Term Project : Temperature Distribution inside Hydrogen Storage Tank

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Abstract

The technical challenges of bringing compressed hydrogen fueling systems to market lie in the storage systems and re-fueling dispensers. With new high pressure tanks becoming available the methods for safely determining max capacity require intimate knowledge of the internal temperature distribution during the fill. The main problem is the requirement for a discrete measurement at every spacial point inside is costly and difficult. Modeling provides a relatively cheap alternative to measurements and can very powerful when used in parallel with experimental measurements. As part of the experimental characterization using an internal sensor array a CFD model will be built and validated. The model will use the experimental conditions as initial parameters and time varying measurements like pressure and inlet temperature for time dependent boundary and inflow conditions. Once validated the model will be used to further explore and confirm the best location to place a feedback thermal sensor that will guarantee the tank is accurately filled safely. Specifically this report proposes experimental methods and procedures for gathering the data necessary for model validation.

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Nomenclature

μ_{JT}	Joule-Thompson Coefficient
ρ	Density kg/m^3
C_P	Pressure Coefficient
m	Mass kg
P	Specific Pressure
p	Pressure MPa
R	Ideal gas constant
T	Temperature K
V	Volume m^3
v	Velocity m/s

1. INTRODUCTION

A Hydrogen has long been in consideration as of the top ecological replacements to gasoline fueled internal combustion engines. Having water as the byproduct burning pure hydrogen produces zero emissions. Although finding pure hydrogen is rare in the earths crust it can be access from many other abundant chemicals via electrolysis or reforming methods. Having a high specific energy density of 39 kWh/kg and only water production as emissions hydrogen fuel could provide an effective alternative. However gaseous hydrogen has a low volumetric energy density 3.5 kWh/m^3 at standard temperatures and conditions making it difficult to store effectively and efficiently.

2. BACKGROUND

2.1. STORAGE SATES

The two prevailing states for storing are in compressed gaseous and cryogenic liquid states, however both methods still present a number technical challenges that need to be overcome before the technology can be successfully implemented into modern transportation infrastructures.

The technical challenges of bringing compressed hydrogen fueling systems to market lie in the storage systems and re-fueling dispensers. At first glance the liquid form seems to be the ideal solution. Having a very high specific and volumetric energy density it can expanded into a gas easily for combustion. The two challenges that are faced with liquid hydrogen are the process for obtaining a liquid state and the measures for preserving that state. Acquiring liquid hydrogen requires various throttling and cool down methods to bring the hydrogen to a low enough temperatures to liquefy. To exist as a liquid the H2 must be cooled below hydrogen's critical point of 33 K and in order to maintain a fully liquid state without boiling at atmospheric pressure needs to be cooled further to 20.28 K. Maintaining the temperatures requires cryogenic storage technology such as thermally insulated containers and requires special handling procedures common to all cryogenic fuels. However even with thermally insulated containers it is difficult to keep such a low temperature, and the hydrogen will gradually leak away usually at a rate of about 1% per day. These technical challenges will require additional expensive and complex systems, which makes liquid hydrogen less ideal as an energy carrier. Gaseous Hydrogen can be compressed and stored in high pressure tanks. Because the hydrogen is at ambient temperatures and in gaseous form there no boiloff risk, which makes its suitable for storage in confined spaces (Like a parking garage). Using gaseous hydrogen however requires significant compression of the gas in order to obtain a viable volumetric energy density +700 bar. In order to obtain these pressures while conforming to certain safety standards special high pressure vessels are required. Type 3 and 4 are typically used for high compression systems 350-700 bar. At these higher pressures the volumetric energy density of hydrogen is found to be 1500 kWh/m^3, which is significantly higher than hydrogen under normal standard conditions, however still does not compare to gasoline fuels which are around 9000 kWh/m^3.

(a)

(b)

Figure 2.1: Compressed Gaseous system (a) vs Liquid hydrogen system (b)

This is offset by hydrogen's high specific energy density and zero emissions. Another technical aspect lies in the behavior of hydrogen under fast filling conditions. In order for the technology to be successful it needs to be as good or better than current technologies. This means the refueling process needs to be as fast or faster than typical gasoline pump times. Compressing or transferring hydrogen into vehicle tanks at these pressures produces significant heat and ultimately limits the attainable fill rates. Additionally the quality of the fill is related to the temperature gain of the hydrogen during transfers. As the hydrogen cools the pressure decreases subsequently causing the tank to become partially filled.

2.2. Tank Types for Gaseous Hydrogen

Pressurized Gaseous Hydrogen can be stored on board vehicles using compressed gas method. This method of storage is the simplest and most cost effective technology for hydrogen storage as it requires little supporting systems for maintenance. The gas undergoes compression at a fueling station and dispensed into the on-board tank of the vehicle. There exists 4 types of tanks used to safely store compressed hydrogen. These types are labeled as type 1,2,3 and 4. Figure 2.2 displays a simple diagram of a type 4 high pressure tank used for hydrogen storage.

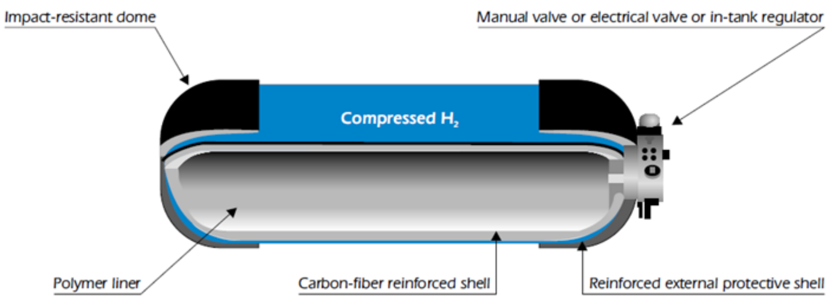

Figure 2.2: Diagram of a hydrogen type 4 storage system

Type 1 is a basic metal tank while type is a metal tank with a fiber wrapping. These are typical of lower pressure systems (sub 300 bar) and have significantly lower performance factors due to their relatively high weight and lower capacities. Type 3 tank is a metal liner with full reinforcing fiber wrapping, while type 4 is the same as type 3 but instead with a polymer liner. These tanks are described as having a very high performance factor, attributed to their design which maximizes volume and pressure while reducing tank construction weight. Currently, majority of demonstration and prototype vehicles employ cylinders capable of storing hydrogen up to 350 bar, while new lightweight composite type 3 and type 4 gas cylinders have been developed to withstand pressures up to 800 bar. Due to these new advances new data is required to understand the challenges with filling these tanks at safe reasonable rates.

2.3. FUELING

Generally the tanks design for fuel storage will not contain any pumps or systems to maintain pressure. Therefore the hydrogen will need to be filled to rated pressure and capacity from an external source. Much like petrol stations hydrogen can be obtain through dispensers and stations in which high-pressure gas is moved from a large station reservoir into the smaller vehicle cylinder. Figure 2.3 displays the general layout for a hydrogen dispenser. Generally the main storage tanks (supply source) will be keep the hydrogen at a lower pressure which will be compressed into buffer tanks when required. The buffer tanks allow the compressed hydrogen to remain cool and provide varying levels of pressure for efficient filling. To avoid overheating hydrogen the buffer tanks will be accessed in ascending orders of pressure. This stepping method reduces the heat and improves efficiency of the dispenser. The rate of gas transfer and safety of filling are controlled by the station dispenser. As the temperature of the gas cools to ambient the pressure also decreases such that the cylinder is no longer filled to design capacity. This is generally termed as under filling. In order to avoid this situation cylinders are filled to rated mass, which due to the temperature increase results in the cylinder being filled beyond the rated service pressure.

