveness NTU
50	0.00129	0.009525	2.394	7.13E-05	15.14788	2.2E-05	7918.72725	NO	0.734	3.66	32.2112	3.66	0.0292	11.220157	473.678	201.3192	318.3115	365.57	0.604900028
75	0.00172	0.009525	2.394	7.13E-05	20.54891	2.2E-05	10350.0504	YES	0.727	3.66	32.0879	3.66	0.0299	11.489134	475.8153	158.7493	288.8448	555.624	0.689351814
100	0.00222	0.009525	2.394	7.13E-05	26.81838	2.2E-05	13244.3694	YES	0.727	3.66	32.0879	3.66	0.0303	11.642835	474.8685	137.3045	272.0454	765.162	0.732277988
Overall Heat Transfer Coef	*Patm (Pa*	*Dexh*	*A_exh*	*m_dot_ex*	*Pho_inf*	*U_inf*	*Di*	*Do*	*Re_Exh*	*Nu*	*hexh*	*Rconv Gas*	*Rcond Steel*	*Rconv Exhaust*	*Rtot*	*UA*	*13. Heat Transfer*	*qmax*	**Effectiveness q/qmax**
50	100779	0.356	0.0995	0.7085	0.446535	15.9402	0.00762	0.009525	1832	20.193	1214.76	1.5551	0.00099562	0.0114914	1.567636	0.637903	203.0519	604.348	0.604900028
75	100779	0.356	0.0995	0.7085	0.444961	15.9966	0.00762	0.009525	1832	20.193	1214.76	1.5187	0.00099562	0.0114914	1.531228	0.653071	188.6361	806.01	0.689351814
100	100779	0.356	0.0995	0.7085	0.444961	15.9966	0.00762	0.009525	1832	20.193	1214.76	1.4987	0.00099562	0.0114914	1.511179	0.661735	180.022	1044.91	0.732277988

APPENDIX G: RAW DATA

A. INDIVIDUAL METER COLD RUNS WITH CARBON DIOXIDE (MANUAL READINGS)

1. 1/6” Nozzle Diameter

Mass Flow (Kg/h)															
	Meter 1				Meter 2				Meter 3				Meter 4		
	50 PSI	75 PSI	100 PSI		50 PSI	75 PSI	100 PSI		50 PSI	75 PSI	100 PSI		50 PSI	75 PSI	100 PSI
1	8.307	11.96	16.17	1	7.768	12.07	16.24	1	7.681	11.11	14.56	1	7.906	10.99	14.37
2	8.433	12.03	16.18	2	8.167	12.02	16.13	2	7.874	11.14	14.69	2	7.858	11.05	14.31
3	8.228	12.05	16.35	3	7.758	12.04	16.15	3	7.725	11.12	14.71	3	7.954	11.32	14.38

Temperature (K)												
Meter 1	Atmospheric Pressure:	30.06										
Timestamp	N1	ND	14	15	16	17	18	19	20	21	22	23
50#-Tdata_20210331_1024_08	0	0	291.8809	292.0735	291.8651	291.8446	291.8522	291.7481	292.3234	292.2557	292.1258	292.1629
50#-Tdata_20210331_1026_11	0	0	291.9421	292.1302	292.0527	292.0283	292.0345	291.7004	292.4121	292.3513	292.1272	292.2004
50#-Tdata_20210331_1027_59	0	0	292.0007	292.1493	292.133	292.0863	292.0884	291.6772	292.4975	292.434	292.1403	292.1851
75#-Tdata_20210331_1029_23	0	0	292.0515	292.1995	292.6621	292.6201	292.6113	291.6283	292.5592	292.5068	292.2643	292.2814
75#-Tdata_20210331_1030_49	0	0	292.0944	292.2412	292.5499	292.505	292.5083	291.5974	292.6128	292.5558	292.2673	292.2445
75#-Tdata_20210331_1031_53	0	0	292.1382	292.2805	292.65	292.5723	292.5954	291.5909	292.6545	292.596	292.2522	292.2266
100#-Tdata_20210331_1033_13	0	0	292.2008	292.3688	293.2672	293.2255	293.2373	291.5603	292.6811	292.6275	292.4406	292.3698
100#-Tdata_20210331_1034_32	0	0	292.2297	292.4097	293.5693	293.5182	293.5981	291.5147	292.7116	292.6517	292.4737	292.3909
100#-Tdata_20210331_1035_56	0	0	292.2682	292.4574	293.6016	293.6372	293.7171	291.4096	292.7451	292.6864	292.4961	292.4076
Meter 2	Atmospheric Pressure:	30.06										
Timestamp	N1	ND	14	15	16	17	18	19	20	21	22	23
100#-Tdata_20210331_1053_31	0	0	292.5632	292.8948	294.0852	294.2825	292.1707	294.6303	293.0761	293.0277	292.9682	292.68
100#-Tdata_20210331_1054_40	0	0	292.6141	292.9872	293.6807	293.8371	291.9599	294.2883	293.1161	293.0858	292.8694	292.5917
100#-Tdata_20210331_1056_02	0	0	292.6785	293.029	293.9097	294.0685	291.8165	294.5686	293.1674	293.1322	292.9578	292.6581
75#-Tdata_20210331_1057_30	0	0	292.7378	293.0318	293.3367	293.413	291.7671	294.0164	293.2019	293.1573	292.7926	292.5241
75#-Tdata_20210331_1100_28	0	0	292.8362	293.0411	293.2795	292.8126	291.7201	294.0341	293.2962	293.259	292.9348	292.6577
75#-Tdata_20210331_1101_49	0	0	292.8828	293.0345	293.3539	293.0666	291.6732	294.0803	293.3339	293.2956	293.0141	292.7196
50#-Tdata_20210331_1107_34	0	0	292.9703	293.1293	293.1516	293.0027	291.9894	293.9499	293.4226	293.3882	293.159	292.9555
50#-Tdata_20210331_1108_41	0	0	293.015	293.158	293.4293	293.3132	292.0194	294.1862	293.4446	293.4159	293.1687	292.9216
50#-Tdata_20210331_1109_53	0	0	293.0595	293.1829	293.4767	293.3798	291.9493	294.226	293.5011	293.4701	293.1004	292.8692
Meter 3	Atmospheric Pressure:	29.9										
Timestamp	N1	ND	14	15	16	17	18	19	20	21	22	23
50#-Tdata_20210401_0908_45	0	0	290.9125	291.3102	291.5542	291.7077	291.5109	291.3504	291.9729	291.9375	291.3464	290.9464
50#-Tdata_20210401_0910_20	0	0	291.0021	291.3532	291.7834	291.7249	291.7301	291.5532	292.0647	292.0186	291.488	290.9695
50#-Tdata_20210401_0911_54	0	0	291.1108	291.4047	291.8773	291.7482	291.814	291.6485	292.1523	292.101	291.5788	291.0202
75#-Tdata_20210401_0915_46	0	0	291.3282	291.584	292.0008	291.8157	291.9207	291.7645	292.2974	292.2329	291.8948	291.3279
75#-Tdata_20210401_0916_54	0	0	291.4145	291.6423	292.2644	291.8395	292.1609	291.9596	292.345	292.2886	291.9518	291.2898
75#-Tdata_20210401_0917_48	0	0	291.4777	291.6783	292.4455	291.8581	292.333	292.0824	292.3861	292.3301	291.9773	291.2955
100#-Tdata_20210401_0922_42	0	0	291.7111	291.9654	292.8649	292.0573	292.7522	292.5345	292.5254	292.4727	292.4152	291.6704
100#-Tdata_20210401_0924_12	0	0	291.8012	292.0819	293.3291	291.9448	293.2976	292.9407	292.5819	292.5266	292.5309	291.7227
100#-Tdata_20210401_0925_51	0	0	291.8785	292.1666	293.4819	291.8129	293.4962	293.151	292.6481	292.5926	292.6417	291.8085
Meter 4	Atmospheric Pressure:	29.9										
Timestamp	N1	ND	14	15	16	17	18	19	20	21	22	23
100#-Tdata_20210401_0931_27	0	0	292.0655	292.3151	291.84	293.6355	293.3782	293.1304	292.8035	292.7453	292.7964	292.1694
100#-Tdata_20210401_0933_49	0	0	292.2031	292.4277	291.6249	294.0964	293.5504	293.2134	292.8839	292.8253	292.7688	292.182
100#-Tdata_20210401_0935_12	0	0	292.27	292.466	291.5175	294.6173	293.9547	293.5121	292.9411	292.881	292.8056	292.2281
75#-Tdata_20210401_0939_18	0	0	292.3639	292.4844	291.6328	294.087	292.9291	292.6363	293.0524	293.0001	292.8783	292.3931
75#-Tdata_20210401_0940_37	0	0	292.4323	292.5493	291.5992	294.2933	293.1144	292.7953	293.104	293.0484	292.814	292.3443
75#-Tdata_20210401_0941_36	0	0	292.4861	292.5946	291.5734	294.4654	293.2754	292.9321	293.1522	293.0876	292.8006	292.3309
50#-Tdata_20210401_0945_58	0	0	292.5954	292.6932	291.8473	294.4073	293.1275	292.7942	293.2899	293.2215	292.94	292.5523
50#-Tdata_20210401_0946_53	0	0	292.6359	292.7313	291.8867	294.5562	293.2788	292.9037	293.3283	293.2566	292.9083	292.52
50#-Tdata_20210401_0951_31	0	0	292.784	292.9283	292.1266	294.6288	293.2572	292.9484	293.422	293.3601	293.1765	292.8434

