

Impacts of Diluting Ethanol on Alcohol Stove Emissions and Efficiencies

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Abstract—Wood and charcoal are common sources of fuel used for personal cooking in developing countries. However, these sources are inefficient and can have significant health risks. A push for cleaner burning fuels, such as ethanol, is occurring, but this push creates market and cost challenges. To ease the cost burden, ethanol diluted with water is considered as an alternative to distilled ethanol. This study used a simple alcohol stove and compared the impacts of water diluent on emissions and efficiencies in accordance with the standard Water Boiling Test protocol. It was found that thermal efficiencies and CO emissions increase with increasing diluent. The CO emissions for all concentrations tested were less than 7 g/MJ, which meets the ISO standard for acceptable CO emissions.

I. INTRODUCTION

A. Motivation

Traditional biomass, mainly firewood and charcoal, is currently the most common fuel used for personal cooking in many Sub-Saharan African countries. The International Energy Agency [1], in coordination with the United Nations Development Programme, estimates 2.7 billion people rely on biomass daily.

However, in recent years, scientists have pushed for cleaner fuel alternatives, such as ethanol, due to detrimental health risks associated with burning biomass [2]. Legros et al [3] estimates that 2 million deaths are caused by pneumonia, chronic lung disease, and lung cancer as a result of exposure to emissions from biomass and coal cooking each year. In MacCarty et al's research [4], significant improvements on emissions and energy usage have been shown for alcohol-burning cookstoves.

Ethanol is being examined as a potential renewable fuel alternative to fossil fuels. Ethanol is not readily available in most locations of Sub-Saharan Africa; however, the potential exists for greater availability and usage as the industry expands. Several countries in Africa are producing ethanol primarily to be used as an additive in transportation fuels. Ongoing projects are attempting to introduce ethanol and ethanol-compatible stoves to specific communities, and a wide acceptance of ethanol gel-fuel in urban areas has been reported by Schlag and Zuzarte [5].

B. Background and Literature Review

Ethanol is produced by fermenting sugars in various types of feedstock that may be grown in Africa such as sugarcane, cassava, sweet sorghum, maize, and wheat. Ethanol solutions used for fuel must have a greater ethanol content than solutions produced by fermentation alone, so the fermented solution must be distilled. Note, Raoult's Law does not allow for ethanol to be perfectly distilled from a water-ethanol mixture. As reported by Brewster et al [6], the absolute maximum that ethanol can be distilled to is 95.57%. Increasing the ethanol content further must be accomplished by using various dehydration methods described by Breaux [7]. To produce pure ethanol, Madson et al [8] states that an additional technique is needed that requires around 14,000 to 17,000 BTU per gallon of ethanol.

In addition to added energy input, manufacturing higher concentrations of ethanol requires added manufacturing costs that a developing country may not be able to support. Ethanol diluted with water, hydrous ethanol, is easier to manufacture than distilled ethanol, which could increase supply for developing countries currently using biomass. However, diluting the ethanol with water may result in lower fuel efficiencies and higher emissions.

Studies on hydrous ethanol have been performed for some combustion applications. For example, Martinez-Frias et al [9] homogeneous charge compression ignition (HCCI) is an emerging technology that can run on hydrous ethanol. This particular engine design can run on fuels containing ethanol as low as 35%, decreasing energy required for distillation. However, Landisch et al [10] shows that 35% ethanol is not very useful in combustion applications. Distilling to 80% ethanol would reduce the distillation energy by three fourths, when compared to 96% ethanol.

Other studies performed by Breaux [7] at Louisiana State University tested diluted ethanol combusted in a swirl-stabilized combustor with a constant air flow from a dump diffuser. Water diluent ranged from 0% to 40%; which is equivalent to ethanol distilled between 60% and 100%. A stable flame was achieved with ethanol consisting of up to 35% diluent. This study showed that the exhaust heat rate was not affected with up to 20% diluent. Ethanol with up to 20% water

content was found to be a practical fuel for continuous flame application. Additionally, 85% ethanol would result in 25% life cycle energy savings, when compared to 100% ethanol, and the global heat release is reduced as much as 60% with the addition of 20% water.

Furthermore, Breaux's research recorded flame temperatures. For 100% ethanol at an equivalence ratio of one with standard air, the average low flame temperature was around 1,155 K. For 80% ethanol, the low flame temperature was around 1,130 K. The reduction in low flame temperature was approximately 2.2% for an addition of 20% water content. This trend is also found in a study looking at diluted ethanol as a rocket fuel that burned diluted ethanol with liquid oxygen (O_2) [11]. The study preformed by Beeton et al [11] found that the maximum combustion temperature for pure ethanol when burned with liquid O_2 , instead of air, was 3,285 K, and the maximum combustion temperature for 85% ethanol was 3,200 K. This represents a 2.6% decrease in temperature for an addition of 15% water content. The similarity between the results for both Breaux and Beeton shows that, across a range of studies, diluting ethanol with water has consistent effects which can be applied to the ethanol stove used in this study.