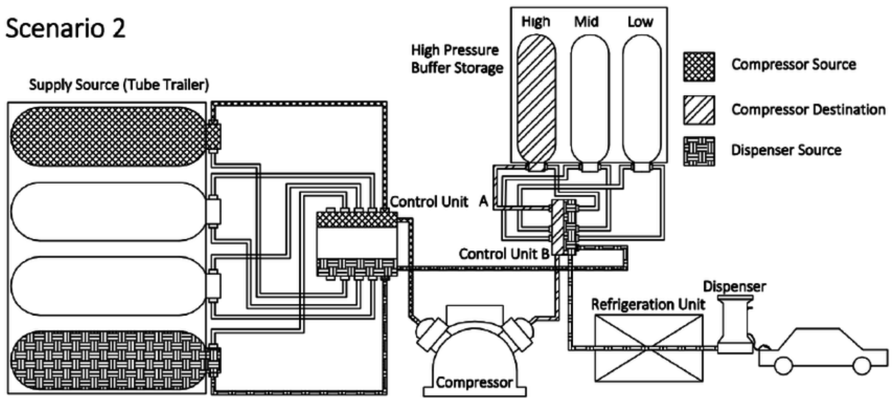

Figure 2.3: Simple Diagram of a hydrogen refueling station

The goal of the dispenser is to fill the cylinder to the rated mass of gas without exceeding the pressure and temperature limits of the cylinder. In order to complete the filling, the dispenser must employ a method for calculating the mass of gas present inside the cylinder. Generally a flow-rate measurement and a pressure measurement will be used to estimate the total mass transferred during the fill. The metering systems for safety will need to know the values of pressure and temperature to a high accuracy and typically will have some way of receiving data from built in sensors on the vehicle tank. In order for this to be possible the temperature and pressure of the gas inside the tank need to be well characterized. With this known the location of the pressure and temperature sensors can be place appropriately as too best represent the state of the gas through out the entire tank. When the sensors are well placed they will best represent accurately the mass of hydrogen moved and allow the dispenser to know when to terminate.

3. THEORY

3.1. GAS HEATING

During the fill process is a significant increase in gas temperature can be seen. The temperature rise during filling is the result of the combination of two dominating phenomena; Joule-Thompson effect and standard gas compression. In thermodynamics the Joule-Thomson effect is a process in which a gas or liquid is forced through a valve or porous plug and as a result experience a temperature change. Generally most gases at room temperature cool upon expansion by the Joule-Thomson process. However a couple gases like hydrogen, helium and neon will heat when throttled. This is because their Joule-Thomson coefficient is negative corresponding to a heating effect during a free expansion. The coefficient is a function of temperature and pressure under isenthalpic conditions as shown in equation 3.2

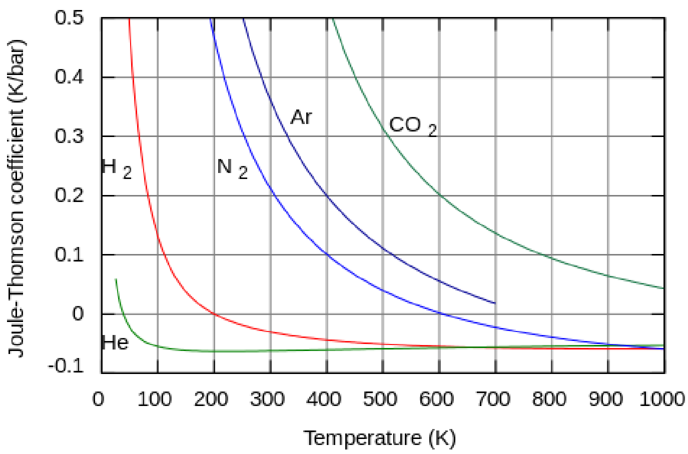

Figure 3.1: Joule-Thompson Coefficients for different gases

Similarly gas and liquids with positive coefficients will be cooled. It should be noted this coefficient is dependent on the state of the gas and therefore exists a point were the sign can flip which is known as the inversion temperature. Hydrogen has a negative Joule-Thomson coefficient at the temperatures and pressures of filling. Therefore when the gas experiences an isenthalpic expansion from the high-pressure tank through the dispenser throttling device into the low-pressure cylinder its temperature will increase. It is important to note that the isenthalpic expansion occurs within the dispenser which results in a higher gas temperature entering the cylinder. Figure 3.1 displays how the effect of temperature on the Joule-Thompson coefficient of a gas.

$$p = \frac{RT}{V_m - b} - \frac{a}{\sqrt{T} V_m (V_m + b)} \tag{3.1}$$

$$\mu_{JT} = \left(\frac{\partial T}{\partial P}\right)_H \tag{3.2}$$

The second phenomenon that causes a temperature rise during filling is the actual compression of the gas inside the cylinder. At the start of filling the gas is compressed by the introduction of the higher-pressure gas from the fueling station. This is repeated throughout the fill as the new gas moving into the cylinder compresses the gas currently in the cylinder. When a gas is compressed generally it will experience a temperature increase as is seen in the Redlich-Kwong model equation 3.1 for an real gas. The increase in temperature is often referred to as the heat of compression [Dicken, 2006].

3.2. MODELLING

The main problem with measuring the temperature distribution in all aspects of the tank is the requirement for a discrete measurement at every spacial point inside. This in practice is nearly impossible for both reasons of cost and invasive action of the process. Modeling provides a relatively cheap alternative to measurements and can very powerful when used in parallel with experimental measurements. As part of the characterization of this process a CFD model will be built and validated using the ANSYS workbench and Fluent. Fluent is a Computation Fluid Dynamics program which uses primarily finite volume methods to calculate numerical solutions to fluid domain problems. In order to describe the problem a spacial domain will need to be define. Fluent does this by generating a geometrical mesh to match the exact dimensions of the tank and fluid domain volume. Once this has been generated a user defined library will have to be added as fluent does not include default libraries for real gas calculations for hydrogen gas. A Redlich-Kwong real gas model will be implement via a user define function (UDF). A UDF can also be created and used to simulate time depend boundary conditions. The Boundary and initial conditions will have to be experimentally recorded along with the data for a fast fill run. The model will use the experimental conditions as initial parameters and time varying measurements like pressure and inlet temperature for time dependent boundary and inflow conditions.

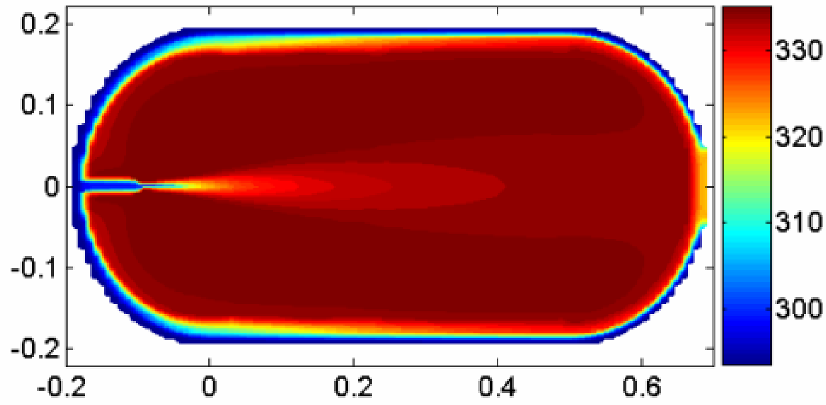

Figure 3.2: Displays model of temperature distribution inside 350bar tank [Dicken, 2006]

Once all the necessary parameters have been set for the model its results will be compared against the actual experimental results. If the average deviation between the model and experiment is below a certain standard the model can be used to accurately predict temperature for all points through-out the tank. If the error is too large the underlying physics of the model will have to be re-evaluated until acceptable error is reached. Figure **??** displays an example of a model evaluated for temperature during a 350 bar tank fill.