Pressure (Pa)																		
Meter 1	Atmospheric Pressure:	30.06																
Timestamp	N1	ND	3_01	3_02	3_03	3_04	3_05	3_06	3_07	3_08	3_09	3_10	3_11	3_12	3_13	3_14	3_15	3_16
50#-Pdata_20210331_1024_08	0	0	15.12	-19.46	7.64	19.22	332208.7	300563.9	-26.82	-22.7	26.96	3.71	15.66	14.69	304328	300609.4	300549.8	300516.1
50#-Pdata_20210331_1026_11	0	0	3.78	-3.89	22.92	3.85	337798.7	309818.6	-11.49	-30.26	34.67	7.41	31.33	25.7	313579.3	309866.4	309794.7	309771.1
50#-Pdata_20210331_1027_59	0	0	11.34	11.68	42.01	11.53	329176.5	294475.6	3.84	-15.13	30.81	14.82	27.41	29.37	298170.9	294543	294456.3	294429.5
75#-Pdata_20210331_1029_23	0	0	11.34	0	38.19	15.37	483134.6	455026	0	-11.34	19.26	14.82	15.67	33.05	459924.2	455108.1	455048.9	454971.5
75#-Pdata_20210331_1030_49	0	0	26.46	31.14	34.38	30.74	483494.3	455437	7.67	-7.56	23.11	18.52	19.58	29.38	460325.9	455517.1	455478.9	455391.5
75#-Pdata_20210331_1031_53	0	0	30.25	15.57	34.38	42.26	483720.6	456158.3	15.34	0	19.26	11.11	0.01	25.7	461062.3	456236.6	456195.5	456102.6
100#-Pdata_20210331_1033_13	0	0	22.68	35.04	34.38	34.58	660135.8	632133.1	3.84	11.36	19.26	18.52	11.75	29.38	638239.6	632222.4	632176.6	632094.4
100#-Pdata_20210331_1034_32	0	0	22.68	19.46	30.56	42.26	665429.3	637210.9	11.5	11.36	23.11	11.11	23.5	22.04	643343	637291.7	637262.4	637171.6
100#-Pdata_20210331_1035_56	0	0	30.24	15.57	22.92	46.11	665444.1	637098.6	0	15.15	26.96	3.71	3.92	25.71	643221	637170.6	637153.9	637061.9
Meter 2	Atmospheric Pressure:	30.06																
Timestamp	N1	ND	3_01	3_02	3_03	3_04	3_05	3_06	3_07	3_08	3_09	3_10	3_11	3_12	3_13	3_14	3_15	3_16
100#-Pdata_20210331_1053_31	0	0	26.46	11.68	22.92	38.43	650228.4	620574.5	3.84	3.79	23.11	3.7	15.67	22.03	620672.9	626960	620606.7	620517.6
100#-Pdata_20210331_1054_40	0	0	37.81	11.68	11.46	30.74	637609.3	608050.6	3.84	0	15.41	-3.7	11.75	22.03	608142.7	614318.9	608095.5	607979.9
100#-Pdata_20210331_1056_02	0	0	34.03	15.57	19.1	26.9	639532.8	609996.4	7.67	7.57	15.41	-3.7	11.75	18.36	610064.4	616276.2	610055.5	609920.7
75#-Pdata_20210331_1057_30	0	0	30.25	15.57	15.28	30.74	477438.4	451369.4	-3.83	7.57	7.71	0.01	15.66	14.69	451434.7	456460.2	451434.9	451294.8
75#-Pdata_20210331_1100_28	0	0	34.03	27.26	26.73	30.74	478135.7	450698.5	0	11.36	19.26	3.71	19.58	18.36	450777.1	455733.2	450788	450648
75#-Pdata_20210331_1101_49	0	0	26.47	23.37	30.55	23.05	477597.9	451423.6	0	7.58	7.71	-7.4	23.49	22.03	451509.5	456426.2	451493	451378.1
50#-Pdata_20210331_1107_34	0	0	64.27	23.37	15.28	23.06	302723.7	275694.7	3.84	11.36	15.41	-7.4	11.75	18.36	275776.8	279295.7	275742	275643.6
50#-Pdata_20210331_1108_41	0	0	22.69	15.58	22.92	34.58	321304.5	295286.9	0	3.79	11.56	-3.7	11.75	18.36	295380.3	299045.1	295336.7	295247.6
50#-Pdata_20210331_1109_53	0	0	26.46	11.68	19.1	30.74	305239.8	276855	0	3.79	15.41	-11.11	11.75	22.03	276959.3	280371.8	276912.6	276813.3
Meter 3	Atmospheric Pressure:	29.9																
Timestamp	N1	ND	3_01	3_02	3_03	3_04	3_05	3_06	3_07	3_08	3_09	3_10	3_11	3_12	3_13	3_14	3_15	3_16
50#-Pdata_20210401_0908_45	0	0	-3.78	23.35	3.82	0.01	321573.1	299346.5	-42.13	41.6	-7.7	18.51	-19.56	-14.69	299383	299341.3	303578.3	299301.9
50#-Pdata_20210401_0910_20	0	0	-7.56	31.13	3.82	-11.51	326404.9	305825.8	-42.13	45.38	-3.85	11.11	-31.29	-40.4	305869.9	305840.4	310111.4	305774.1
50#-Pdata_20210401_0911_54	0	0	-18.89	15.57	34.37	0	321598.2	297774.1	-38.3	30.25	11.55	51.82	-39.11	-33.05	297820.2	297776.7	301942.6	297724.1
75#-Pdata_20210401_0915_46	0	0	11.34	46.7	15.29	-3.84	477541	454160.5	-26.81	64.29	11.56	14.81	-11.73	-7.34	454242.7	454158.2	459698.9	454112
75#-Pdata_20210401_0916_54	0	0	0	27.25	0	-7.68	479416.3	456393.3	-26.81	68.07	3.85	3.71	-11.73	-11.02	456458.1	456379.5	461918.6	456335.6
75#-Pdata_20210401_0917_48	0	0	0	35.03	3.82	-3.84	480939.5	457439.1	-30.64	60.51	0	0.01	-19.56	-7.34	457504.9	457431.5	462937.4	457371.7
100#-Pdata_20210401_0922_42	0	0	-3.78	23.35	26.74	7.68	631773.4	604273.6	-53.63	37.82	-19.24	22.21	-23.47	-22.03	604326.6	604276.8	611031.2	604181.2
100#-Pdata_20210401_0924_12	0	0	7.56	7.79	26.74	15.36	638382.2	610727.5	-42.13	30.27	0.01	-0.01	-31.29	-29.38	610746.6	610718	617502.9	610594.5
100#-Pdata_20210401_0925_51	0	0	0	23.35	7.65	-11.51	639497.1	611790.5	-11.5	37.83	26.96	-3.69	-39.11	-36.71	611798.3	611743.8	618566.2	611694.6
Meter 4	Atmospheric Pressure:	29.9																
Timestamp	N1	ND	3_01	3_02	3_03	3_04	3_05	3_06	3_07	3_08	3_09	3_10	3_11	3_12	3_13	3_14	3_15	3_16
100#-Pdata_20210401_0931_27	0	0	-15.11	50.59	7.64	-11.51	636186.3	607975	-42.13	45.38	11.55	7.41	-3.91	-3.67	608043.1	607976.4	608075.4	614261.3
100#-Pdata_20210401_0933_49	0	0	11.34	27.24	3.82	0	641740	613353.2	-30.64	49.18	-3.84	-7.4	0	-7.34	613405.7	613353.3	613467.3	619672.4
100#-Pdata_20210401_0935_12	0	0	-3.78	38.92	34.38	-11.51	644672.8	616325.5	-45.97	41.61	3.85	-11.11	-7.82	-11.02	616343.5	616297.8	616428.4	622663
75#-Pdata_20210401_0939_18	0	0	-7.55	31.15	15.28	-34.54	491313.7	456514.2	-30.65	41.62	23.11	11.11	-27.38	-14.69	456555.1	456512.1	456600.8	461690.9
75#-Pdata_20210401_0940_37	0	0	-22.67	42.82	15.28	-26.87	487391.7	460522.5	-19.16	30.27	30.8	0.01	-19.55	-3.67	460585.7	460520.9	460613.9	465700.4
75#-Pdata_20210401_0941_36	0	0	-22.67	70.06	15.28	-26.87	489000.5	462954.9	-22.99	34.05	26.95	0	-19.56	-14.69	463016.1	462961.7	463054.4	468175.8
50#-Pdata_20210401_0945_58	0	0	26.45	66.16	-3.82	0	336169.1	309873.6	-26.82	34.07	19.25	-3.7	-23.47	-33.04	309937.5	309901.2	309965.8	313839.6
50#-Pdata_20210401_0946_53	0	0	11.34	35.03	7.64	-3.84	332209.9	304023.8	-19.16	26.49	11.55	-44.41	-31.29	-22.03	304082.6	304033.6	304087.4	307955.4
50#-Pdata_20210401_0951_31	0	0	-11.34	38.94	19.11	-23.03	337380.9	310135.5	-38.3	49.19	7.71	-3.7	0	3.67	310189.5	310139.5	310250.1	314176.1

2. 1/8” Nozzle Diameter

Mass Flow (Kg/h)															
	Meter 1				Meter 2				Meter 3				Meter 4		
	50 PSI	75 PSI	100 PSI		50 PSI	75 PSI	100 PSI		50 PSI	75 PSI	100 PSI		50 PSI	75 PSI	100 PSI
1	16.35	22.37	31.06	1	15.8	22.29	29.59	1	14.08	19.67	27.01	1	14.42	21.3	30.13
2	16.21	22.39	31.19	2	15.71	22.33	29.46	2	14.03	19.61	26.94	2	14.45	21.75	29.95
3	16.14	22.47	30.95	3	15.81	22.01	28.93	3	14.05	19.59	26.9	3	14.46	21.43	29.97

Temperature (K)												
Meter 1	Atmospheric Pressure:	29.9										
Timestamp	N1	ND	14	15	16	17	18	19	20	21	22	23
50#-Tdata_20210401_1057_27	0	0	293.8249	294.17	294.8487	294.7814	294.4093	293.0267	293.8832	294.2369	293.9667	293.9971
50#-Tdata_20210401_1101_37	0	0	293.9182	294.2068	294.6295	294.5302	294.1878	292.8081	293.9599	294.3101	294.0401	293.8724
50#-Tdata_20210401_1105_02	0	0	293.9629	294.2322	294.6668	294.5678	294.2656	292.7125	294.013	294.3437	294.105	293.7965
75#-Tdata_20210402_0912_25	0	0	289.8138	290.029	290.9222	290.9556	290.9555	291.1111	290.1296	291.1037	290.1032	290.395
75#-Tdata_20210402_0913_43	0	0	289.8895	290.132	291.2459	291.3326	291.3357	291.0596	290.1376	291.1123	290.1326	290.4179
75#-Tdata_20210402_0914_48	0	0	289.9502	290.1808	291.4978	291.5927	291.601	290.9442	290.1635	291.0949	290.1808	290.413
100#-Tdata_20210402_0916_37	0	0	290.0726	290.3182	291.751	291.8806	291.8916	290.212	290.3951	291.0934	290.4512	290.5331
100#-Tdata_20210402_0917_48	0	0	290.1368	290.3319	291.8994	292.0632	292.0668	289.451	290.4069	291.0946	290.5123	290.3763
100#-Tdata_20210402_0919_45	0	0	290.2132	290.4096	291.7288	291.9015	291.9065	287.9594	290.4302	291.0574	290.5871	289.7661
Meter 2	Atmospheric Pressure:	29.97										
Timestamp	N1	ND	14	15	16	17	18	19	20	21	22	23
50#-Tdata_20210402_0923_03	0	0	290.2726	290.4394	291.2096	291.3405	288.1803	289.1893	290.4814	291.1669	290.5915	290.2045
50#-Tdata_20210402_0924_22	0	0	290.2889	290.4615	291.3964	291.5507	287.9818	289.6827	290.4817	291.1964	290.6236	290.2421
50#-Tdata_20210402_0925_44	0	0	290.3036	290.4794	291.5374	291.6994	287.7867	290.0718	290.4962	291.187	290.6642	290.2917
75#-Tdata_20210402_0927_35	0	0	290.2983	290.551	291.7736	291.9597	287.1553	290.6107	290.4671	291.1373	290.7492	290.3728
75#-Tdata_20210402_0928_52	0	0	290.2715	290.5731	291.7485	291.9905	287.0495	290.7815	290.3891	291.1243	290.7243	290.3597
75#-Tdata_20210402_0930_34	0	0	290.2367	290.6143	291.6416	291.883	286.9844	290.9049	290.3612	291.1143	290.7488	290.3937
100#-Tdata_20210402_0932_32	0	0	290.2	290.6688	291.8811	292.1227	286.4335	291.4127	290.2737	291.0971	290.8716	290.4189
100#-Tdata_20210402_0934_49	0	0	290.1173	290.6936	291.6833	291.9122	285.6069	291.4832	290.1099	291.0562	290.8665	290.396
100#-Tdata_20210402_0936_47	0	0	290.0419	290.64	291.7029	291.9451	284.9853	291.6981	290.0135	291.072	290.8707	290.3513
Meter 3	Atmospheric Pressure:	29.97										
Timestamp	N1	ND	14	15	16	17	18	19	20	21	22	23
50#-Tdata_20210402_0939_39	0	0	290.0094	290.6632	291.3634	287.1786	286.7508	291.4926	290.3609	291.1143	290.3781	290.4041
50#-Tdata_20210402_0940_59	0	0	290.0506	290.6062	291.5488	287.0865	287.5235	291.7377	290.4006	291.1385	290.1484	290.3893
50#-Tdata_20210402_0942_18	0	0	290.0951	290.5571	291.6628	287.0773	288.0416	291.9073	290.4137	291.1424	289.7949	290.379
75#-Tdata_20210402_0944_13	0	0	290.0911	290.4575	291.9512	286.9611	288.9456	292.3247	290.3672	291.1045	289.0828	290.3718
75#-Tdata_20210402_0945_40	0	0	290.0365	290.4176	291.8703	287.051	289.2279	292.2978	290.2923	291.1411	288.7499	290.3553
75#-Tdata_20210402_0946_47	0	0	290.0109	290.4321	291.9499	287.1732	289.6239	292.4076	290.2419	291.1294	288.7457	290.3169
100#-Tdata_20210402_0948_31	0	0	289.9862	290.4319	292.0128	287.057	290.0248	292.5747	290.2568	291.1622	288.5086	290.439
100#-Tdata_20210402_0950_09	0	0	289.9651	290.453	291.9877	286.9968	290.3467	292.6013	290.2013	291.2142	288.4136	290.4378
100#-Tdata_20210402_0952_02	0	0	289.9646	290.4517	291.915	286.7897	290.6148	292.5667	290.1807	291.2857	288.3837	290.468
Meter 4	Atmospheric Pressure:	29.97										
Timestamp		N1	13	14	15	16	17	18	19	20	21	22
50#-Tdata_20210402_0954_29	0	0	289.9872	290.5445	288.1568	287.861	290.5931	292.1991	290.3317	291.4132	289.0762	290.5138
50#-Tdata_20210402_0955_41	0	0	290.0634	290.5821	288.1221	288.5367	290.9848	292.3842	290.3242	291.4564	289.2851	290.5492
50#-Tdata_20210402_0956_47	0	0	290.1317	290.6172	288.1372	289.0215	291.2457	292.5062	290.1196	291.4758	289.424	290.5609
75#-Tdata_20210402_0958_01	0	0	290.1979	290.6649	287.9008	289.8358	291.8824	292.95	289.7532	291.4846	289.6263	290.5942
75#-Tdata_20210402_0959_08	0	0	290.2352	290.6709	287.8823	290.0684	291.9773	292.9044	289.4524	291.4708	289.7173	290.5969
75#-Tdata_20210402_1000_55	0	0	290.2399	290.6827	287.9006	290.2847	291.8975	292.7131	289.2553	291.4779	289.9159	290.6639
100#-Tdata_20210402_1002_44	0	0	290.2602	290.7413	287.5173	290.8039	292.1554	292.8766	289.007	291.4765	290.2541	290.8078
100#-Tdata_20210402_1004_17	0	0	290.2466	290.7434	287.1199	291.1595	292.3234	292.9301	288.8175	291.5249	290.3996	290.8129
100#-Tdata_20210402_1005_47	0	0	290.211	290.7362	286.5815	291.4917	292.4958	292.9778	288.6395	291.5533	290.5254	290.8199