Also, as a valuable side note, according to Breaux's research, the relative light intensity only decreased from 16 ABU for 100% ethanol to 8 ABU for 90% ethanol and appeared to remain approximately 8 ABU between 90% and 80% ethanol. Although not a primary focus of this research study, relative light intensity is mentioned because there is a concern for injuries due to low visibility flames when cooking. Should there have been a more dramatic decrease in relative light intensity when burning diluted ethanol, as compared to pure ethanol, further research into this topic would have been necessary to establish appropriate safety precautions.

Results showed that combustion efficiency and combustor thermal efficiency were not negatively affected by elevated water content between 80% and 100% ethanol. The combustion temperature was negatively affected by the water content. The negatively impacted temperature coupled with the additional mass flow rate resulted in minimal effects on the net exhaust heat rate [7].

C. Objectives

With this background, this project focuses on testing the efficiency and emissions of an ethanol-burning cookstove with varying concentrations of ethanol diluted with water. The cookstove is a similar design to the stove modeled by United States of America Patent No. 766,618 [12] and is shown in Figure 1, at right. The simple personal cookstove was chosen because it can use local technology and can be produced inexpensively. This particular cookstove design also holds potential for use in urban areas where living space is limited, ethanol is more accessible, and food is typically cooked in smaller quantities.

The alcohol cookstove was used to burn ethanol-water mixtures in a controlled environment. The fuel dilutions had ethanol mass percentages of 100%, 90%, 80%, and 70%. Fuel with ethanol concentrations less than 95% will be referred to as wet ethanol. A water boiling test (WBT), which enables the comparison of a wide variety of stoves, was implemented



Fig. 1. The alcohol stove in use with the pot on top filled with deionized water. Note that the flames are anchored to the small jets.

to measure the efficiency of the stove with the diluted fuel. This test compared the energy adsorbed by a pot of water to the energy released by the fuel. A gas analyzer measured the carbon monoxide (CO) concentrations of the exhaust. A stagnation style flow meter measured the exhaust flow rate traveling through the hood. The exhaust flow rate and CO concentrations were used to calculate a fuel burn efficiency. The CO emissions of the burn are a health concern since the stoves will be used in an enclosed environment. In addition, the efficiency of the stove will determine if dilution of the fuel is a feasible alternative to pure ethanol, enabling a more cost effective source of cleaner energy.

II. EXPERIMENTAL APPROACH AND ANALYSIS

A. Experimental Design

A simple personal cookstove was constructed from aluminum beverage cans. The stove construction featured a small fuel reservoir central to the stove axis, and had a vaporization chamber on the outside of the stove, surrounding the reservoir. Small holes, acting as jets, were punched near the top of the vaporization chamber for fuel vapors to escape. An image of the stove in use can be seen in Figure 1 and a cross section that shows the pressure chamber and fuel reservoir can be found in Figure 23 of Appendix I.

The procured ethanol fuel used was 200 proof fuel with ethanol content greater than 99.5%. The 200 proof fuel will be referred to as 100% ethanol concentration throughout the paper. The Fuel concentrations were mixed in batches and the details of which can be found in Appendix G). A container was placed on a scale and the scale was tared. A predetermined volume of ethanol was added to the container, and then a calculated volume of deionized water was added to the ethanol. The mixed fuels were stored in sealed containers until used.

All procedures involving the use of ethanol fuel were carried out quickly to minimize evaporation of ethanol, and rubber stoppers were used on any graduated cylinders containing ethanol fuel when not in use.

A pitot tube type flow meter (Nailor Industries Inc. Model: 36FMS) measured the flow in the exhaust duct work. A differential pressure transducer (Series MS Magnehelic) measured the difference between the stagnation pressure and the static pressure.

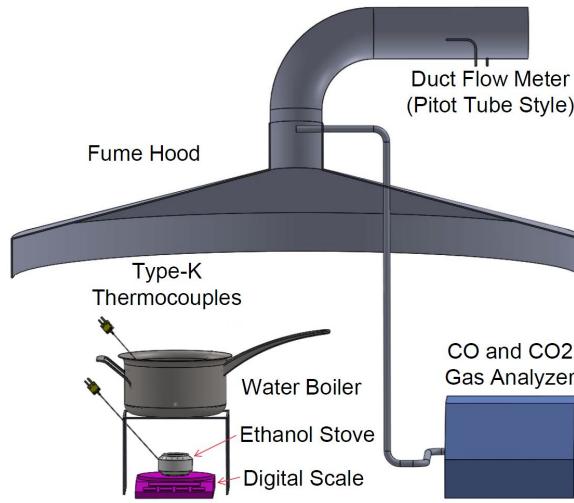


Fig. 2. The experimental setup indicating stove and measurement devices used.

The Portable Emissions Measurement System (PEMS), developed by the Aprovecho Research Center, measured the constituents of the exhaust. The PEMS monitored and recorded emission levels of CO, in real time via a data acquisition system connected through a software interface. These concentrations were used to calculate fuel burn efficiency.

An aluminum pot with a measured mass was suspended above the stove. The pot contained five hundred grams of room-temperature deionized water. A type-K thermocouple was placed in the water to measure the water temperature during the burn. This water temperature is required for calculations in the WBT.

Fifty milliliters of diluted ethanol fuel was used for the test, and a graduated cylinder was used to measure the quantities needed. The mass of the fuel was measured. These measurements of fuel mass and volume were performed immediately prior to ignition to minimize evaporation of ethanol.