3.3. TEMPERATURE

The final results of the model is a temperature distribution inside the tank, therefore temperature will need to be measured at key locations inside the tank to validate model. Temperature is hard to measure directly and its usually easy to measure another phenomenon closely associated with it. A thermocouple is an electrical device consisting of two or more conductors of differing material which in turn form electrical junctions at differing temperatures. At the atomic scale, an applied temperature gradient across a conductor causes charge carriers in the material to diffuse from the hot side to the cold side. Therefore the device produces a temperature-dependent voltage as a result of the thermoelectric effect. This voltage can be interpreted and calibrated to measure temperature. A thermocouple is displayed in figure 3.3

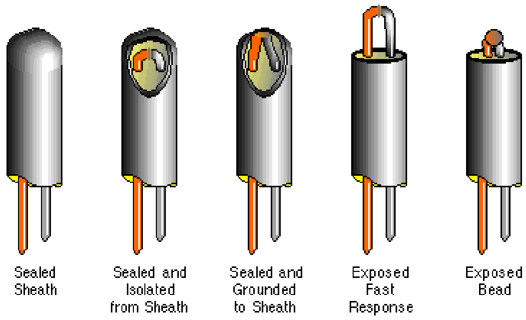

Figure 3.3: Different thermocoupler ends

3.4. Mechanical Force

Pressure is another property that is hard to directly measure. Fortunately pressure can apply a mechanical force to an object causing displacement over time which is something relatively easy to measure directly. Diaphragm transducers use a diaphragm to make a relative measurement between two pressure sources. When the sources are of equal pressure then equal force is applied to both side of diaphragm keeping it stationary and undeformed. If one source were greater than the older the diagram will have unbalance forces acting on it causing it to deform slightly. This deformation can be measured using strain gauges or capacitance sensors and thus provides a means of turning mechanic force into an electric signal which is directly proportional to pressure.

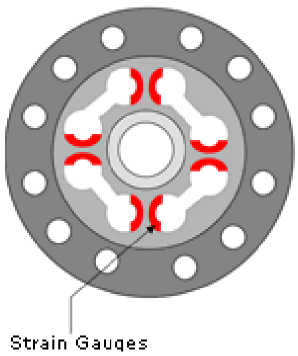

Figure 3.4: Cross section of pancake style load cell displaying locations of strain gauges

Strain gauge load cells convert the load acting on them into electrical signals. Much like in the pressure transducer the strain gauges themselves are bonded onto a beam or structural support that deforms when force is applied. Generally a load cell will contain a compression orientated and a tension orientated strain gauge. When weight is applied to the load cell, some strain gauges compress decreasing their resistances while simultaneously the tension ones stretch increasing their resistances. The difference in resistance causes different currents to run through each, thus creating a potential difference that can be measured. The gauges are often mounted in a differential bridge to enhance the accuracy of the measurement. Figure 3.4 displays the cross section of a pancake style load cell.

4. METHODOLOGY

For this project the requirements are to map out the temperature distribution inside a hydrogen tank during a fast fill to provide a solid measure of average temperature and to find a suitable temperature location that best represents such. A combination of both modeling and experimental studies will be used to determine such point. Modeling given its valid should show the ideal location for temperature measurement. Therefore an experimental apparatus is created to help validate the thermodynamic model produced. In order to validate the model measurements of temperature at keys locations, pressure, and mass flow rate need to be recorded accurately during the entire fast fill cycle. The constraints for the experimental validation are displayed in table 4.1

Constraint	**Description**	**Solution**
2D $\triangle T$	Map out 2D temperature distribution within tank during transient fill	Array of sensors with exact locations known inside tank
$\triangle m$	Measure accurately mass before fill, end of fill, and after cool down	Use high accuracy scale
$\triangle P$	Measure Transient pressure during fast fill and cool down	Pressure Sensor at inlet and far end of tank
Semi-Portable	System needs to be semi portable as system will need to be transported to hydrogen dispenser	Design experimental apparatus and DAQ to fit on transportable push trolley
Standard Tank	No modifications to tank are permitted	Collapsible sensor array to be inserted and expanded inside tank
Adhere to SAEJ2601	Adhere to standards and procedures for the fast filling of hydrogen type 4 tanks	Have 1-2 sensors report data to dispenser
Non-Invasive	Reduce the effects of the measurement on the internal process	Use insulating materials for sensor support, minimize size and fluid obstruction of array.

Table 4.1: Constraints for experimental validation

4.1. EXPERIMENTAL SETUP

The overview of the proposed experimental setup is displayed in figure 4.1 A tank will be mount to a trolley with a load cell buffer in between, which will allow for mass change measurements. The tank will be a type 4 700 bar rated capacity tank specialized for hydrogen storage. The cylinder is manufactured by Luxfer Industries (part# M030H) which has an internal volume that translates into 1.12 kg of stored hydrogen at a pressure of 700 bar (69.95MPa) with a temperature of 15 °C (288 K). The entire tank including fuel will weigh approximately 60 pounds. The diagram of the tank to be used in the experiment is displayed in figure 4.2.

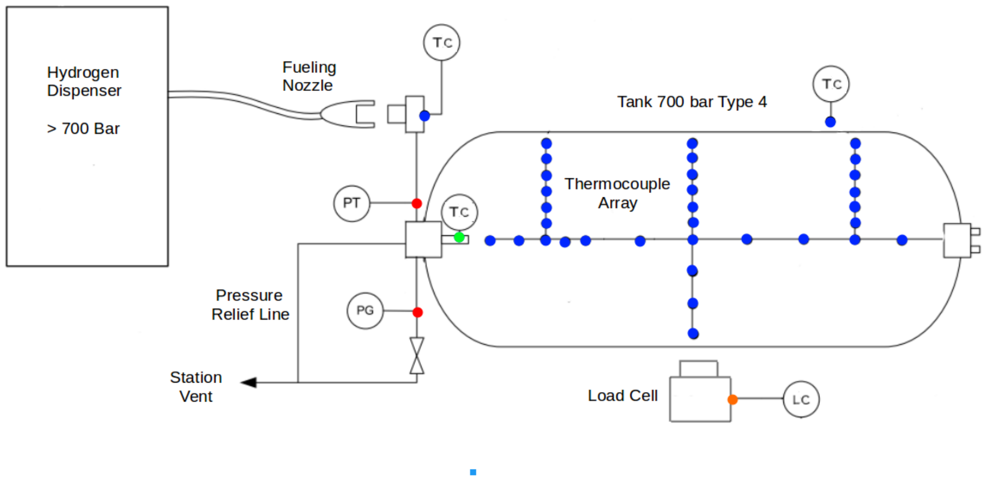

Figure 4.1: Diagram of the proposed experimental setup

The tank contains two openings each with a 2" threaded insert. One side will be used for attaching the filling equipment while the other for the array matrix. The filling side of the cylinder will be equipped with either an off the shelf or custom internal tank valve block assembly. The assembly will house a solenoid or pneumatic valve, a manual shutoff valve, a pressure relief device, and a Bourbon reference gauge. Likely an off the shelve block will also include a thermistor mounted internally for dispenser communication. The opposite end of the cylinder will have a custom built block with support bracket for the array as well as a sealed conduit for the thermocouple wire management.