Pressure (Pa)																		
Meter 1	Atmospheric Pressure:	29.9																
Timestamp	N1	ND	3_01	3_02	3_03	3_04	3_05	3_06	3_07	3_08	3_09	3_10	3_11	3_12	3_13	3_14	3_15	3_16
50#-Pdata_20210401_1057_27	0	0	0	27.26	22.92	49.95	-999999	121656.1	7.67	3.79	19.26	11.12	27.41	22.04	143460.9	121697.6	121612.4	121596.6
50#-Pdata_20210401_1101_37	0	0	22.68	19.47	38.2	34.58	-999999	117251.5	-3.83	0	15.41	11.12	31.33	29.38	138543	117326.8	117213.3	117237.9
50#-Pdata_20210401_1105_02	0	0	30.25	31.15	38.19	15.37	-999999	117876.2	0	15.14	26.97	7.41	15.66	29.38	139348.9	117929.3	117845.3	117843.5
75#-Pdata_20210402_0912_25	0	0	-3.78	27.23	26.73	-42.2	-999999	189568.9	-3.83	11.34	-7.69	-11.1	-23.46	-33.05	217252.4	189517.5	189573.8	189533.1
75#-Pdata_20210402_0913_43	0	0	-18.89	15.57	7.64	-19.19	-999999	189305.1	-3.83	7.56	-23.07	-25.9	-39.1	-3.67	216945.3	189259.6	189333.1	189268
75#-Pdata_20210402_0914_48	0	0	-7.56	19.46	0	-19.19	-999999	189258.4	-7.66	0	-7.69	-33.3	-31.28	-3.67	216929.4	189198.9	189282.6	189233.7
100#-Pdata_20210402_0916_37	0	0	7.55	-3.89	0	-46.06	-999999	286098.6	-7.66	-3.78	7.7	-44.4	-23.46	-3.67	321453.7	286055.6	286113.3	286059.2
100#-Pdata_20210402_0917_48	0	0	0	0	3.82	-34.54	-999999	288322.8	15.31	-7.56	3.85	-7.4	-7.82	0	323850	288296.4	288356.6	288302.2
100#-Pdata_20210402_0919_45	0	0	-15.11	42.8	22.92	-38.37	-999999	283746.1	15.32	-11.34	0	-25.9	-11.73	-22.03	318809.4	283703.8	283764.7	283705.8
Meter 2	Atmospheric Pressure:	29.97																
Timestamp	N1	ND	3_01	3_02	3_03	3_04	3_05	3_06	3_07	3_08	3_09	3_10	3_11	3_12	3_13	3_14	3_15	3_16
50#-Pdata_20210402_0923_03	0	0	7.56	31.14	26.75	-11.51	-999999	109738.5	0	7.57	-7.7	0	-15.65	-18.36	109804.3	131385	109714.2	109653.8
50#-Pdata_20210402_0924_22	0	0	3.78	27.24	11.46	-38.38	-999999	107794.7	0	7.56	-11.54	-3.7	-27.38	-33.05	107874.5	129197.7	107783.3	107695.5
50#-Pdata_20210402_0925_44	0	0	0	11.68	11.46	-38.38	-999999	108838.1	-3.83	0	-11.54	-11.1	-35.2	-25.71	108925.9	130357	108822.2	108744.4
75#-Pdata_20210402_0927_35	0	0	0	54.48	38.21	-15.35	-999999	193646.8	26.81	11.34	23.11	-3.7	-11.73	0	193714.5	222757.8	193644.5	193621.2
75#-Pdata_20210402_0928_52	0	0	22.67	50.59	19.1	-15.35	-999999	193592.5	19.15	37.81	11.55	-7.4	3.91	0	193659.5	222700.9	193574.8	193564.4
75#-Pdata_20210402_0930_34	0	0	11.34	38.92	15.28	-30.7	-999999	187422.7	11.49	26.47	11.55	-3.7	0	-11.01	187493.4	215978	187401.6	187369.1
100#-Pdata_20210402_0932_32	0	0	3.78	46.71	11.47	-38.38	-999999	278163	15.32	15.12	3.85	-25.9	-11.73	-11.02	278286.2	314206.9	278153.3	278117.5
100#-Pdata_20210402_0934_49	0	0	-3.78	35.03	11.46	-46.06	-999999	273143.1	0	7.56	0	-29.61	-11.73	-7.35	273242.8	308753.1	273111.7	273105.2
100#-Pdata_20210402_0936_47	0	0	-15.12	27.24	3.83	-42.22	-999999	271867.5	-3.83	0	-3.85	-11.1	-7.82	-7.34	271957	307360.2	271842.4	271781.2
Meter 3	Atmospheric Pressure:	29.97																
Timestamp	N1	ND	3_01	3_02	3_03	3_04	3_05	3_06	3_07	3_08	3_09	3_10	3_11	3_12	3_13	3_14	3_15	3_16
50#-Pdata_20210402_0939_39	0	0	11.34	31.14	38.2	-30.7	-999999	108362.5	-19.15	-3.78	-7.69	-7.41	-7.82	-22.04	108419.5	108363.3	132064.1	108246.1
50#-Pdata_20210402_0940_59	0	0	7.56	50.6	26.75	-34.54	-999999	107757	30.64	0	23.11	-33.31	-31.29	-22.03	107788.9	107737.8	131357.8	107613.5
50#-Pdata_20210402_0942_18	0	0	0	58.38	34.39	-34.54	-999999	107318.6	15.32	-3.78	26.96	-25.9	-27.38	-25.7	107359.1	107290.5	130870.1	107185.6
75#-Pdata_20210402_0944_13	0	0	-3.78	50.6	15.28	-53.73	-999999	183529.6	11.49	-11.34	19.25	-11.1	-43.03	-22.03	183626.4	183599.6	214710.7	183465.3
75#-Pdata_20210402_0945_40	0	0	-7.56	58.38	15.28	-53.73	-999999	183873	7.66	-7.56	11.55	-7.4	0	3.67	183956.2	183930	214947.1	183794.8
75#-Pdata_20210402_0946_47	0	0	-3.78	46.7	3.82	-65.25	-999999	183509.8	15.33	22.69	15.41	-22.21	-3.91	0	183566.4	183570.4	214656.5	183438.9
100#-Pdata_20210402_0948_31	0	0	-3.78	31.14	3.82	-34.55	-999999	269202.8	3.83	3.78	7.71	-18.5	-3.91	7.34	269272.3	269275.8	308017.5	269072.4
100#-Pdata_20210402_0950_09	0	0	15.12	42.81	11.46	-38.39	-999999	268175.2	7.66	7.57	3.85	-25.91	-15.65	-3.67	268253.6	268260.6	306916.9	268066.1
100#-Pdata_20210402_0952_02	0	0	11.34	38.92	26.74	-49.9	-999999	268186.8	0	15.13	-3.85	-48.11	-15.65	-3.67	268281.1	268279.5	306932.3	268093.4
Meter 4	Atmospheric Pressure:	29.97																
Timestamp	N1	ND	3_01	3_02	3_03	3_04	3_05	3_06	3_07	3_08	3_09	3_10	3_11	3_12	3_13	3_14	3_15	3_16
50#-Pdata_20210402_0954_29	0	0	3.78	35.04	26.75	-42.22	-999999	104352.3	-3.83	0	3.85	-11.1	-23.47	-7.34	104413.8	104356.4	104413.4	129166.2
50#-Pdata_20210402_0955_41	0	0	3.78	50.61	22.92	-49.9	-999999	104682.6	-11.49	7.57	15.41	-7.4	-11.73	-7.35	104737.4	104708.9	104743.4	129495.7
50#-Pdata_20210402_0956_47	0	0	0	31.15	38.2	-46.06	-999999	105471	0	3.78	38.5	-14.81	-7.82	-3.68	105521.9	105485.9	105527.5	130378.1
75#-Pdata_20210402_0958_01	0	0	-7.56	42.82	15.28	-57.57	-999999	185395.5	34.48	0	42.36	-14.81	-27.38	-29.37	185460.8	185461.7	185494.4	218678.8
75#-Pdata_20210402_0959_08	0	0	-11.34	54.49	22.92	-46.06	-999999	187781.3	15.33	-7.57	26.96	-22.21	-15.65	-11.02	187847.2	187849	187884.7	221312.5
75#-Pdata_20210402_1000_55	0	0	0	54.49	15.29	-30.71	-999999	186664.1	26.82	0	15.4	-33.31	-31.29	-14.68	186749.2	186738.8	186775.9	220033.5
100#-Pdata_20210402_1002_44	0	0	26.46	70.06	26.75	-30.71	-999999	275560.1	15.33	-15.13	26.96	-22.2	-11.73	-25.7	275690.2	275665.7	275742	317551.8
100#-Pdata_20210402_1004_17	0	0	37.79	46.7	0.01	-30.71	-999999	275062.4	22.99	-15.13	19.25	-48.11	-27.38	-18.36	275180.5	275180.8	275203.4	316969
100#-Pdata_20210402_1005_47	0	0	30.24	46.7	7.64	-38.39	-999999	274887.9	15.33	-11.35	11.55	-33.31	-39.11	-14.69	275020.4	275002.7	275040.6	316753.3

B. ALL METERS ONLINE COLD RUNS WITH CARBON DIOXIDE (MANUAL READINGS)

1. 3/16” Nozzle Diameter

Mass Flow (Kg/h)															
	Meter 1				Meter 2				Meter 3				Meter 4		
	50 PSI	75 PSI	100 PSI		50 PSI	75 PSI	100 PSI		50 PSI	75 PSI	100 PSI		50 PSI	75 PSI	100 PSI
1	3.319	4.227	10.19	1	5.614	6.995	7.954	1	5.752	6.356	5.915	1	1.83	5.992	7.216
2	3.404	4.217	9.58	2	5.204	6.997	7.772	2	5.544	6.313	5.612	2	2.513	5.994	6.942
3	3.425	4.205	9.49	3	5.169	6.895	7.749	3	5.257	6.221	5.692	3	2.593	6.195	6.953

Temperature (K)												
All 4 Meters	Atmospheric Pressure:	30.16										
Timestamp	N1	ND	14	15	16	17	18	19	20	21	22	23
Tdata_20210408_0913_33	0	0	285.9809	286.0841	290.6476	290.3956	290.3009	290.2715	286.1668	286.6533	286.2328	286.2507
Tdata_20210408_0916_02	0	0	286.2205	286.3579	290.5882	290.4048	290.3317	290.2911	286.3274	286.3679	286.7599	286.6504
Tdata_20210408_0918_15	0	0	286.3385	286.5792	290.578	290.3792	290.3226	290.2848	286.4416	285.8845	287.003	286.8362
Tdata_20210408_0920_32	0	0	286.4695	286.659	290.0046	289.98	289.9369	290.0059	286.6592	285.922	287.234	287.0994
Tdata_20210408_0922_28	0	0	286.3259	286.4937	289.4096	289.4036	289.3855	289.5939	286.7149	285.2601	287.2041	287.0503
Tdata_20210408_0923_59	0	0	286.5988	286.9772	288.88	288.9156	288.907	289.2057	286.9804	286.1018	287.3548	287.2215
Tdata_20210408_0926_40	0	0	287.0781	287.5773	287.3077	287.5012	287.3234	287.0672	287.5748	286.9919	287.827	288.0845
Tdata_20210408_0928_53	0	0	287.5433	288.0334	286.0404	286.2697	285.963	285.4021	288.0725	288.0138	288.2404	288.6697
Tdata_20210408_0930_46	0	0	287.7584	288.1924	285.0822	285.296	284.914	284.1954	288.2784	288.0716	288.4436	288.5834