Data acquisition occurs two minutes prior to testing to ensure that ambient conditions could be subtracted from the collected data. The fuel was ignited from the reservoir; the stove required a few minutes to preheat the fuel inside the pressure chamber for the ignition of the jets. A thermocouple within the cookstove measured the pressure chamber temperature to provide additional flame characterization data.

The weight of the pot and the remaining water was measured immediately after the flame extinguished, and the apparatus was allowed to cool to room temperature. The PEMS was run for 10 minutes after the flame was extinguished to ensure that the ambient conditions had not changed and to

purge the gas analyzers. After each test was completed, the pot was thoroughly cleaned to ensure any soot buildup had been removed; soot build up can affect the heat transfer to the water in the pot. The experiment was repeated for each of the four ethanol concentrations, and duplicate tests were run as time permitted.

B. Methodology

The collected data was used to determine the stove efficiency for each concentration of ethanol. The stove efficiency described below is similar to the High Power Thermal Efficiency standard derived from the standardized WBT. The difference is that this test examined the entirety of the burn and not just the peak power production from the stove. According to the WBT protocol, the highest standard requires the stove efficiency to be greater than 45% [13]. The scale of the test performed is smaller than the standardized WBT as well; only 0.5 liters of water were used instead of the standard 1.0 liters. This test examined the entirety of the test, instead of dividing the test into Hot Start, Cold Start, and Simmer as done in the standardized WBT [14]. These changes were necessary because the small size of the stove precluded boiling large volumes of water and the stove design did not permit throttling.

The stove efficiency was calculated using the following equation:

$$h_c = \frac{\Delta E_{H_2O,heat} + \Delta E_{H_2O,evap}}{E_{released}} \quad (1)$$

where h_c is the thermal efficiency, $\Delta E_{H_2O,heat}$ is the change in energy of the water in the pot, $\Delta E_{H_2O,evap}$ is the energy spent evaporating water, and $E_{released}$ is the energy released by the stove [14].

The energy released by the stove was determined by multiplying the mass of the ethanol solution by the calorific value of the solution, 29.64 MJ/kg [15]. Note that the water in the solution did not add to the energy released, and therefore the mass used in this calculation varied based on the concentration, even if the same volume was used each repetition of the experiment.

The heat energy in the pot was calculated using the temperature data from the thermocouple in the pot and the specific heat equation:

$$\Delta E_{H_2O,heat} = m_{water}c_{p_w}\Delta T + m_{pot}c_{p_m}\Delta T \quad (2)$$

where m_{water} is the mass of the water remaining in the metal pot at the end of the test, m_{pot} is the mass of the aluminum pot, c_{p_w} is the specific heat of the water, c_{p_m} is the specific heat of the aluminum, and ΔT is the change in temperature in the water between when the fuel was ignited and when the flame was extinguished.

The energy spent evaporating the water was calculated using the loss of mass of the water in the pot plus the mass of water lost in the ethanol solution using the equation for the latent heat of vaporization:

$$\Delta E_{H_2O,evap} = m_{evap}h_v \quad (3)$$

where m_{evap} is the mass of the water evaporated due to boiling and h_v is the latent heat of vaporization of water.

The time for the water to reach boiling was measured using data from the thermocouple in the pot. This was the time measured between ignition of the fuel and when the temperature plot reached a plateau around 98°C.

The fuel burn efficiency was based on how much of the carbon is released as CO. The CO content was determined by the emissions analyzer, the volumetric flow rate, and temperature of the exhaust recorded by the PEMS.

The percentage (ϵ) of carbon in the ethanol fuel that was consumed in the production of CO was calculated using the following equation:

$$\epsilon = \frac{n_{CO}}{2n_{ethanol}} \quad (4)$$

where n_{CO} is the number of molecules of CO produced and $n_{ethanol}$ is the number of ethanol molecules in the fuel. Note that there are two carbon atoms in each ethanol molecule. The variable n_{CO} was calculated using the following equation:

$$n_{CO} = \frac{N_A P_{static} C_{CO} V}{R * T_{ambient}} \quad (5)$$

where N_A is Avogadro's constant, P_{static} is the static pressure in the fume hood exhaust, C_{CO} is the average concentration of CO measured by the PEMS in parts per million over the course of the experiment, $T_{ambient}$ is the ambient temperature, V is the volume of air that passes through the fume hood over the course of the experiment, and R is the ideal gas constant. The variable V was in turn calculated by multiplying the volumetric flow rate through the fume hood exhaust, u , by the burn time in seconds. The volumetric flow rate through the fume hood exhaust in units of cubic feet per minute was found using the following equation:

$$u = C * 215\sqrt{\Delta P} \quad (6)$$

in which ΔP is the differential pressure across the pitot tube flow meter in inches of units of water and C is the calibration correction constant. The initial equation for the volumetric flow rate was provided by the manufacturer of the pitot tube flow meter shown in Equation 9. The calibrated correction constant was found using Equation 10.