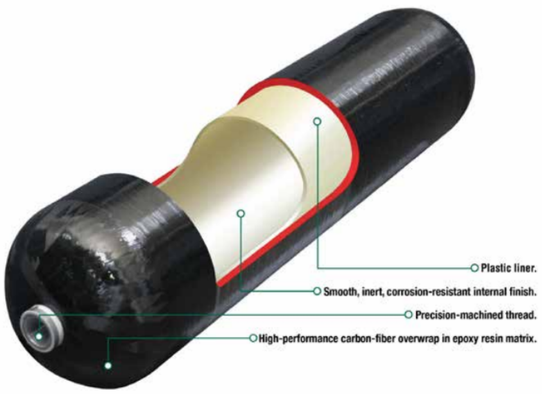

Figure 4.2: Layer diagram of Tank selected for fast fill characterization

4.2. DAQ

The data acquisition system was chosen with accuracy and precision in mind while maintaining the ability to remain semi portable. The large thermocouple array requires at least 32 channels for transient measurements along with another 2-4 additional measurements. For these reasons a National Instruments System Was selected. Table 4.2 displays the devices used for collecting and managing sensor data. The Heart of the system is the eDAQ-9174 which serves as the step between the ADC and the software. It runs a user define program compile from Labview for gathering data from all modules and organizing it relative to a time stamp or sample count. All of this is then compressed and communicated to a local system running labview via a simple USB interface for storage. This 9174 contains 3 card slots for running different acquisition modules simultaneously. This provides a great tool for collecting and organizing all the time dependent data and eliminates the need for complex syncing schemes. Two types of ADC's have been selected to run with the experiment.

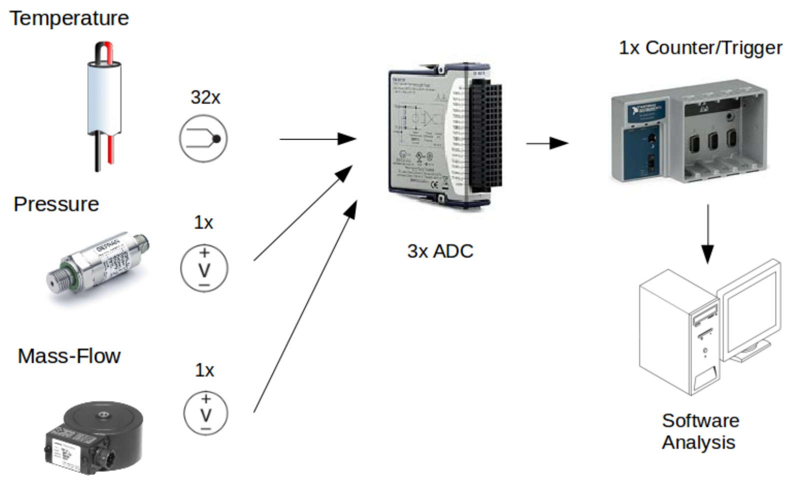

Figure 4.3: Diagram of the data acquisition system

The NI 9213 ADC is a module optimized for thermocouple measurement. Each module features a ±78 input with 16 channels and an internal cold-junction compensation sensor. The card runs a 24bit ADC at a 100kS/s sampling rate making it perfect for large transient data collections. For the pressure and load cell data aquisition a 4ch high speed 16 bit ADC was selected. The system features 0-10V and ±5V input range making it easy to couple most devices with DC output.

Figure 4.3 displays the general layout of the DAQ system.

Device	Description	Specifications	Price
2x NI 9213	Thermocouple ADC	-16ch 24 bit ADC -±78.125mV input range - 78 S/s sampling rate -accuracy with type T ±0.02°C	1730.00
1x NI 9215	Pressure and Mass ADC	-4ch 16 bit ADC - ±10V input range - 100 kS/s sample rate - ≤ 0.2% error (calibrated)	805.00
eDAQ-9174	Data Acquisition System and Counter/TDC	Input FIFO size: 127 samples/s-lot -Timing accuracy: 50 ppm of sample rate -Timing resolution: 12.5 ns counter 4x 32bit @100kHz	1195.00

Table 4.2: List of components used in DAQ system

4.3. Temperature

The spacial distribution of temperature is this case is the most challenging aspect of the measurement system. The system needs to attain a fairly high level of accuracy while maintaining sensitivity all while needing to fit through a 2" hole. For these reason thermocouples were chosen as the most suitable sensor.

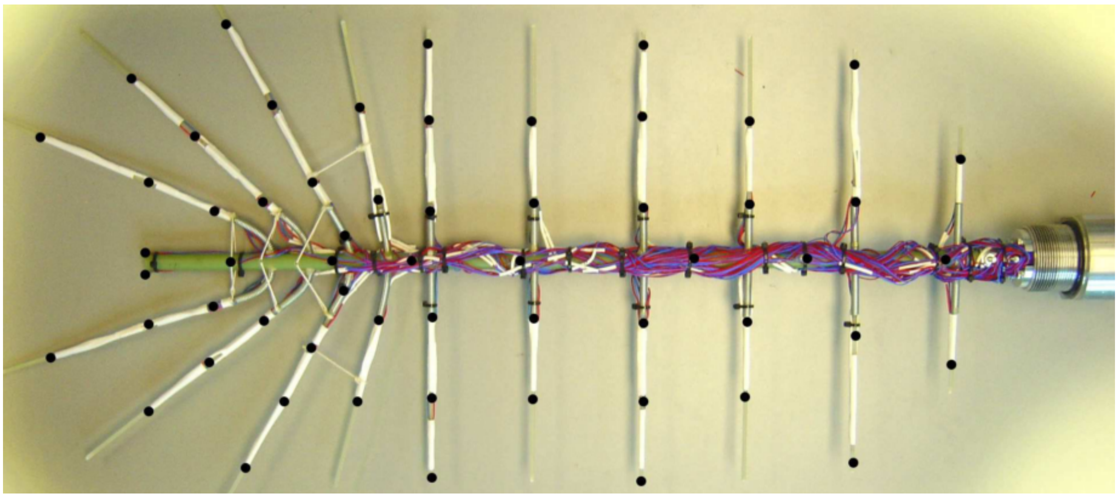

Figure 4.4: Example of a collapsible thermocoupler array to be inserted into tank [Dicken, 2006]

Thermocouples are self powered and will not require additional excitation which due to the shear number of sensors used in the array is a huge advantage. Running an extra line for every device for excitation would add a lot of complexity to the sealed conduit as well as taking up additional volume inside the cylinder. Another advantage of thermocouplers is there sensitivity to transient events. During the fast fill process a dynamic process is expect therefore a device with transient capabilities is needed. The main limitation with thermocouples however can be accuracy in the respect that system errors of less than one degree Celsius (°C) can be difficult to achieve. Due to there transient nature however the error can be mitigated by running an averaging scheme at high refresh rates. Thermocouples come in many varieties and are characterized by the materials used as the conductors. For this experiment a T type thermocouple was selected to be used in the internal array. The T type contains copper-constantan junction which makes it suitable for a large range of measurements. Type T is non-reactive with hydrogen and has a fast response making it ideal for this application. The complete device specifications are found in table 4.3. An collapsible structure will be fabricated of insulating materials such as ABS or PLA in order to strategically set the thermocouplers to a known position. The structure will be collapse before inserted and will be erected either from external intervention or automatically by a rubber elastic spring system. Figure 4.4 displays an example of a collapsible array of thermocouples used in similar studies [Dicken, 2006].