Pressure (Pa)																		
All 4 Meters	Atmospheric Pressure:	30.16																
Timestamp	N1	ND	3_01	3_02	3_03	3_04	3_05	3_06	3_07	3_08	3_09	3_10	3_11	3_12	3_13	3_14	3_15	3_16
50#-Pdata_20210408_0913_33	0	0	15.11	0	-30.53	3.84	-999999	31366.07	-3.83	-18.91	-11.54	-7.4	-35.19	-29.38	33619.62	37637.93	39032.56	32305.47
50#-Pdata_20210408_0916_02	0	0	30.22	23.34	-3.81	-15.35	-999999	31695.86	0	-15.13	-23.08	-11.09	-39.1	-40.4	34069.02	36974.57	38788.01	33479.46
50#-Pdata_20210408_0918_15	0	0	22.66	15.56	-3.82	-26.86	-999999	30977.76	-7.66	3.78	-30.77	-3.7	-39.1	-18.36	33345.77	36243	37658.89	32820.38
75#-Pdata_20210408_0920_32	0	0	34	19.46	-7.64	7.68	-999999	58888.61	-22.97	0	-11.53	-14.8	-50.83	-11.02	61842.61	66069.57	66394.6	65666.95
75#-Pdata_20210408_0922_28	0	0	22.67	11.68	-22.9	-3.84	-999999	59162.61	-34.46	-3.78	3.85	0	-11.74	-18.36	62131.92	66350.11	66696.95	65924.6
75#-Pdata_20210408_0923_59	0	0	22.66	3.9	-22.89	-23.03	-999999	59370.22	0	-15.13	-3.85	-3.7	-19.56	-14.69	62367.39	66380.26	66686.04	66481.36
100#-Pdata_20210408_0926_40	0	0	7.56	35.02	7.64	-3.83	-999999	95431.31	3.83	22.69	-7.7	-3.7	-23.47	-25.71	106124.6	102784.9	101182.8	102847.1
100#-Pdata_20210408_0928_53	0	0	37.78	27.25	0	3.84	-999999	89765.97	-3.83	7.57	-3.85	3.7	-39.11	-33.05	99938.54	97055.29	95264.05	96872.28
100#-Pdata_20210408_0930_46	0	0	37.78	23.35	-7.63	0	-999999	90227.68	-22.98	3.78	-11.54	3.7	-35.2	-33.05	100081.1	97584.61	95935.13	97353.04

C. ALL METERS ONLINE COLD RUNS WITH CARBON DIOXIDE (DAQ SYSTEM)

1. 1/16” Nozzle Diameter

Mass Flow (Kg/h)			
	50 PSI	75 PSI	100 PSI
Meter 1	2.555	3.442	4.448
Meter 2	1.743	2.377	2.864
Meter 3	1.677	2.175	2.766
Meter 4	2.319	3.041	3.736
Timestamp	8_56	1_42	3_46

Temperature (K)												
All Meters	Atmospheric Pressure:	30.03										
Timestamp	N1	ND	14	15	16	17	18	19	20	21	22	23
Tdata_20210719_1008_56	0	0	292.5724	292.6078	295.7799	296.4058	295.8491	295.4661	293.169	293.1192	292.8825	292.7723
Tdata_20210719_1011_42	0	0	292.6705	292.9284	295.1511	295.7359	295.2957	294.8453	293.181	293.1459	292.9637	292.9981
Tdata_20210719_1013_46	0	0	292.7242	293.3459	294.7795	295.3589	295.046	294.5531	293.1868	293.1618	293.1115	293.4656

Pressure (Pa)																		
All Meters	Atmospheric Pressure:	30.03																
Timestamp	N1	ND	3_01	3_02	3_03	3_04	3_05	3_06	3_07	3_08	3_09	3_10	3_11	3_12	3_13	3_14	3_15	3_16
Pdata_20210719_1008_56	0	0	-22.67	15.58	30.56	15.37	349451.1	331719.9	-42.15	-18.91	-26.95	-29.61	-19.56	-18.35	332228.4	332070	332051.8	332080.4
Pdata_20210719_1011_42	0	0	-45.34	0.01	61.11	49.95	479768	458198.7	-57.48	-41.61	-53.88	-22.2	7.85	22.03	458861.8	458630.6	458613.5	458596.3
Pdata_20210719_1013_46	0	0	-34.01	-19.45	7.64	19.22	608126.9	584559.6	-26.82	-22.69	-38.5	-62.93	-43.02	-18.35	585341.3	585022.5	585018.3	584997

2. 1/8” Nozzle Diameter

Mass Flow (Kg/h)			
	50 PSI	75 PSI	100 PSI
Meter 1	2.020	4.095	11.231
Meter 2	3.253	5.653	7.587
Meter 3	6.529	8.875	3.380
Meter 4	1.920	2.838	6.686
Timestamp	2_23	2_57	9_60

Temperature (K)												
All Meters	Atmospheric Pressure:	29.94										
Timestamp	N1	ND	14	15	16	17	18	19	20	21	22	23
Tdata_20210602_1049_60	0	0	291.0798	291.5283	290.79	291.5795	290.8151	290.3928	291.5057	291.3244	291.4567	291.8475
Tdata_20210602_1052_57	0	0	291.0901	291.7669	290.8021	290.2806	290.4106	290.3335	291.4832	291.3611	291.6968	291.8322
Tdata_20210602_1102_23	0	0	291.1235	291.6564	291.1918	290.3942	290.8264	290.9608	291.4223	291.311	291.713	291.5428

Pressure (Pa)																		
All Meters	Atmospheric Pressure:	29.94																
Timestamp	N1	ND	3_01	3_02	3_03	3_04	3_05	3_06	3_07	3_08	3_09	3_10	3_11	3_12	3_13	3_14	3_15	3_16
Pdata_20210602_1049_60	0	0	-15.12	31.15	38.21	-3.84	318168.3	284727.9	26.84	-7.56	30.82	0	31.33	-3.67	291061.5	288139.4	285878.3	287729.7
Pdata_20210602_1052_57	0	0	15.12	35.05	53.49	-11.52	235459	204000.1	11.5	-3.78	26.97	7.41	27.41	7.34	205464.4	206808	211703.4	204770.9
Pdata_20210602_1102_23	0	0	-26.46	27.25	45.86	-3.84	127212.5	100753.1	15.34	-18.91	34.67	-7.4	31.33	-3.67	101505.3	102398.6	107224.1	101405.9

3. 3/16” Nozzle Diameter

Mass Flow (Kg/h)			
	50 PSI	75 PSI	100 PSI
Meter 1	3.319	4.227	10.19
Meter 2	5.614	6.995	7.954
Meter 3	5.752	6.356	5.915
Meter 4	1.83	5.992	7.216
Timestamp	6_02	3_59	0_46

Temperature (K)												
All Meters	Atmospheric Pressure:	30.16										
Timestamp	N1	ND	14	15	16	17	18	19	20	21	22	23
Tdata_20210408_0916_02	0	0	286.2205	286.3579	290.5882	290.4048	290.3317	290.2911	286.3274	286.3679	286.7599	286.6504
Tdata_20210408_0923_59	0	0	286.5988	286.9772	288.88	288.9156	288.907	289.2057	286.9804	286.1018	287.3548	287.2215
Tdata_20210408_0930_46	0	0	287.7584	288.1924	285.0822	285.296	284.914	284.1954	288.2784	288.0716	288.4436	288.5834

Pressure (Pa)																		
All Meters	Atmospheric Pressure:	30.16																
Timestamp	N1	ND	3_01	3_02	3_03	3_04	3_05	3_06	3_07	3_08	3_09	3_10	3_11	3_12	3_13	3_14	3_15	3_16
Pdata_20210408_0916_02	0	0	30.22	23.34	-3.81	-15.35	-999999	31695.86	0	-15.13	-23.08	-11.09	-39.1	-40.4	34069.02	36974.57	38788.01	33479.46
Pdata_20210408_0923_59	0	0	22.66	3.9	-22.89	-23.03	-999999	59370.22	0	-15.13	-3.85	-3.7	-19.56	-14.69	62367.39	66380.26	66686.04	66481.36
Pdata_20210408_0930_46	0	0	37.78	23.35	-7.63	0	-999999	90227.68	-22.98	3.78	-11.54	3.7	-35.2	-33.05	100081.1	97584.61	95935.13	97353.04

D. METER 1 HOT RUNS WITH CARBON DIOXIDE (DAQ SYSTEM)

1. 1/16” Nozzle Diameter

Mass Flow (Kg/h)			
	50 PSI	75 PSI	100 PSI
Meter 1	6.721	8.998	10.885
Meter 2	0.058	0.077	0.105
Meter 3	0.039	0.070	0.112
Meter 4	0.058	0.063	0.087
Timestamp	4_19	8_31	1_04

Temperature												
Meter 1	Atmospheric Pressure:	30.01										
Timestamp	N1	ND	14	15	16	17	18	19	20	21	22	23
Tdata_20210825_0924_19	46000	4800	804.8357	781.1196	294.9691	295.2077	295.1909	295.5647	380.8627	368.7415	392.128	630.1264
Tdata_20210825_0928_31	46000	4800	806.4003	784.3339	297.1812	297.3562	297.3093	297.771	393.1454	384.3398	446.1607	681.6951
Tdata_20210825_0931_04	46000	4800	805.9483	784.0555	298.4922	298.6349	298.545	298.4758	393.0564	385.6647	453.8676	688.2825

Pressure (Pa)																		
Meter 1	Atmospheric Pressure:	30.01																
Timestamp	N1	ND	3_01	3_02	3_03	3_04	3_05	3_06	3_07	3_08	3_09	3_10	3_11	3_12	3_13	3_14	3_15	3_16
Pdata_20210825_0924_19	46000	4800	-8298.15	-536.84	416216.3	403709.1	358523.6	354246.7	1685.23	1554.35	2121.62	1629.47	1565.26	1374.1	358420.2	354237.2	354314.9	354290.4
Pdata_20210825_0928_31	46000	4800	-8087.07	-544.62	415076.7	402413.1	541696	536966.8	1670.39	1524.65	2122.02	1588.58	1550.01	1359.41	541576.7	536966.4	537052.4	537016.9
Pdata_20210825_0931_04	46000	4800	-7958.06	-505.89	411623.2	399067.4	676247.2	670952.7	1673.88	1517.08	2079.3	1603.95	1511.04	1337.37	676074	670974.1	671026.1	670981.1

2. 1/8” Nozzle Diameter

Mass Flow (Kg/h)			
	50 PSI	75 PSI	100 PSI
Meter 1	15.179	21.539	27.437
Meter 2	0.020	0.042	0.060
Meter 3	0.019	0.047	0.076
Meter 4	0.030	0.028	0.051
Timestamp	7_10	2_42	5_51

Temperature (K)												
Meter 1	Atmospheric Pressure:	29.95										
Timestamp	N1	ND	14	15	16	17	18	19	20	21	22	23
Tdata_20210819_0917_10	46000	4800	807.6569	785.0954	297.5042	297.6211	297.6588	297.884	393.0676	382.3272	432.9535	674.6356
Tdata_20210819_0922_42	46000	4800	810.4243	787.0835	301.1011	301.2263	301.1052	298.917	395.4555	387.3421	458.5814	684.9091
Tdata_20210819_0925_51	46000	4800	811.3198	787.1875	302.3764	302.453	302.2938	298.2126	388.5821	385.676	460.2889	673.4508

Pressure (Pa)																		
Meter 1	Atmospheric Pressure:	29.95																
Timestamp	N1	ND	3_01	3_02	3_03	3_04	3_05	3_06	3_07	3_08	3_09	3_10	3_11	3_12	3_13	3_14	3_15	3_16
Pdata_20210819_0917_10	46000	4800	-8058.43	-536.84	411192.5	398506.2	212564.5	185884.1	1616.89	1490.61	2040.95	1603.96	1537.89	1395.74	211694.5	185855.6	185910.6	185908
Pdata_20210819_0922_42	46000	4800	-7786.79	-513.67	407708.6	395044.5	338148.6	306606.6	1601.58	1438.17	2056.23	1537.3	1479.75	1366.79	337030.5	306620.9	306648.9	306608.4
Pdata_20210819_0925_51	46000	4800	-7723.77	-525.17	403679.5	391338.8	451004.4	414324.5	1563.83	1452.85	1999.2	1578	1483.61	1384.7	449637	414365.2	414417.6	414385.1