The number of ethanol molecules in the fuel was found using the following equation:

$$n_{ethanol} = \frac{N_A m_{fuel} C_x}{M_{ethanol}} \quad (7)$$

where m_{fuel} is the mass of the fuel added to the stove, C_x is the ethanol concentration of the solution, and $M_{ethanol}$ is the molar mass of ethanol.

In addition to determining the thermal efficiency and CO production, the normalized CO production σ was calculated using the following equation:

$$\sigma = \frac{n_{CO} M_{ethanol} N_A}{\Delta E_{H_2O,heat} + \Delta E_{H_2O,evap}} \quad (8)$$

The value $n_{CO} M_{ethanol} N_A$ in the numerator of the equation represents the mass of CO released by the stove in grams, and $\Delta E_{H_2O,heat} + \Delta E_{H_2O,evap}$ in the denominator represents the energy that went into the pot. The highest standard requires the normalized CO emissions to be less than 8 g/MJ [13].

C. Design Stage Uncertainty Analysis

A design stage uncertainty analysis of the thermal efficiency was performed using the equipment tolerances found in Appendix E1, test information from a test run at the Aprovecho Research Center, and a review of literature. The analysis was performed using the Kline McClintock method and was implemented in Python with the code included in Appendix H. More details of the design stage and higher order uncertainty, including uncertainty tree diagrams, can be found in Appendix B.

A relative uncertainty of 20% or better for both the thermal efficiency and the CO production percentage is proposed as a target for the measurements in this experiment. This target value is reasonable for cookstove applications because it has been shown that tests of the same stove at the same laboratory can vary 5–25% [4].

The uncertainty analysis concluded that the thermal efficiency can be expected to have a relative uncertainty of approximately 1.5–2%. The majority of measurements used to calculate the thermal efficiency are measurements of mass, and consequently the relative uncertainty is largely impacted by the accuracy of the scale.

The uncertainty analysis concluded that the CO production percentage can be expected to have a relative uncertainty of approximately 5–7%. The greatest source of uncertainty for the CO production percentage was the CO sensor of the PEMS. Although the 0.5 ppm accuracy of the unit is highly sensitive for most applications, the CO production rate from the stove is very small, therefore the relative error is very large.

D. Calibration and Measurements

In order to apply the water boiling test and gather data, measurements of the mass of the fuel and temperature of the water were required. The equations of interest and the corresponding error analysis can be found in Appendices A and B. Omega type-K thermocouples and a Ohaus Scout scale were used and calibrated. The PEMS was used for measuring the CO and CO₂ emissions. The PEMS is calibrated every 6 months by Aprovecho Research Center and is outside of the scope for this experiment. The PEMS samples the emissions from the exhaust flow, and thus the flow velocity needed to be known. A Naior Industries 36FMS was used to measure the flow and required calibration. The flow-meter is a 4-point stagnation pitot tube that measures pressure drop in the system. This pressure drop was measured using the differential pressure transducer on board the PEMS, a series MS MagneSense differential pressure transmitter. This differential pressure transmitter was also calibrated by the Aprovecho Research Center and thus was not calibrated as part of the test procedure. Details and specifications of each instrument can be found in Appendix E.

Calibration of type-K thermocouples was performed using a 2-point method, achieved using an ice bath and a boiling

bath. The modules used during calibration were a SCXI 1303 for the cold-junction, a SCXI 1102 amplifier and module, a SCXI 1000 chassis for signal conditioning, and a PCI-6023E module to convert the analog signal to digital. The connection chart found in Appendix D has been included to help understand the required modules. The software reading the temperature measurements was National Instruments Laboratory Virtual Instrument Engineering Workbench (LabVIEW™). This software has calibration properties for each channel; the results of these calibrations are shown in Appendix I. The maximum and minimum tolerances were taken for the ice and boiling baths resulting in ranges for low and high of -0.402 to 0.136 °C and 98.45 to 99.1 °C. Caution was used to ensure that the thermocouple did not touch the bottom of the pot, as this could have skewed the temperature measurements.

Precision weights were used in calibration/verification of the scales. For calibration of scales and balances, the American Society for Testing and Materials (ASTM) International [16] recommends that the precision weights used have a tolerance that is a factor smaller than the readability of the scale. For example if a scale reads to 1 gram, the precision weights are required to have a tolerance of 0.1–0.9 grams at most. The scale used for this experiment has a readability limit of 1 gram, and the weights used had precision on the order of ± 0.001 grams, satisfying ASTM's recommendation. If the value displayed from the scale differs from that shown on the mass, the scale offers the ability to calibrate to the mass weight. Images of the calibration/verification can be found in Appendix E5. Using this calibration method ensures that the largest source of error is the instrumentation error in the scale.

The flow-meter was calibrated by creating a velocity profile using a pitot tube, see Appendix E. The average of the velocity profile measurements for 4 different volumetric flow rates were compared to the volumetric flow rate calculated from an equation provided by the manufacturer of the flow-meter, found in Figure 3 and provided as follows:

$$u = 215\sqrt{\Delta P} \quad (9)$$

in which u is the volumetric flow rate and ΔP is the differential pressure across the flow-meter. The calibration was applied to this equation by multiplying by a calibration constant C , which was determined as follows:

$$C = \frac{v_{Pitot}A}{215\sqrt{\Delta P}} \quad (10)$$

in which v_{Pitot} is the average velocity through the duct determined using the pitot tube and A is the measured cross sectional area of the duct. The calibration constant was found to be approximately 1.6 with a relative uncertainty of approximately 4%, as seen in Figure 3. This calibration constant is implemented in the flow rate equation (Equation 6) provided above.