Sensor	**Specifications**	**Input/Output**	**Calibration**
Type T Thermocouple	-Exposed 0.008mm End - Special Grade - $\pm 0.5°$C or 0.4% accuracy - $\tau = 0.15$ s response	-No excitation -Differential Output ± 78 mV	- NIST rational polynomial method - Cold Junction Sensor
Gefran KS Pressure Transducer	- 0-100 MPa range -± 0.5% accuracy FS - 10^{-3} s $10-90$% response	- 0-10V output - 30Vdc excitation	Calibration Curve
Honeywell 3397 Load Cell	- 0-200lb range - 2mV/V ± 0.25% accuracy - 1.0s response 10-90%	- With Universal Inline Amplifier ± 10Vdc - 30Vdc excitation	Experimental Calibration Curve

Table 4.3: List of sensors with pertinent specifications

In addition to the array there will be discrete temperature measurements made at key locations around the experiment. The inlet temperature of the incoming hydrogen will be measured using both a Type T thermocouple and a thermistor provided by the selected block valve. The thermistor will be used as the input for the dispenser and its value will not be logged using the DAQ and instead will be noted for consistency. The thermocouplers will be calibrated and referenced using the rational polynomial function approximation for Type T thermocouples. Using a least squares curve fitting procedure we will fit the National Institute of Standards and Technology (NIST) type T thermocouple data with a rational function which is found in the appendix.

4.4. PRESSURE

The pressure for the experiment will be measured at the inlet of the tank. Again the sensor needs to be able to cope with high pressures and temperature fluctuations while maintaining accuracy and response. For these reasons a diaphragm transducer sensor was selected. For this experiment The Gefran KS series pressure transducer was selected which uses a capacitance film on a stainless steel diaphragm. A capacitance type sensor was selected for its robust construction, relative low dependence on temperature and its suitability for most transient processes. The sensor however requires an external excitation, but fortunately just one sensor is required and is accessed externally and therefore is not a major concern. The specifications of the sensor are displayed in table 4.3

(a) (b) (c)

Figure 4.5: Displays the sensors selected for experiment: Type T thermocouple (a) GEFRAN pressure Transducer (b) and a Honeywell load cell (c)

The pressure transducer will be mounted using standard practices such as welded nipple or tapped 'T' section. This measurement can skewed because of the pressure gradient that exists between the buffer tank in the dispenser and the vehicle side tank. Therefore its paramount that the pressure sensor be mounted as close to the tank inlet as possible as to best represent the pressure inside the tank. Because this is a relative measurement the sensor cannot be mounted internally as its needs exposure to the outside ambient pressure. A barometer will be used to measure the ambient temperature and pressure conditions.

4.5. MASS

The amount of hydrogen fuel moved into the tank will be measured using a simple load cell method. The load cell will be used to measure the change of mass of the tank during the fast fill and cool down period. The load cell method has some advantages and disadvantages versus a flow meter. Some of the advantages include its simplicity, relative low expense and its accuracy in comparison to flow meter methods. Additionally the load cell will be mounted externally from the tank and therefore will not be exposed to temperature fluctuations that could induce inaccuracies. However standard load cells can have a slow response which may lead to error describing the mass relative to time. One would have to make adjustments in order to match the data correctly. Fortunately the initial and final measurements for this process are the minimum that are required for model validation as the model uses pre-determined flow-rates. Therefore measurements can be made at a much slower rate as we're not as concerned as much with the instantaneous rate of change but rather the overall rate of change. For these reasons employing a load cell is more effective method. A Honeywell Model 3397 load cell was selected for mass change measurements and its specifications are displayed in table 4.3. It was be run with a linear amplifier circuit in order to convert its AC output to a DC 0-10V range making it easy to couple with standard DAQ systems. The load cell system will be calibrated by adding known mass and generating a calibration curve.

4.6. Uncertainty

The uncertainty in the measurement was calculated using the taylor series method which simplifies to the sum of relative uncertainties. Table 4.4 summarizes the uncertainty calculated for each measurement. Both the error in the sensor and the data acquisition system were taken into account.

- Temperature: T $\pm$0.16%
- Pressure: P $\pm$0.22%
- Mass: m $\pm$0.45%
- Length: L $\pm$0.5mm
- Radius: r $\pm$0.5mm

Table 4.4: Summary of estimated uncertainty in measurements

The error was significantly improved for the temperature and pressure measurements as the response of the sensors was fast enough that multiple measurements could be averaged for one sample. Therefore the uncertainty in the measurement (mean) becomes the uncertainty in the mean. This can be calculated using equation 4.1

$$\triangle x_{mean} = \frac{\triangle x}{\sqrt{N}} \tag{4.1}$$

Were N is the number of samples averaged over a measurement sample. The uncertainty for the mass was the summed relative error for the sensor and ADC. An averaging scheme is not possible for this sensor as its sampling rate is too slow.

- Transport Calibrated Apparatus to Dispensing site
- Purge Tank and Set Pressure to 50 Bar
- Allow Temperature/Pressure to Stabilize
- Record Initial Conditions
- Apply Required Ramp Rate
- Measure P, T @ 10S/s m @ 1S/s during Fast fill
- Measure P, T @ 10S/s m @ 1S/s during cool down
- Record Final Conditions
- Repeat for different array configurations recording new sensor positions

Table 4.5: General Procedure for Each Fast Fill Run

Once the experimental apparatus has been tested and all sensors properly connected and calibrated the apparatus will be taken to a dispensing facility. The Thermocoupler array will be inserted and properly erected with locations of a sensors measured and recorded using a precision ruler. The array will be run in different configurations to effective map out the behavior of the gas for a large region inside the tank. Once properly set the internal valve block assembly will be attached and the tank purged with nitrogen to avoid explosion hazards. The system will then be connected to hydrogen dispenser and re-purged this time with hydrogen. The dispenser will require input from an internal thermister built into the block value. All excess and vented gas will be directed to the station/dispenser vent. After ensuring all air and then nitrogen have been removed from the system the tank will be filled to 50 Bar and left to stabilize. Once stabilized all initial data will be recorded; initial tank mass, initial temperature, ambient references and selected ramp rates. The DAQ system will begin recording ensuring stable values. The fill will then be initiated as per SAEJ2601 standards for fast filling. Its likely due to the time requirements and expense of the hydrogen gas only one ideal ramp rate will be selected and studied. Pressure and Temperature with be sampled at 20S/s and averaged at 0.5 second intervals while the mass and ambient sensors @ 1S/s during Fast fill. The fill will either be halted when the pressure reaches the rated capacity for the tank (700Bar) or a maximum temperature of 80$\circ$C is reached for the internal block valve thermister. The tank will then be left to cool. Data will be recorded until temperature has stabilized at ambient at which point the final conditions will be recorded ending the run. The gas will be vented back down to 50 Bar and allowed to re-stabilized so that another run can be taken. This process will be repeated 5 times for each array arrangement y for up to 10 different arrangements to ensure reproducibility and adequate spacial coverage respectively. To ensure continuity between measurements several sensors in the array will remain in the same positions for every measurement. Table 4.5 summarizes the steps for the experimental procedure.