3. 3/16” Nozzle Diameter

Mass Flow (Kg/h)			
	50 PSI	75 PSI	100 PSI
Meter 1	16.543	23.228	29.832
Meter 2	0.005	0.015	0.026
Meter 3	0.000	0.000	0.008
Meter 4	0.000	0.005	0.017
Timestamp	4_04	7_00	1_13

Temperature (K)												
Meter 1	Atmospheric Pressure:	29.76										
Timestamp	N1	ND	14	15	16	17	18	19	20	21	22	23
Tdata_20210827_0944_04	46000	4800	804.1649	780.7118	298.7973	299.1386	299.1549	298.1923	389.3445	379.197	487.6603	679.6973
Tdata_20210827_0947_00	46000	4800	806.472	782.0896	299.7235	300.066	300.0294	297.7378	391.1375	382.635	470.3052	676.3016
Tdata_20210827_0951_13	46000	4800	807.5683	783.043	302.7882	303.0971	303.0024	296.776	389.1003	383.4058	457.2963	658.4666

Pressure																		
Meter 1	Atmospheric Pressure:	29.76																
Timestamp	N1	ND	3_01	3_02	3_03	3_04	3_05	3_06	3_07	3_08	3_09	3_10	3_11	3_12	3_13	3_14	3_15	3_16
Pdata_20210827_0944_04	46000	4800	-7930.4	-486.43	406859	394568	109776.9	58138.22	1629.61	1480.36	1999.24	1608.29	1546.9	1420.98	108204.8	58142.8	58193.5	58186.42
Pdata_20210827_0947_00	46000	4800	-7869.92	-490.32	406359.7	394077.2	167453.9	100181.2	1637.27	1465.21	2033.91	1589.75	1535.15	1387.93	165294.6	100236.6	100268.4	100274.3
Pdata_20210827_0951_13	46000	4800	-7663.5	-502	401709.6	389353.4	232746	152279.3	1575.9	1427.33	1956.84	1560.08	1488.14	1395.26	229995.4	152369.6	152415	152418.5

E. METER 1 HOT RUNS WITH CARBON DIOXIDE (DAQ SYSTEM)

1. 1/16” Nozzle Diameter

Run 1

Mass Flow (Kg/h)			
	50 PSI	75 PSI	100 PSI
Meter 1	1.841	2.522	3.209
Meter 2	1.558	2.310	2.865
Meter 3	1.451	1.960	2.537
Meter 4	1.318	1.773	2.244
Timestamp	5_46	9_03	2_03

Temperature												
All Meter	Atmospheric Pressure:	30.01										
Timestamp	N1	ND	14	15	16	17	18	19	20	21	22	23
Tdata_20210825_0935_46	46000	4800	807.6829	782.1752	300.6985	301.1675	301.452	301.1678	407.7129	385.5512	596.2347	605.4305
Tdata_20210825_0939_03	46000	4800	808.2228	782.1407	301.33	301.8084	302.1757	301.9718	414.5509	392.9199	627.2332	615.7705
Tdata_20210825_0942_03	46000	4800	810.7752	783.5525	302.2646	302.6609	303.0864	303.0261	415.8544	396.7427	651.3819	626.8488

Pressure (Pa)																		
All Meters	Atmospheric Pressure:	30.01																
Timestamp	N1	ND	3_01	3_02	3_03	3_04	3_05	3_06	3_07	3_08	3_09	3_10	3_11	3_12	3_13	3_14	3_15	3_16
Pdata_20210825_0935_46	46000	4800	-8044.97	-521.38	414211.5	401746.2	349536.9	348843.2	1659.05	1536.02	2118.06	1607.18	1542.38	1377.8	349522	349478	349535.1	349511.8
Pdata_20210825_0939_03	46000	4800	-7945.56	-521.46	412919.4	400244.3	519790.9	519000.6	1682.05	1502.45	2098.59	1585.46	1530.64	1366.79	519749.8	519706.8	519769.2	519762
Pdata_20210825_0942_03	46000	4800	-7770.9	-521.32	408878.8	396511.4	672820.5	671932.2	1674.64	1494.79	2053.13	1596.59	1538.48	1336.96	672760.2	672733.3	672784.7	672770.1

Run 2

Mass Flow (Kg/h)			
	50 PSI	75 PSI	100 PSI
Meter 1	1.842	2.522	3.201
Meter 2	1.583	2.309	2.869
Meter 3	1.465	1.990	2.560
Meter 4	1.323	1.767	2.274
Timestamp	1_4A	6_23	8_28

Temperature (K)												
All Meter	Atmospheric Pressure:	29.87										
Timestamp	N1	ND	14	15	16	17	18	19	20	21	22	23
Tdata_20210820_0941_4A	46000	4800	807.0415	781.1411	301.9485	302.3215	302.6042	302.5016	405.7473	385.5401	596.0688	593.5143
Tdata_20210820_0936_23	46000	4800	806.5143	780.6717	302.9787	303.3457	303.7248	303.6991	410.0346	390.8397	627.1827	610.2016
Tdata_20210820_0938_28	46000	4800	808.1831	780.9305	303.3516	303.713	304.1258	304.1373	411.7357	395.5579	645.5102	619.2491

Pressure																		
All Meter	Atmospheric Pressure:	29.87																
Timestamp	N1	ND	3_01	3_02	3_03	3_04	3_05	3_06	3_07	3_08	3_09	3_10	3_11	3_12	3_13	3_14	3_15	3_16
Pdata_20210820_0941_4A	46000	4800	-7951.01	-529.061	408463.3	395896	351934.1	351288.1	1609.832	1528.476	2022.313	1585.474	1538.479	1414.086	351904.3	351895.9	351914.1	351901.9
Pdata_20210820_0936_23	46000	4800	-7794.35	-498.11	406305.8	393843	519036.3	518318.1	1632.84	1494.96	2006.2	1596.65	1522.83	1384.71	518965.4	518978.1	519010.8	518973.1
Pdata_20210820_0938_28	46000	4800	-7856.02	-505.89	410262.6	397840.7	670879.7	670088.7	1652.01	1502.53	2068.56	1578.24	1535.14	1396.21	670801.3	670827.2	670842.5	670832.7

2. 1/8” Nozzle Diameter

Mass Flow (Kg/h)			
	50 PSI	75 PSI	100 PSI
Meter 1	4.184	5.647	7.136
Meter 2	3.894	5.440	6.903
Meter 3	3.192	4.388	5.753
Meter 4	3.157	4.325	5.526
Timestamp	7_37	0_19	4_35

Temperature (K)												
All Meter	Atmospheric Pressure:	29.87										
Timestamp	N1	ND	14	15	16	17	18	19	20	21	22	23
Tdata_20210820_0917_37	46000	4800	805.5696	772.4248	294.5931	294.9408	295.1056	295.1653	393.8403	374.8162	616.4336	595.6884
Tdata_20210820_0920_19	46000	4800	807.7025	774.1744	295.9315	296.3712	296.6116	296.6719	406.2216	390.3387	662.3153	647.7464
Tdata_20210820_0924_35	46000	4800	812.5831	776.3767	297.3305	297.7439	298.0977	298.1402	406.6214	397.774	687.6582	680.4382

Pressure																		
All Meter	Atmospheric Pressure:	29.87																
Timestamp	N1	ND	3_01	3_02	3_03	3_04	3_05	3_06	3_07	3_08	3_09	3_10	3_11	3_12	3_13	3_14	3_15	3_16
Pdata_20210820_0917_37	46000	4800	-8369.95	-536.84	415690.3	403257.5	183154.9	179636.1	1639.63	1554.36	2075.43	1588.63	1561.35	1414.52	182986.1	183072.9	183119.1	183086.3
Pdata_20210820_0920_19	46000	4800	-8144.56	-548.51	411966.3	399485.5	305187	301199.4	1632.14	1517.02	2045.07	1596.04	1542.07	1381.45	304942.8	305072.9	305134.9	305099.6
Pdata_20210820_0924_35	46000	4800	-7868.92	-521.28	407594.2	394941.7	422464.1	418134	1605.39	1509.32	2010	1548.19	1530.07	1384.67	422249.2	422371.8	422413.9	422381.6

3. 3/16” Nozzle Diameter

Mass Flow (Kg/h)			
	50 PSI	75 PSI	100 PSI
Meter 1	4.651	6.185	7.990
Meter 2	4.318	5.953	7.832
Meter 3	3.517	4.785	6.319
Meter 4	3.474	4.763	6.204
Timestamp	5_12	8_39	0_33

Temperature (K)											
All Meters	Atmospheric Pressure:	29.76									
Timestamp	N1	ND	14	15	16	17	18	19	20	21	22	23
Tdata_20210827_0935_12	46000	4800	804.3104	768.4485	294.3029	294.626	294.7658	294.7705	390.0305	368.8876	620.9261	602.9912
Tdata_20210827_0938_39	46000	4800	806.7666	771.5559	295.1409	295.5414	295.74	295.7406	401.8938	384.5952	662.0632	648.0173
Tdata_20210827_0940_33	46000	4800	809.2754	771.2817	295.7184	296.1518	296.4012	296.4132	406.974	389.6653	682.7766	671.9709

Pressure																		
All Meters	Atmospheric Pressure:	29.76																
Timestamp	N1	ND	3_01	3_02	3_03	3_04	3_05	3_06	3_07	3_08	3_09	3_10	3_11	3_12	3_13	3_14	3_15	3_16
Pdata_20210827_0935_12	46000	4800	-8293.3	-486.43	413323.7	401017.6	62284.73	54792.71	1679.41	1510.46	2114.83	1626.83	1570.42	1439.36	61881.05	62099.68	62149.08	62118.83
Pdata_20210827_0938_39	46000	4800	-8123.2	-478.65	409664.3	397424.5	109618.4	100432.1	1660.3	1491.68	2091.71	1600.89	1566.5	1413.65	109072.6	109405	109424.7	109422.7
Pdata_20210827_0940_33	46000	4800	-8006.01	-470.87	407857.4	395369.2	171677.7	160938.5	1656.46	1484.16	2060.89	1608.3	1546.91	1409.97	171001	171422.8	171494.1	171459.5

APPENDIX H: SERIES HEAT EXCHANGER CALCULATIONS

A. CALCULATED VS. MEASURED MASS FLOW RATES- METER 4

1. 1/8” Nozzle Calculations

2. Mass Flow

Meter 4											
Total Pressure (Pa)	Recorded Pressure Brick Port 6 Gage Values (Pa)	Recorded Pressure Brick Atmospheric Values (Pa)	Diameter exit (in)	Diameter exit (m)	Area exit (m^2)	Mach Number (M)	Choked Flow? (M > 1)	Calculated Mass Flow Rate (Kg/s)	Calculated Mass Flow Rate (Kg/h)	Recorded Flow Meter Mass Flow Rate (Kg/h)	Error (%)
344738 (50 psi)	153160.32	255056.75	1/8	0.003175	7.9173E-06	1.26	Yes	0.004110632	14.798274	12.722	16.32458476
517107 (75 psi)	262842.79	364739.22	1/8	0.003175	7.9173E-06	1.51	Yes	0.005703432	20.53235342	18.523	10.84602309
689476 (100 psi)	363628.16	465524.59	1/8	0.003175	7.9173E-06	1.68	Yes	0.007282041	26.21534861	25.339	3.456461034