III. RESULTS AND DISCUSSION

The thermal efficiency of the stove was determined using the WBT and Equation 1. These results are shown in Figure 4. The stove is most efficient at lower concentrations of ethanol (70% and 80%), where the efficiency is around 43.5%. The stove is least efficient at 100% ethanol where the stove efficiency is around 39%. These efficiencies are below the highest

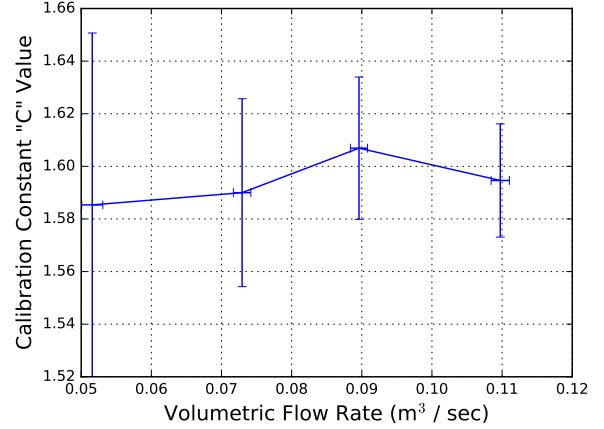


Fig. 3. Calibration curve for the FMS36 flow-meter. These values are found using Equation 10 found in the Experimental Approach and Analysis section. The calibration constant at each flow rate fall within the uncertainty of calibrations constants for the other flow rates.

standard of 45% but fall within the acceptable standards of greater than 35% efficiency [13]. The lower efficiency is most likely due to a simplified one person cookstove setup that does not contain the heat released and allows it to transfer to ambient air.

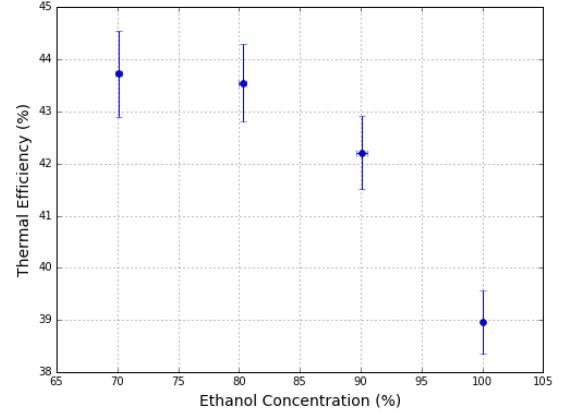


Fig. 4. The stove efficiency with respect to the ethanol concentration. This is found using the water boil test (Equation 1). The efficiency increased for increasingly diluted ethanol with uncertainties less than $\pm 1\%$.

For our case, the lower stove efficiency for the pure ethanol is most likely due to convective heat transfer characteristics. The higher concentration of ethanol would consume fuel more quickly and have a larger flame. This allowed for more of the energy to bypass the the pot and transfer to the ambient air. For the lower ethanol concentrations the flames were smaller and the fuel took longer to burn. The smaller flames rose to a lower height along the side of the pot than the larger flames from the higher ethanol concentration. This allowed more energy to transfer to the pot instead of going to ambient air.

In addition, note that the increase in efficiency from 80% to 70% ethanol is minimal and due to uncertainty we are unable to conclude if there is an increase or a plateau in efficiency.

The majority of measurements used to calculate the thermal efficiency are measurements of mass and temperature, and consequently the relative uncertainty is largely impacted by the accuracy of the scale and thermocouple in the water, which can be seen in the thermal efficiency uncertainty tree found in Appendix B. To better determine a trend in the thermal efficiency, selecting a more accurate scale and thermocouple can achieve this. To illustrate the effect of improving the accuracy of the scale, the Python code in Appendix H was modified to determine the uncertainty of a A thermocouple with 10 times greater accuracy (0.22°C versus 2.2°C). The modified code demonstrated that the relative uncertainty would be reduced by approximately 20.1% with the more accurate thermocouple. In the future, more accurate measuring devices could be beneficial for understanding the physics impacting the thermal efficiency changes in diluting ethanol.

There were concerns that thermal efficiency would decrease when using lower ethanol concentrations because some of the energy is needed to evaporate the water within the fuel. These concerns were not realized because efficiency increased when using lower ethanol concentrations. This is believed to occur because the water in the fuel vaporized, increasing the mass flow rate of the flame and heat transfer to the pot. The increased mass flow rate allows similar stove efficiencies.