5. CONCLUSION

Once all the necessary parameters have been measured, values will be compared against the CFD model results. If the average deviation between the model and experiment is below 5% the model can be used to accurately predict temperature for all points through-out the tank.

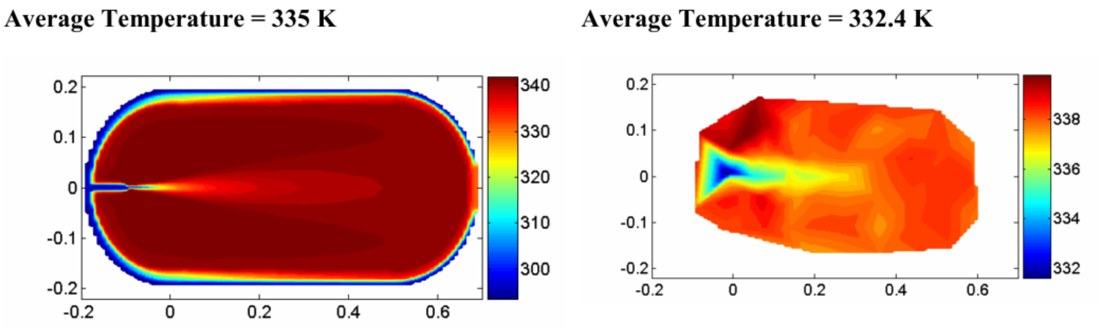

Figure 5.1: Example of Temperature Distribution for both CFD model and Experimental values [Dicken, 2006]

This value is based on the resulting pressure change caused in the error of temperature value responsible for shutting down the tank. A temperature change any greater than this error will push the pressure beyond acceptable overfill limits of the tank. If the error is too large the underlying physics of the model will have to be re-evaluated until acceptable error is reached. Figure 5.1 displays an example of a model evaluated for temperature during a 350 bar tank fill and its experimentally collected data. Once validated the model will be used to further explore and confirm the best location to place a dispenser controlling thermister that will guarantee the tank is accurately filled safely.

REFERENCES

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A. Appendix

A.1. Gefran Pressure Transducer

GEFRAN

KS

PRESSURE TRANSMITTER

Main Features

- *Ranges: from 1 to 1000 bar*
- *Nominal Output Signal:*
  4...20mA (2 wires)
  0...10Vdc / 0.1...5.1Vdc / 0.1... 10.1Vdc / 0...5Vdc /
  1...5Vdc / 1...6Vdc / 1... 10Vdc / 0.2...10.2Vdc (3 wires)
  0.5...4.5Vdc (3 wires - ratiometric)
- *Compact size*
- *Wetted parts: Stainless steel*
- *SIL 2 certified according to IEC/EN 62061:2005*

KS transmitters are based on film sensing element deposited on stainless steel diaphragm.
Thanks to the latest state of the art SMD electronics and compact all stanless steel construction, these products are extremely robust and reliable, with SIL2 certification supplied as standard.
KS transmitters are suitable for all industrial applications, specially on hydraulics (presses, pumps, power pack, fluid power, etc.) with severe conditions usually with high level of shock, vibration, and pressure and temperature peaks.

This symbol present on the product label stands for further indications on product manual. For correct and safe installation, follow the instructions and observe the warnings contained in this manual. No hazards shall arise by any reasonably foreseeable misuse in a way not intended, and not described in this manual. The complete manual is available for download from the website www.gefran.com.
UL file number E216851

TECHNICAL DATA

Output signal	VOLTAGE	RATIOMETRIC	CURRENT
Non Linearity (BFSL)	± 0.15% FS (typ) ± 0.25% FS (max)		
Hysteresis	± 0.1% FS (typ) ± 0.15% FS (max)		
Repeatability	± 0.025% FS (typ) ± 0.05% FS (max)		
Zero offset tolerance	± 0.15% FS (typ) ± 0.25% FS (max)		
Span offset tolarance	± 0.15% FS (typ) ± 0.25% FS (max)		
Accuracy at room temperature (1)	< ± 0.5% FS		
Pressure ranges (2)	From 1 bar to 1000 bar (See table)		
Resolution	Infinite		
Overpressure (without degrading performance)	See table		
Pressure containment (burst test)	See table		
Pressure Media	Fluids compatible with Stainless Steel AISI 430F and 17-4 PH		
Housing	Stainless Steel AISI 304		
Power supply (4)	B/M/P 10...30Vdc R 11...30Vdc N/C/T/Q 15...30Vdc	5Vdc ±0,25V	10...30Vdc
Max current absorption	15mA		35mA
Dielectric strenght	250 Vdc		
Zero output signal	B/M/P/R/N/C/T/Q	0.5Vdc (X)	4 mA (E)
Full scale output signal	B/M/P/R/N/C/T/Q	4.5Vdc (X)	20 mA (E)
Allowed load	≥5KΩ		see load diagram
Long term stability	< 0.2% FS/per year		
Operating temperature range (process)	-40...+125°C (-40...+257°F)		
Operating temperature range (ambient)	-40...+105°C (-40...+221°F)		
Compensated temperature range	-20...+85°C (-4...+185°F)		
Storage temperature range	-40...+125°C (-40...+257°F)		
Temperature effects over compensated range (zero)	± 0.01% FS/°C typ. (± 0.02% FS/°C max.)		
Temperature effects over compensated range (span)	± 0.01% FS/°C typ. (± 0.02% FS/°C max.)		
Response time (10...90%FSO)	< 1 msec.		
Warm-up time (3)	< 30 sec.		
Mounting position effects	Negligible		
Humidity	Up to 100%RH non-condensing		
Weight	80-120 gr. nominal		
Mechanical shock	100g/11msec according to IEC 60068-2-27		
Vibrations	20g max at 10...2000 Hz according to IEC 60068-2-6		
Ingress protection	IP65/IP67		
Output short circuit and reverse polarity protection	YES		
EC Conformity	According to Directive 2014/30/EU		

FS = Full scale
1 Incl. Non-Linearity, Hysteresis, Repeatability, Zero-offset and Span-offset (acc. to IEC 61298-2)
2 The operating pressure range is intended from 0.5% to 100% FS
3 Time within which the rated performance is achieved
4 The devices must be supplied with a Class 2 Power Supply (as for NEC) or LPS Power Supply (as for EN 60950). If devices are permanently connected to the machine it's requested an external switch or circuit breaker and external overcurrent protection.

Model 3397

PERFORMANCE SPECIFICATIONS

Characteristic	Measure
Load range[1]	25, 50, 100, 200, 300 lb
Non-linearity	±0.05 % of rated output
Hysteresis	±0.05 % of rated output
Repeatability	±0.02 % of rated output
Output @ rated capacity	2 mV/V ±0.25 % (nominal)
Operation	Tension/compression
Resolution	Infinite
Standard calibration	Tension (+) and compression (-)

ENVIRONMENTAL SPECIFICATIONS

Characteristic	Measure
Temperature, operating	-54 °C to 93 °C [-65 °F to 200 °F]
Temperature, compensated	21 °C to 77 °C [70 °F to 170 °F]
Temperature effect, zero	±0.002 % of rated output/°F
Temperature effect, output	±0.002 % of reading/°F

ELECTRICAL SPECIFICATIONS

Characteristic	Measure
Strain gage type	Foil
Excitation (maximum)	20 Vdc or Vac RMS
Insulation resistance	> 5000 mOhm @ 50 Vdc
Bridge resistance (tolerance)	350 ohm
Number of bridges	1 or 2
Zero balance	±5.0 %
Electrical termination	PT02E-10-6P mates with PT06W-10-6S