3. Efficiency

METER 4																				
Pressure (psi)	Mass Flow Rate (kg/s)	4in Coil Tube Diameter (m) *(3/8 inch diam. tubing)*	4in Coil Tube Length (m) *(6 foot tubing)*	Area (m^2)	Calculated Velocity (m/s)	Dynamic Viscosity (N-s/m^2)	Calculated Reynolds No. (-)	Turbulent Condition? (Re > 10000)	Pr	Nu Laminar Flow	Nu Turbulent	Nu Approx.	Thermal Conductivity (W/mK)	Heat Transfer Coefficient	Delta T_o	Delta T_i	Delta T_lm	q	Effectiveness NTU
50	0.00353	0.009525	17.698	7.12557E-05	32.7193	2.181E-05	21658.41	YES	0.734	3.66	59.773334	59.773	0.0292	183.24214	488.3426	233.0703	345.1132	841.731	0.52680318
75	0.00515	0.009525	17.698	7.12557E-05	48.0342	2.219E-05	30995.88	YES	0.727	3.66	79.320375	79.32	0.0299	248.99519	492.1025	191.8055	318.7172	1440.06	0.61382456
100	0.00704	0.009525	17.698	7.12557E-05	65.85434	0.0000224	42004.19	YES	0.727	3.66	101.15229	101.15	0.0303	321.77578	490.8039	191.7096	318.1641	1972.04	0.6141925
Overall Heat Transfer Coef	***Patm (Pa***	***Dexh***	***A_exh***	***m_dot_exh***	***Pho_inf***	***U_inf***	***Di***	***Do***	***Re_Exh***	***Nu***	***hexh***	***Rconv Gas***	***Rcond Steel***	***Rconv Exhaust***	***Rtot***	***UA***	***13. Heat Transfer***	***qmax***	***Effectiveness q/qmax***
50	100779	0.356	0.0995	0.7085	0.440923	16.143116	0.00762	0.009525	1832	20.193	1214.7584	0.0129	0.00013468	0.0015544	0.01457	68.63345	23686.31	1597.81	0.52680318
75	100779	0.356	0.0995	0.7085	0.444406	16.016577	0.00762	0.009525	1832	20.193	1214.7584	0.0095	0.00013468	0.0015544	0.011169	89.53662	28536.86	2346.04	0.61382456
100	100779	0.356	0.0995	0.7085	0.444406	16.016577	0.00762	0.009525	1832	20.193	1214.7584	0.0073	0.00013468	0.0015544	0.009025	110.8094	35255.58	3210.79	0.6141925

B. METER 4 HOT RUNS WITH CARBON DIOXIDE THROUGH SERIES HEAT EXCHANGER (DAQ SYSTEM) RAW DATA

1. 1/8” Nozzle Diameter

Mass Flow (Kg/h)			
	50 PSI	75 PSI	100 PSI
Meter 1	0.036	0.032	0.060
Meter 2	0.038	0.058	0.080
Meter 3	0.026	0.040	0.074
Meter 4	12.722	18.523	25.339
Timestamp	9_26	5_01	3_57

Temperature (K)																				
Meter 4	Atmospheric Pressure:	30.09																		
Timestamp	N1	ND	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Tdata_20211008_0919_26	46000	4800	786.5605	791.9057	819.5996	2566.637	919.4514	2566.364	2566.364	816.4616	807.9493	785.8048	294.1531	295.4169	295.4343	295.0009	388.8385	420.5776	383.8265	600.1961
Tdata_20211008_0925_01	46000	4800	787.0981	792.435	820.1862	2566.706	1156.611	2566.43	2566.43	817.0525	809.1872	787.8578	294.1322	296.3686	296.394	295.7553	395.5548	443.8405	410.864	600.6295
Tdata_20211008_0953_57	46000	4800	792.9136	798.4897	826.6847	2567.605	1024.674	2567.305	2567.305	822.0789	815.1209	794.2882	304.0363	307.445	307.1442	305.9456	417.5974	459.5227	426.8464	565.4194

Pressure (Pa)																		
Meter 4	Atmospheric Pressure:	30.09																
Timestamp	N1	ND	3_01	3_02	3_03	3_04	3_05	3_06	3_07	3_08	3_09	3_10	3_11	3_12	3_13	3_14	3_15	3_16
Pdata_20211008_0919_26	46000	4800	-8296.82	-509.78	417958.6	405535	530608	363628.2	1678.28	1536.57	2141.03	1596.41	1561.9	1392.32	-47.29	-53.09	529941.7	-15.15
Pdata_20211008_0925_01	46000	4800	-8200.16	-517.39	418225.5	405725	398533.8	262842.8	1686.48	1566.31	2157.13	1622.51	1612.85	1414.08	-43.34	-26.55	398039.5	-3.79
Pdata_20211008_0953_57	46000	4800	-7792.76	-466.97	411590	398942.4	259717.6	153160.3	1656.42	1499.27	2103.22	1560.09	1554.72	1398.93	-51.23	-49.3	259337.6	-22.73

APPENDIX I: COMPRESSOR MAPPING/CFX RESULTS

A. CFX RESULTS

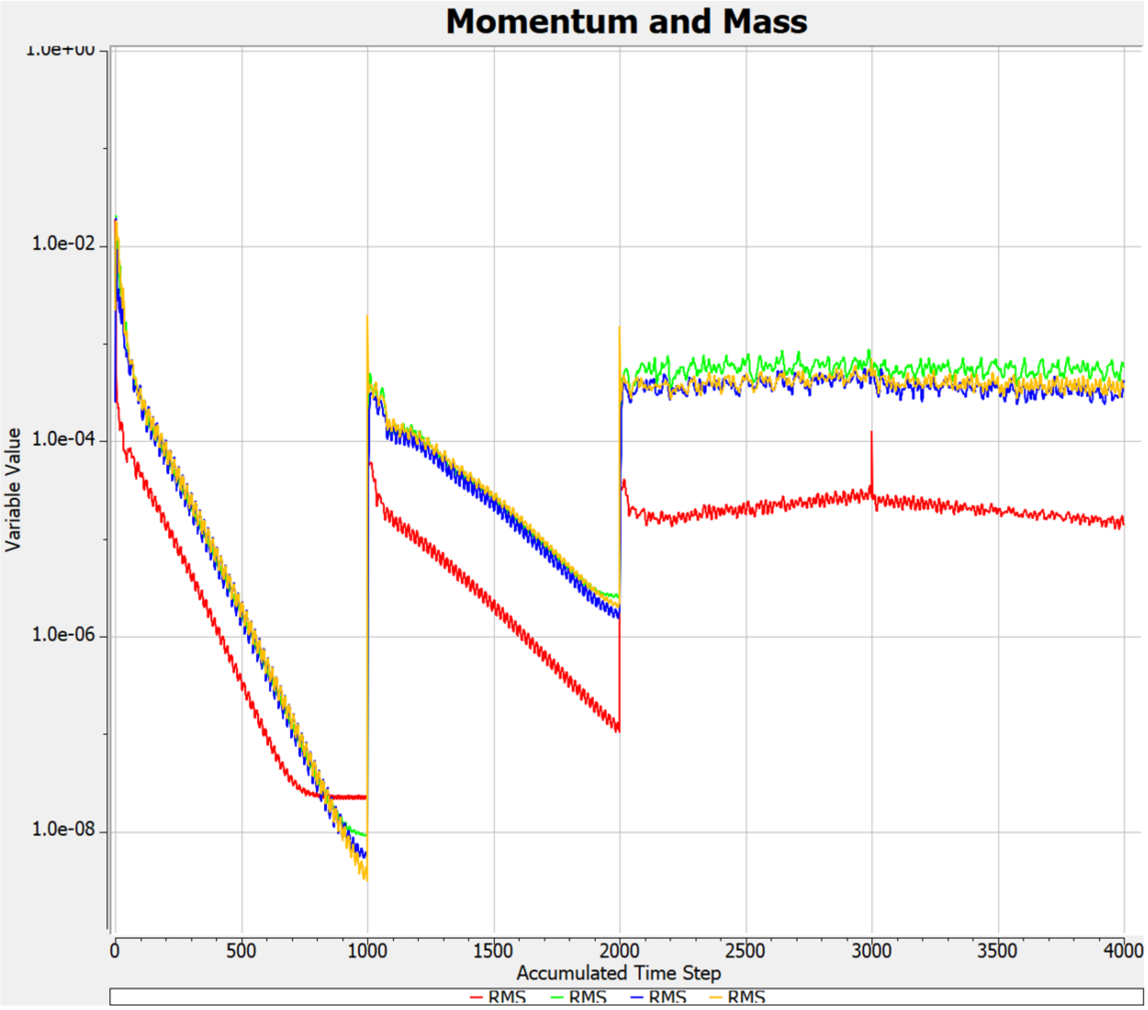


Figure 35. Momentum and Mass RMS Residuals (50,000 RPM)

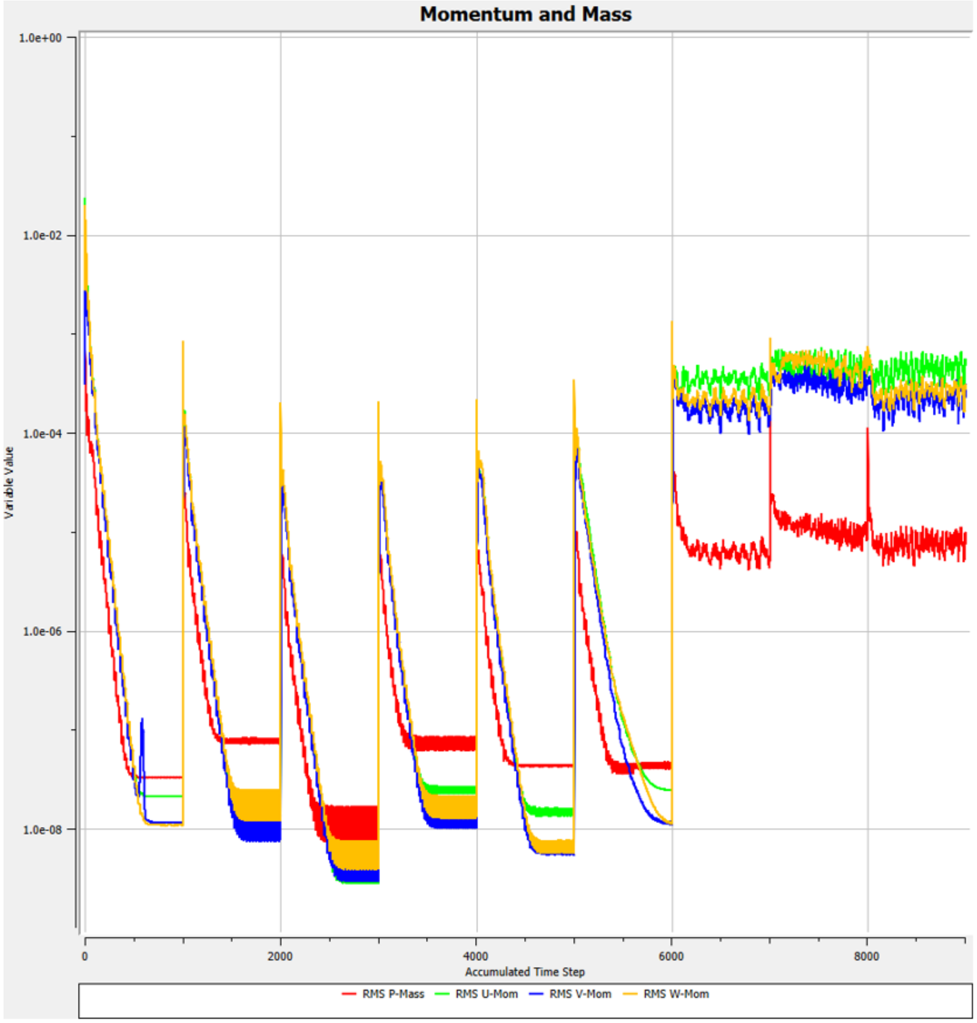


Figure 36. Momentum and Mass RMS Residuals (75,000 RPM)