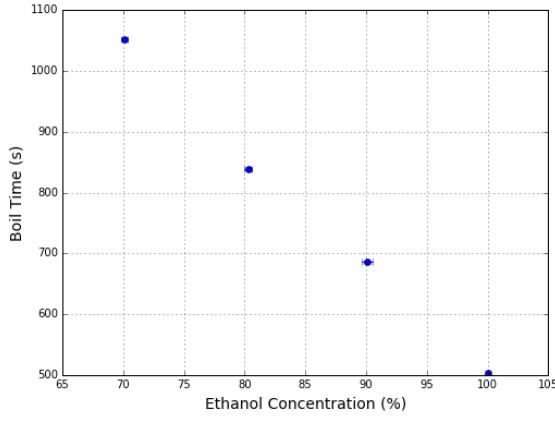


Fig. 5. The time required to reach 98°C with respect to the ethanol concentration. This temperature was used to represent boiling temperature and the time has a resolution error of ± 3 seconds which is to small to display.

The water took much longer to reach boiling temperature when lower concentrations of ethanol were used, as shown in Figure 5. The additional water reduced the flame heat and intensity, which in turn reduced the speed at which the fuel was consumed. The stove using fuel with 70% ethanol content took twice as long to reach boiling compared to the stove using fuel with 100% ethanol content. The fuel concentrations of 70%, 80%, 90%, and 100% took 17.5, 14, 11.5 and 8.4 minutes to boil respectively. These times show that the rate of energy released from the stove was much larger for higher ethanol concentrations.

The slower energy release was also observed by the intensity of the boil. The stove using fuel with 70% ethanol content had a simmering boil from a few locations within the pot, while the stove using fuel with 100% ethanol content had

a rolling boil. Despite the differences in boiling intensity, the stove boiled the water using all of the different concentrations of ethanol, thus all concentrations tested may be used as a cooking fuel.

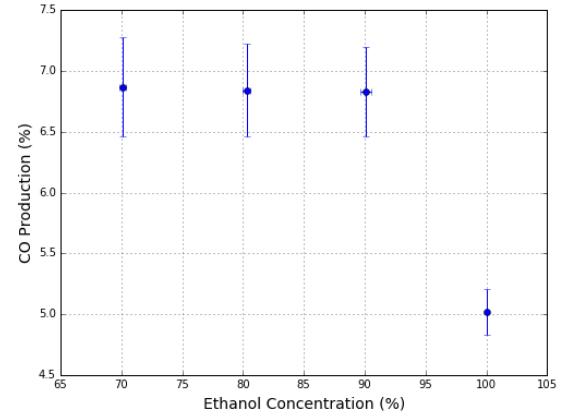


Fig. 6. The percent of carbon atoms in the fuel that became CO versus the ethanol concentration. This is found using Equation 4 found in the Experimental Approach and Analysis section.

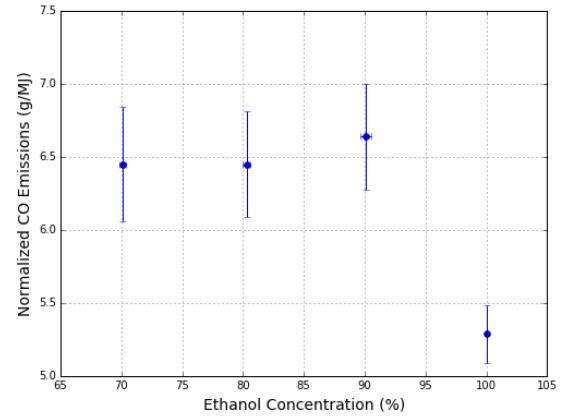


Fig. 7. The normalized CO emissions with respect to the ethanol concentration. This is found using Equation 8 found in the Experimental Approach and Analysis section. Due to the error overlap for the diluted contractions differences between the diluted fuels could be a plateau.

The CO emissions from diluted ethanol were higher than pure ethanol as shown in Figure 6. The percentage of carbon that became CO was around 5.0% for 100% ethanol and around 6.8% for diluted ethanol conditions with uncertainties of $\pm 0.5\%$. The elevated CO is a result of incomplete combustion. The added water in the fuel can act as a heat sink lowering the flame temperature and increasing the mass flow rate of the mixture. The affects of increased mass flow rate paired with the lower flame temperatures could change residence time of the combustion process and thus the time for converting CO to CO_2 is reduced resulting in increased production of CO.

The CO does not share the same trend as the thermal efficiencies, and the concentrations for 70%, 80% and 90% are the same and encompassed by the uncertainties. This could be

due to CO production being inhibited by the water-gas shift reaction ($\text{CO} + \text{H}_2\text{O} \rightleftharpoons \text{CO}_2 + \text{H}_2$). As the content of water is increased in the fuel mixture, more of it is present and water-gas shift will seek to balance out. This will result in a shifting of the equilibrium towards more CO_2 and less CO.

The CO emissions were normalized to how much CO emissions were produced to the amount of energy that went into the pot as shown in Figure 7. The normalized CO emissions are representative of how much CO is produced for cooking the same meal. All of the diluted ethanol mixtures have higher normalized CO emissions than the pure ethanol. The 90% ethanol concentration produced the most emissions for cooking with the normalized CO shown at 6.7 g/MJ, but the uncertainty falls within the range of 70% and 80% ethanol concentrations. The 100% ethanol concentration produced 25% less CO emission when providing the same energy for cooking. The normalized CO emissions all fall within the highest standard of emission [13].