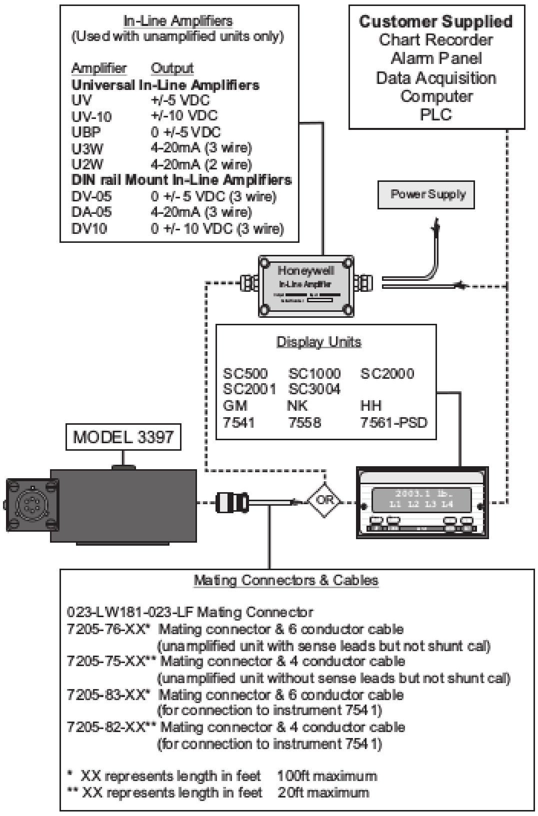
MECHANICAL SPECIFICATIONS

Characteristic	Measure
Static overload capacity	150 % of nominal capacity
Material	Carbon steel
Natural frequency	See table

WIRING CODES

Cable	
Red	(+) excitation
Black	(-) excitation
Green	(+) output
White	(-) output

TYPICAL SYSTEM DIAGRAM



NI 9213 Specifications

The following specifications are typical for the range -40 °C to 70 °C unless otherwise noted.

Caution Do not operate the NI 9213 in a manner not specified in this document. Product misuse can result in a hazard. You can compromise the safety protection built into the product if the product is damaged in any way. If the product is damaged, return it to NI for repair.

Warm-up time	15 minutes

Input Characteristics

Number of channels	16 thermocouple channels, 1 internal autozero channel, 1 internal cold-junction compensation channel
ADC resolution	24 bits
Type of ADC	Delta-Sigma
Sampling mode	Scanned
Voltage measurement range	±78.125 mV
Temperature measurement ranges	Works over temperature ranges defined by NIST (J, K, T, E, N, B, R, S thermocouple types)

Table 1. Timing Modes

Timing Mode	Conversion Time (Per Channel)	Sample Rate[1] (All Channels[2])
High-resolution	55 ms	1 S/s
High-speed	740 µs	75 S/s

Common-mode voltage range	
Channel-to-COM	±1.2 V minimum
COM-to-earth ground	±250 V

Common-mode rejection ratio	
High-resolution mode (at DC and 50 Hz to 60 Hz)	
Channel-to-COM	100 dB
COM-to-earth ground	>170 dB
High-speed mode (at 0 Hz to 60 Hz)	
Channel-to-COM	70 dB
COM-to-earth ground	>150 dB
Input bandwidth	
High-resolution mode	14.4 Hz
High-speed mode	78 Hz
High-resolution noise rejection (at 50 Hz and 60 Hz)	60 dB
Overvoltage protection	±30 V between any two inputs
Differential input impedance	78 MΩ
Input current	50 nA
Input noise	
High-resolution mode	200 nVrms
High-speed mode	7 µVrms
Gain error	
High-resolution mode	
at 25 °C	0.03% typical
at -40 °C to 70 °C	0.07% typical, 0.15% maximum
High-speed mode	
at 25 °C	0.04% typical
at -40 °C to 70 °C	0.08% typical, 0.16% maximum
Offset error	
High-resolution mode	4 µV typical, 6 µV maximum
High-speed mode	14 µV typical, 17 µV maximum
Offset error from source impedance	Add 0.05 µV per Ω, when source impedance >50 Ω

A.4. NI9215 DATA

NI 9215 Specifications

The following specifications are typical for the range -40 °C to 70 °C unless otherwise noted.

Caution Do not operate the NI 9215 in a manner not specified in this document. Product misuse can result in a hazard. You can compromise the safety protection built into the product if the product is damaged in any way. If the product is damaged, return it to NI for repair.

Input Characteristics

Number of channels	4 analog input channels
ADC resolution	16 bits
Type of ADC	Successive approximation register (SAR)
Input range	±10.0 V

Input Voltage Ranges	
Measurement Voltage, AI+ to AI-	
Minimum[1] (V)	±10.2
Typical (V)	±10.4
Maximum (V)	±10.6
Maximum Voltage (Signal + Common Mode)	
NI 9215 with screw terminal	Each channel must remain within ±10.2 V of common.
NI 9215 with spring terminal	Each channel must remain within ±10.2 V of common.
NI 9215 with BNC	All inputs must remain within 10.2 V of the average AI- inputs.
Overvoltage protection	±30 V
Conversion time	
Channel 0 only	4.4 µs
Channels 0 and 1	6 µs
Channels 0, 1, and 2	8 µs
Channels 0, 1, 2, and 3	10 µs

Table 1. Accuracy

Measurement Conditions		Percent of Reading (Gain Error)	Percent of Range[2] (Offset Error)
Calibrated	Maximum (-40 °C to 70 °C)	0.2%	0.082%
	Typical (23 °C ±5 °C)	0.02%	0.014%
Uncalibrated[3]	Maximum (-40 °C to 70 °C)	1.05%	0.82%
	Typical (23 °C ±5 °C)	0.6%	0.38%