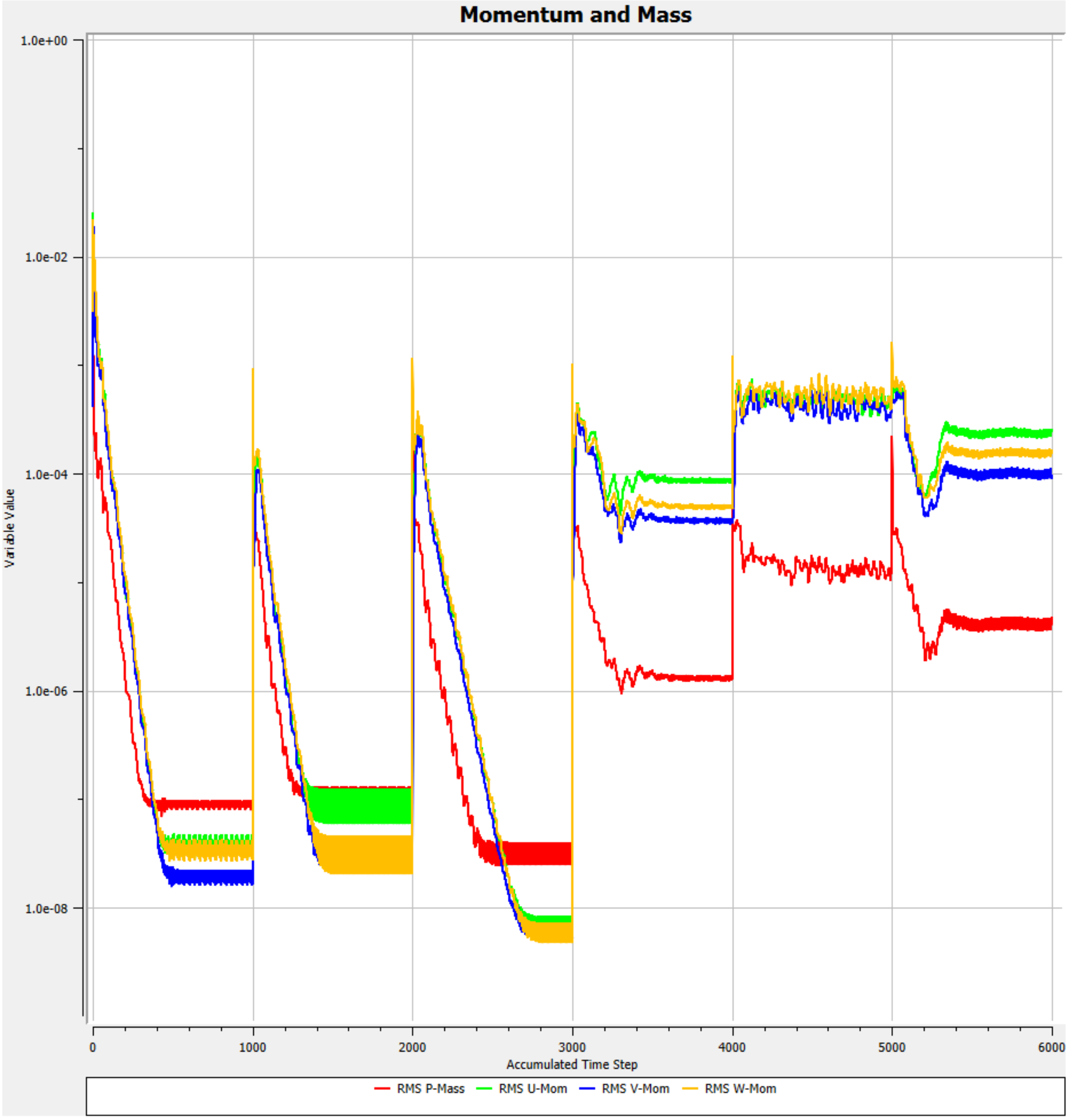


Figure 37. Momentum and Mass RMS Residuals (100,000 RPM)

B. CFX CALCULATIONS

COMPRESSOR PERFORMANCE-50000 RPM DATA				
OutletBackPres[atm]	mdot_in [kg s^-1]	mdot_out [kg s^-1]	mdot_delta (%)	total to total pressure ratio
0.075	0.0267842	-0.029898	-11.62551056	1.090042075
0.068	0.0331325	-0.031336	5.422168566	1.086437105
0.06	0.0354151	-0.0353847	0.085839091	1.082589144
0.055	0.0373799	-0.0373864	-0.017389025	1.081737415
0.05	0.0390977	-0.039096	0.004348082	1.078338289
0	0.0524069	-0.052407	-0.000190815	1.054696917
OutletBackPres[atm]	total to total temp ratio	Total-to-total isen. efficiency	Torque (all blades)kg m^2 s^-2	Power (all blades)kg m^2 s^-3
0.075	1.033887865	73.5932	0.0510585	267.342
0.068	1.032673386	79.1465	0.0580779	304.095
0.06	1.032230048	71.1512	0.0623377	326.4
0.055	1.031812087	71.3628	0.0648482	339.545
0.05	1.03140877	69.3524	0.0669242	350.414
0	1.027781363	55.1867	0.0788972	413.105
COMPRESSOR PERFORMANCE-75000 RPM DATA				
OutletBackPres[atm]	mdot_in [kg s^-1]	mdot_out [kg s^-1]	mdot_delta (%)	total to total pressure ratio
0.18	0.0406572	-0.040768	-0.272522456	1.20827347
0.165	0.047088	-0.0471029	-0.031642881	1.205308484
0.15	0.0508393	-0.0508485	-0.018096237	1.196556507
0.095	0.0642735	-0.0642735	0	1.171799553
0.08	0.0669911	-0.0669911	0	1.164896208
0.07	0.0687979	-0.0687979	0	1.16060782
0.06	0.0704921	-0.0704921	0	1.156213113
0.05	0.0720879	-0.0720879	0	1.151731657
0	0.0787139	-0.0787139	0	1.127635309
OutletBackPres[atm]	total to total temp ratio	Total-to-total isen. efficiency	Torque (all blades)kg m^2 s^-2	Power (all blades)kg m^2 s^-3
0.18	1.076902815	72.2243	0.116961	918.613
0.165	1.074866443	73.1996	0.129853	1019.86
0.15	1.073451366	70.7415	0.13704	1076.31
0.095	1.069053609	67.1057	0.161951	1271.96
0.08	1.068038745	65.5127	0.166211	1300
0.07	1.067378258	64.522	0.168959	1327
0.06	1.0667318	63.4531	0.1714	1346.18
0.05	1.066132095	62.2807	0.173649	1363.83
0	1.063164551	55.2786	0.180841	1420.32
COMPRESSOR PERFORMANCE-100,000 RPM DATA				
OutletBackPres[atm]	mdot_in [kg s^-1]	mdot_out [kg s^-1]	mdot_delta (%)	total to total pressure ratio
0.35	0.0460195	-0.0462137	-0.421995024	1.389587993
0.03	0.063365	-0.063359	0.00946895	1.370258948
0.275	0.06956	-0.069562	-0.002875216	1.35757135
0.2	0.0840131	-0.0840131	0	1.326002366
0.1	0.0962554	-0.096255	0.000415561	1.28191178
0	0.104117	-0.104117	0	1.233600935
OutletBackPres[atm]	total to total temp ratio	Total-to-total isen. efficiency	Torque (all blades)kg m^2 s^-2	Power (all blades)kg m^2 s^-3
0.35	1.140939174	69.9323	0.750389	7858.06
0.03	1.1326432	70.9981	0.233311	2443.22
0.28	1.130213767	70.0924	0.250404	2622.22
0.2	1.124715796	67.3199	0.288292	3018.99
0.1	1.119016122	61.7866	0.314616	3294.65
0	1.114146318	54.1564	0.326059	3414.48
Red	Large Error-Indications of Stalled Contions			
Green	Optimal Mass Flow			

C. COMPRESSOR MAPS

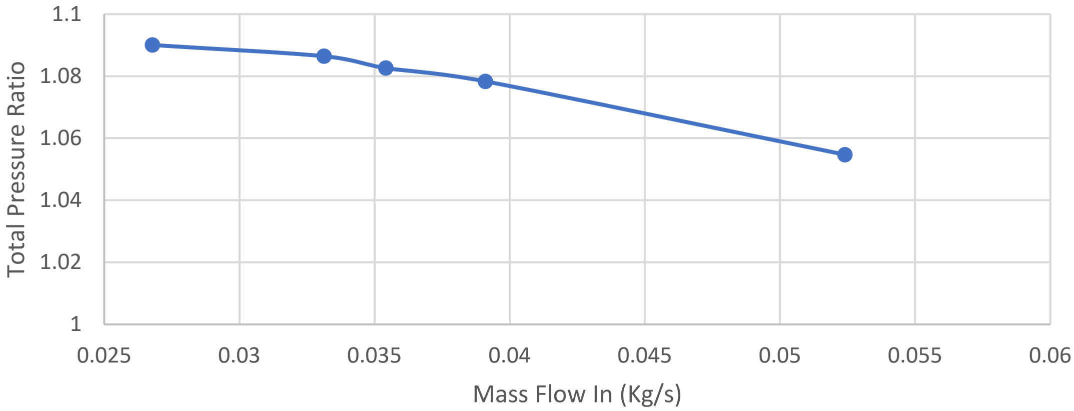


Figure 38. Total pressure Ratio vs. Mass Flow (50,0000 RPM)

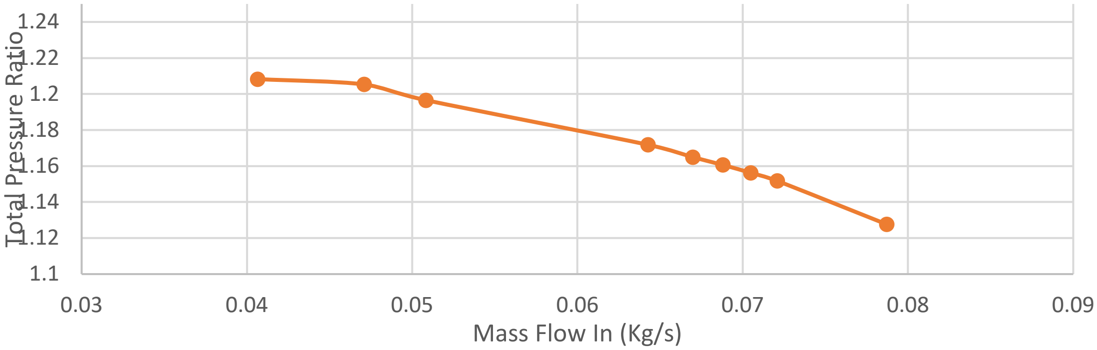


Figure 39. Total pressure Ratio vs. Mass Flow (75,0000 RPM)

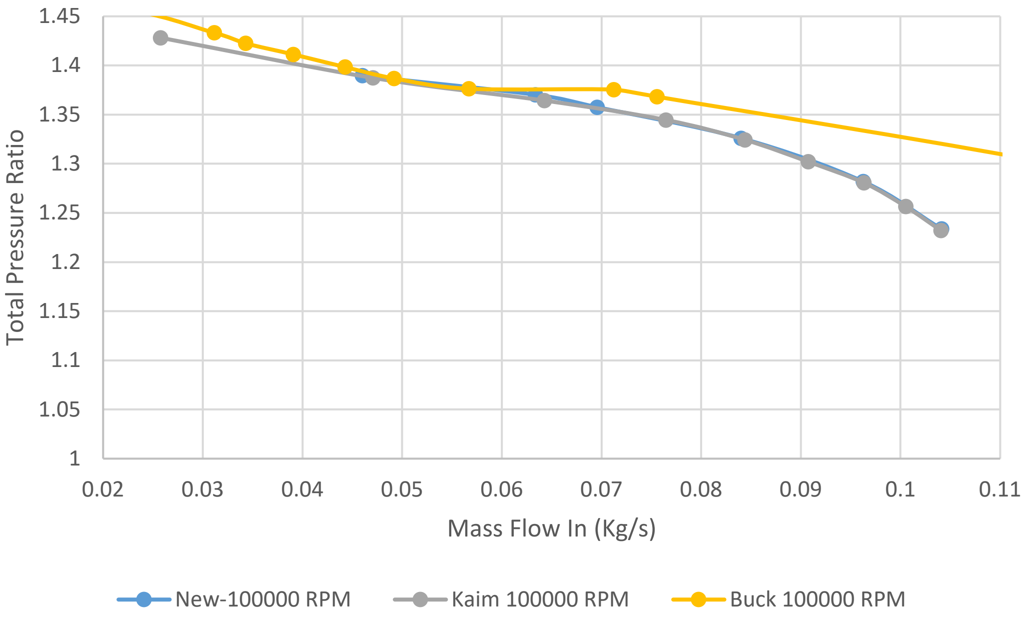


Figure 40. Total pressure Ratio vs. Mass Flow Comparisons (100,0000 RPM)