IV. SUMMARY AND CONCLUSION

In this work, water-diluted ethanol was burned in a personalized alcohol cookstove, and a stove efficiency test was performed. The efficiency was determined by a small scale water boiling test. All the efficiencies fell below the highest standard but were still within the acceptable range of greater than 35% [13]. These efficiencies suggest that wet ethanol can be used as a cooking fuel. Ethanol concentrations of 70% to 90% exhibited greater efficiency as compared to 100% ethanol. This change in efficiency may be due to stove design and setup where higher intensity flames lose more heat to the ambient air. All of the concentrations both ignited and were able produce sufficient heat to boil the water. Fuels containing less ethanol yielded flames that burned at lower temperatures, as evidenced by lower intensity boiling. Diluting the ethanol resulted in higher CO emissions, as compared to pure ethanol. However, the maximum normalized CO emissions was around 6.7 g/MJ which is within the the ISO standard [13] of less than 8 g/MJ. The higher CO emissions at higher dilutions may have been caused by the water within the fuel decreasing the flame temperature.

A. Future Work

This work provides promising results for wet ethanol as a fuel source. As a personal cookstove was used, further testing is required to determine the scalability for the results to a stove suitable for an entire family's cooking needs. As there are already several such stoves available on the market, the principles and procedures used in this work can be applied to these larger alcohol-burning cookstoves. These larger stoves would also provide enough energy to perform the standardized WBT, which would be of significant benefit in making these results more comparable to all biomass stoves [14]. The larger flow rate will also allow for less uncertainty in the results from this paper. To further improve the uncertainty, much interest exists in using the Aprovecho Research Center's more robust and accurate Laboratory Emissions Measurement System (LEMS) instead of the PEMS used for this work.

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- [13] ISO. Guidelines for evaluating cookstove performance. *International Workshop Agreement (IWA)*, 11(E):1–6, 2012.
- [14] Robert van der Plas and H. S. Mukunda. The water boiling test version 4.1.2, January 2009.
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APPENDIX