Stability	
Gain drift	10 ppm/°C
Offset drift	60 µV/°C

A.5. NIST TABLE FOR TYPE T

```
ITS-90 Table for type T thermocouple
 C      0     -1     -2     -3     -4     -5     -6     -7     -8     -9    -10
                             Thermoelectric Voltage in mV

-270 -6.258
-260 -6.232 -6.236 -6.239 -6.242 -6.245 -6.248 -6.251 -6.253 -6.255 -6.256
    -6.258
-250 -6.180 -6.187 -6.193 -6.198 -6.204 -6.209 -6.214 -6.219 -6.223 -6.228
    -6.232

-240 -6.105 -6.114 -6.122 -6.130 -6.138 -6.146 -6.153 -6.160 -6.167 -6.174
    -6.180
-230 -6.007 -6.017 -6.028 -6.038 -6.049 -6.059 -6.068 -6.078 -6.087 -6.096
    -6.105
-220 -5.888 -5.901 -5.914 -5.926 -5.938 -5.950 -5.962 -5.973 -5.985 -5.996
    -6.007
-210 -5.753 -5.767 -5.782 -5.795 -5.809 -5.823 -5.836 -5.850 -5.863 -5.876
    -5.888
-200 -5.603 -5.619 -5.634 -5.650 -5.665 -5.680 -5.695 -5.710 -5.724 -5.739
    -5.753

-190 -5.439 -5.456 -5.473 -5.489 -5.506 -5.523 -5.539 -5.555 -5.571 -5.587
    -5.603
-180 -5.261 -5.279 -5.297 -5.316 -5.334 -5.351 -5.369 -5.387 -5.404 -5.421
    -5.439
-170 -5.070 -5.089 -5.109 -5.128 -5.148 -5.167 -5.186 -5.205 -5.224 -5.242
    -5.261
-160 -4.865 -4.886 -4.907 -4.928 -4.949 -4.969 -4.989 -5.010 -5.030 -5.050
    -5.070
-150 -4.648 -4.671 -4.693 -4.715 -4.737 -4.759 -4.780 -4.802 -4.823 -4.844
    -4.865

-140 -4.419 -4.443 -4.466 -4.489 -4.512 -4.535 -4.558 -4.581 -4.604 -4.626
    -4.648
-130 -4.177 -4.202 -4.226 -4.251 -4.275 -4.300 -4.324 -4.348 -4.372 -4.395
    -4.419
-120 -3.923 -3.949 -3.975 -4.000 -4.026 -4.052 -4.077 -4.102 -4.127 -4.152
    -4.177
-110 -3.657 -3.684 -3.711 -3.738 -3.765 -3.791 -3.818 -3.844 -3.871 -3.897
    -3.923
-100 -3.379 -3.407 -3.435 -3.463 -3.491 -3.519 -3.547 -3.574 -3.602 -3.629
    -3.657

 -90 -3.089 -3.118 -3.148 -3.177 -3.206 -3.235 -3.264 -3.293 -3.322 -3.350
     -3.379
 -80 -2.788 -2.818 -2.849 -2.879 -2.910 -2.940 -2.970 -3.000 -3.030 -3.059
     -3.089
```

```
-70 -2.476 -2.507 -2.539 -2.571 -2.602 -2.633 -2.664 -2.695 -2.726 -2.757
    -2.788
-60 -2.153 -2.186 -2.218 -2.251 -2.283 -2.316 -2.348 -2.380 -2.412 -2.444
    -2.476
-50 -1.819 -1.853 -1.887 -1.920 -1.954 -1.987 -2.021 -2.054 -2.087 -2.120
    -2.153

-40 -1.475 -1.510 -1.545 -1.579 -1.614 -1.648 -1.683 -1.717 -1.751 -1.785
    -1.819
-30 -1.121 -1.157 -1.192 -1.228 -1.264 -1.299 -1.335 -1.370 -1.405 -1.440
    -1.475
-20 -0.757 -0.794 -0.830 -0.867 -0.904 -0.940 -0.976 -1.013 -1.049 -1.085
    -1.121
-10 -0.383 -0.421 -0.459 -0.496 -0.534 -0.571 -0.608 -0.646 -0.683 -0.720
    -0.757
  0  0.000 -0.039 -0.077 -0.116 -0.154 -0.193 -0.231 -0.269 -0.307 -0.345
      -0.383

C      0     -1     -2     -3     -4     -5     -6     -7     -8     -9    -10

ITS-90 Table for type T thermocouple
C      0      1      2      3      4      5      6      7      8      9     10
                             Thermoelectric Voltage in mV

  0  0.000  0.039  0.078  0.117  0.156  0.195  0.234  0.273  0.312  0.352  0.391
 10  0.391  0.431  0.470  0.510  0.549  0.589  0.629  0.669  0.709  0.749  0.790
 20  0.790  0.830  0.870  0.911  0.951  0.992  1.033  1.074  1.114  1.155  1.196
 30  1.196  1.238  1.279  1.320  1.362  1.403  1.445  1.486  1.528  1.570  1.612
 40  1.612  1.654  1.696  1.738  1.780  1.823  1.865  1.908  1.950  1.993  2.036

 50  2.036  2.079  2.122  2.165  2.208  2.251  2.294  2.338  2.381  2.425  2.468
 60  2.468  2.512  2.556  2.600  2.643  2.687  2.732  2.776  2.820  2.864  2.909
 70  2.909  2.953  2.998  3.043  3.087  3.132  3.177  3.222  3.267  3.312  3.358
 80  3.358  3.403  3.448  3.494  3.539  3.585  3.631  3.677  3.722  3.768  3.814
 90  3.814  3.860  3.907  3.953  3.999  4.046  4.092  4.138  4.185  4.232  4.279

100  4.279  4.325  4.372  4.419  4.466  4.513  4.561  4.608  4.655  4.702  4.750
110  4.750  4.798  4.845  4.893  4.941  4.988  5.036  5.084  5.132  5.180  5.228
120  5.228  5.277  5.325  5.373  5.422  5.470  5.519  5.567  5.616  5.665  5.714
130  5.714  5.763  5.812  5.861  5.910  5.959  6.008  6.057  6.107  6.156  6.206
140  6.206  6.255  6.305  6.355  6.404  6.454  6.504  6.554  6.604  6.654  6.704

150  6.704  6.754  6.805  6.855  6.905  6.956  7.006  7.057  7.107  7.158  7.209
160  7.209  7.260  7.310  7.361  7.412  7.463  7.515  7.566  7.617  7.668  7.720
170  7.720  7.771  7.823  7.874  7.926  7.977  8.029  8.081  8.133  8.185  8.237
180  8.237  8.289  8.341  8.393  8.445  8.497  8.550  8.602  8.654  8.707  8.759
190  8.759  8.812  8.865  8.917  8.970  9.023  9.076  9.129  9.182  9.235  9.288

200  9.288  9.341  9.395  9.448  9.501  9.555  9.608  9.662  9.715  9.769  9.822
```

210	9.822	9.876	9.930	9.984	10.038	10.092	10.146	10.200	10.254	10.308	10.362
220	10.362	10.417	10.471	10.525	10.580	10.634	10.689	10.743	10.798	10.853	10.907
230	10.907	10.962	11.017	11.072	11.127	11.182	11.237	11.292	11.347	11.403	11.458
240	11.458	11.513	11.569	11.624	11.680	11.735	11.791	11.846	11.902	11.958	12.013
250	12.013	12.069	12.125	12.181	12.237	12.293	12.349	12.405	12.461	12.518	12.574
260	12.574	12.630	12.687	12.743	12.799	12.856	12.912	12.969	13.026	13.082	13.139
270	13.139	13.196	13.253	13.310	13.366	13.423	13.480	13.537	13.595	13.652	13.709
280	13.709	13.766	13.823	13.881	13.938	13.995	14.053	14.110	14.168	14.226	14.283
290	14.283	14.341	14.399	14.456	14.514	14.572	14.630	14.688	14.746	14.804	14.862
300	14.862	14.920	14.978	15.036	15.095	15.153	15.211	15.270	15.328	15.386	15.445
310	15.445	15.503	15.562	15.621	15.679	15.738	15.797	15.856	15.914	15.973	16.032
320	16.032	16.091	16.150	16.209	16.268	16.327	16.387	16.446	16.505	16.564	16.624
330	16.624	16.683	16.742	16.802	16.861	16.921	16.980	17.040	17.100	17.159	17.219
340	17.219	17.279	17.339	17.399	17.458	17.518	17.578	17.638	17.698	17.759	17.819
350	17.819	17.879	17.939	17.999	18.060	18.120	18.180	18.241	18.301	18.362	18.422
360	18.422	18.483	18.543	18.604	18.665	18.725	18.786	18.847	18.908	18.969	19.030
370	19.030	19.091	19.152	19.213	19.274	19.335	19.396	19.457	19.518	19.579	19.641
380	19.641	19.702	19.763	19.825	19.886	19.947	20.009	20.070	20.132	20.193	20.255
390	20.255	20.317	20.378	20.440	20.502	20.563	20.625	20.687	20.748	20.810	20.872
400	20.872										
C	0	1	2	3	4	5	6	7	8	9	10

A.6.