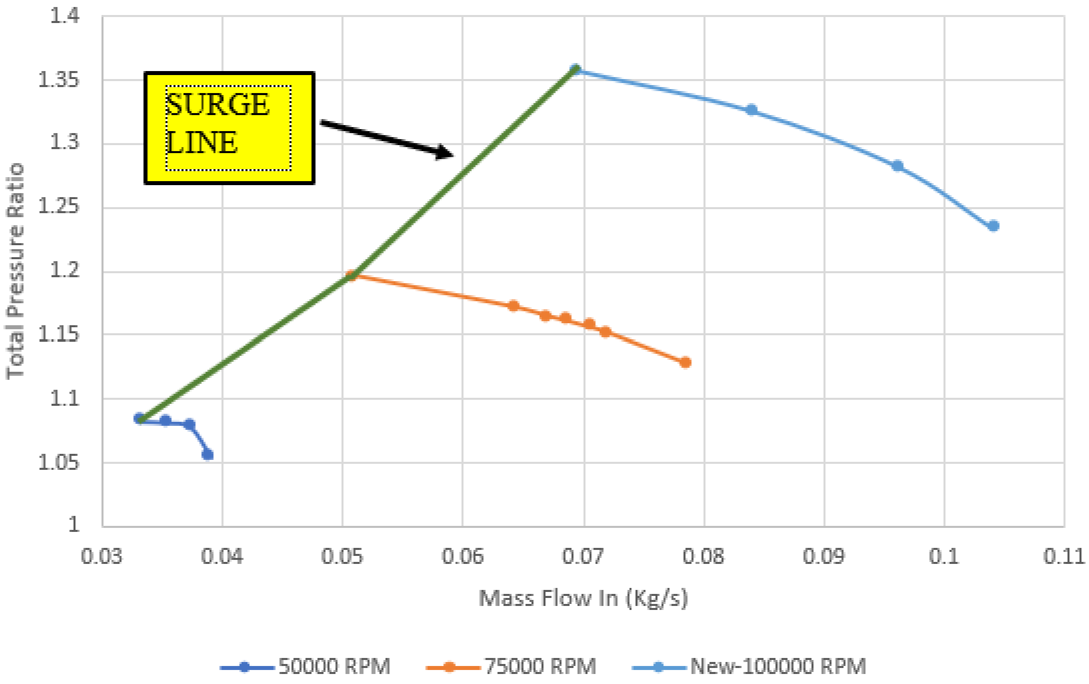


Figure 41. Total pressure Ratio vs. Mass Flow Combined Map

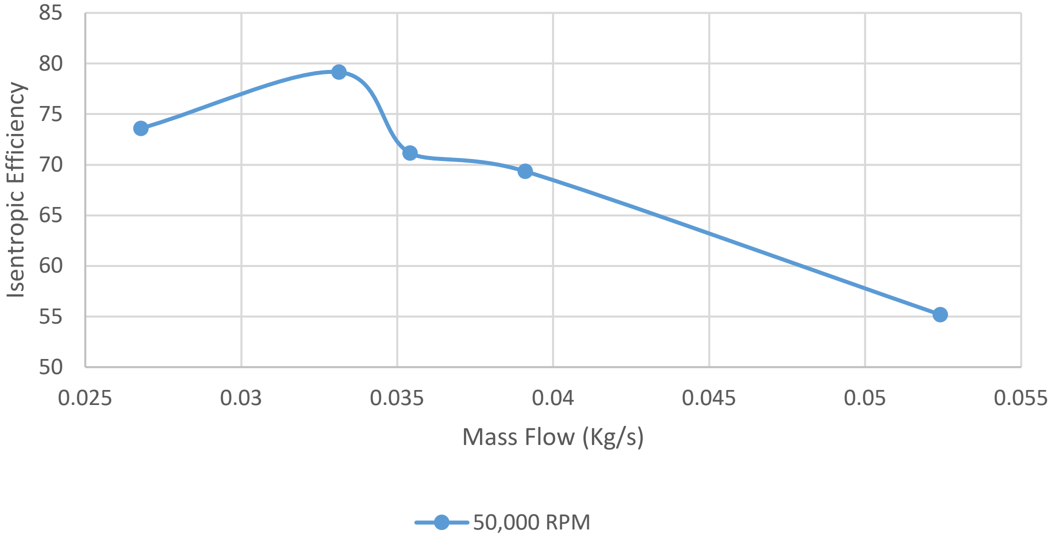


Figure 42. Total to Total Efficiency vs. Mass Flow (50,000 RPM)

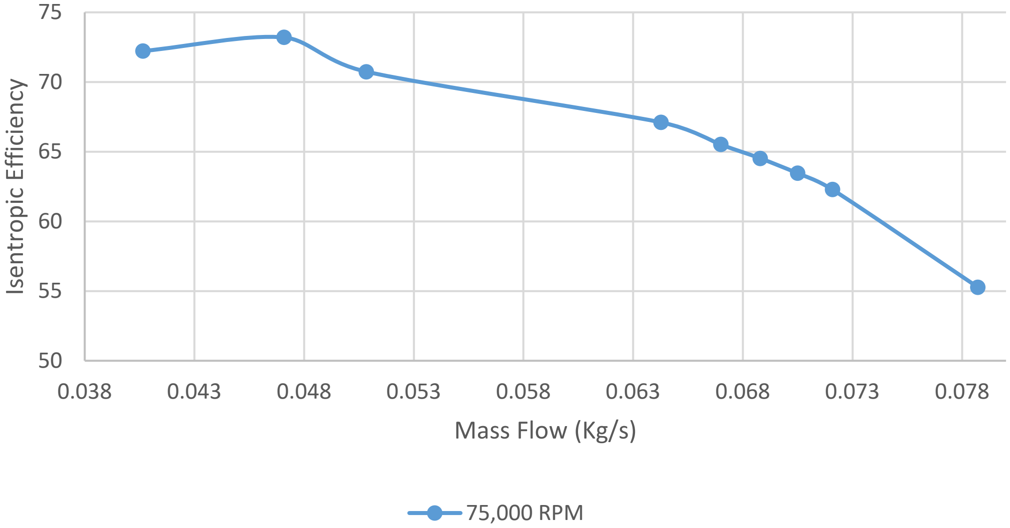


Figure 43. Total to Total Efficiency vs. Mass Flow (75,000 RPM)

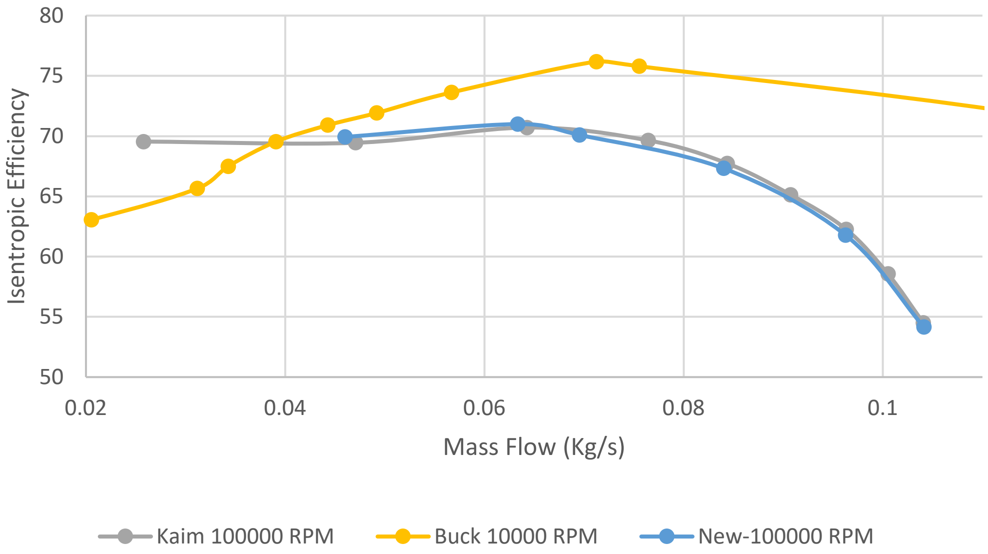


Figure 44. Total to Total Efficiency vs. Mass Flow Comparison (100,000 RPM)

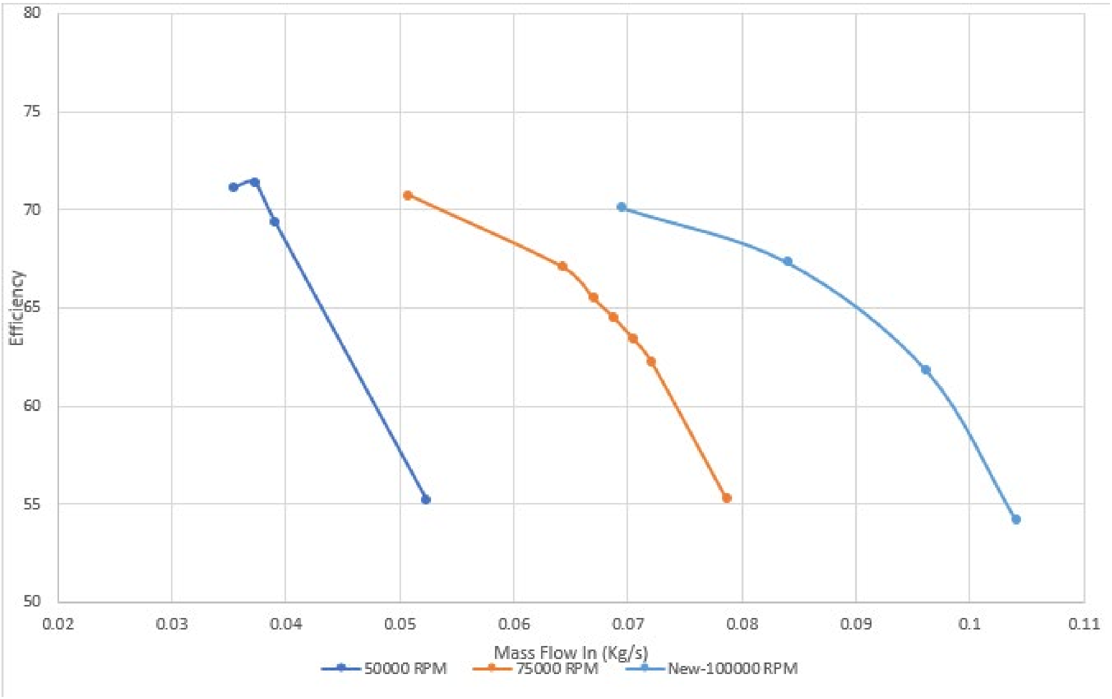


Figure 45. Total to Total Efficiency vs. Mass Flow Combined Map

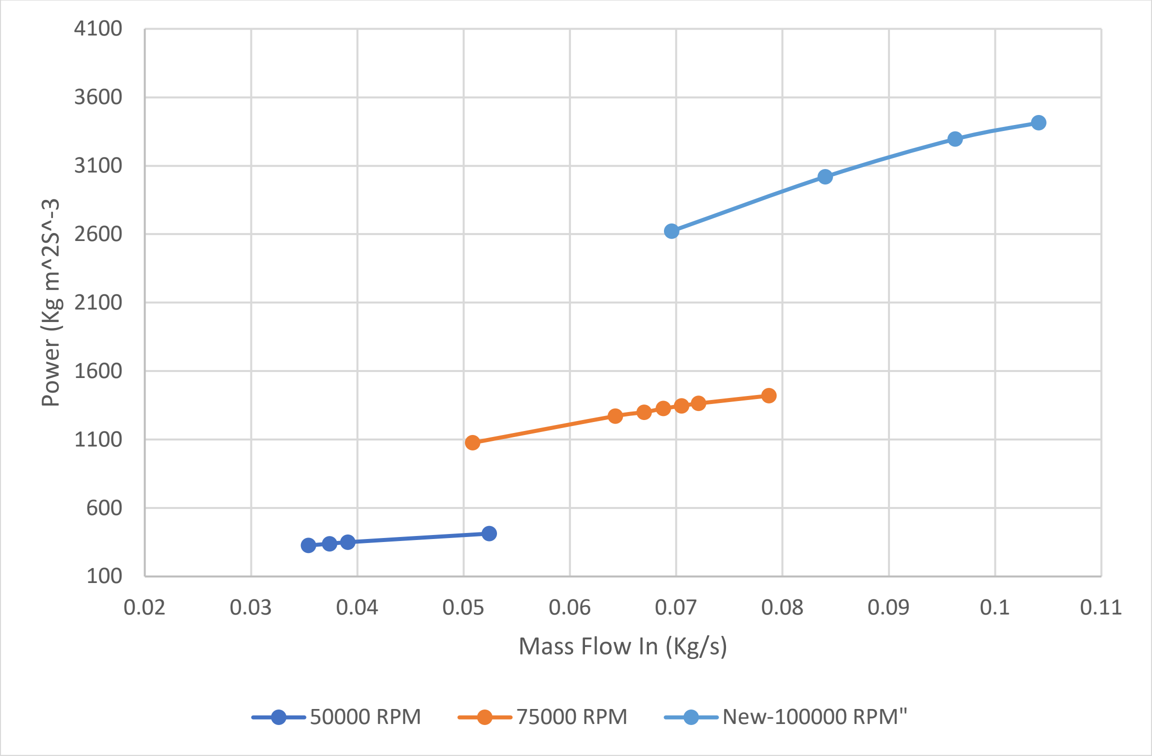


Figure 46. Power vs. Mass Flow Combined Map

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