A. Experimental Design and Analysis

1) Experiment Set Up: Below is a schematic of the experiment

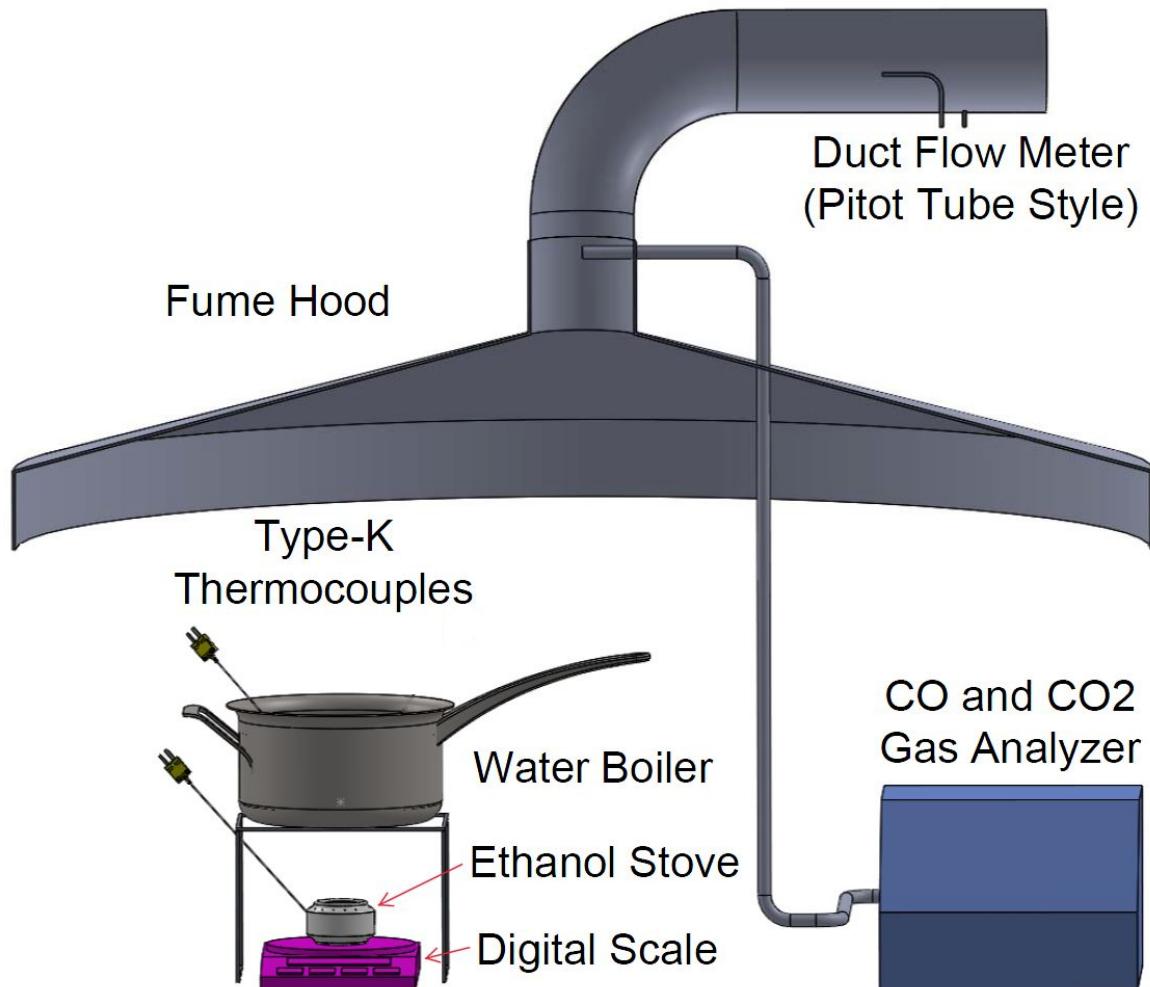
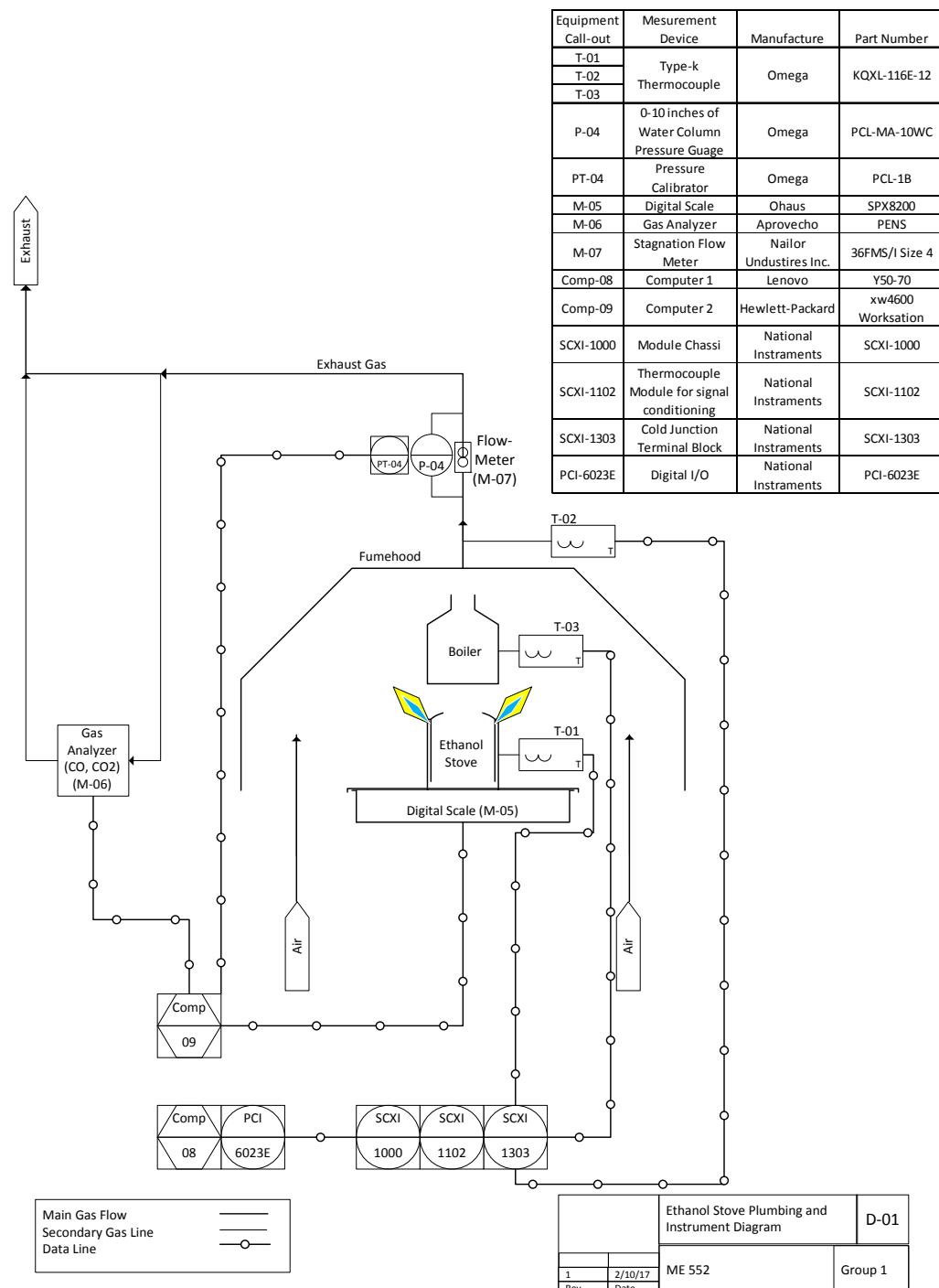


Fig. 8. CAD model of the the experimental set up

2) Experiment Flow Chart: below is a chart depicting the experimental setup



B. Uncertainty Design Analysis

An uncertainty analysis of the thermal efficiency was performed using the equipment tolerances found in appendix E1, test information from a test run at the Aprovecho Research Center, and a review of literature. The analysis was performed using the Kline McClintock method and was implemented in Python with the code included in appendix H.

A relative uncertainty of 20% or better for both the thermal efficiency and the CO production percentage is proposed as a target for the measurements in this experiment. This target value is reasonable for cook stove applications because it has been shown that variability between tests of the same stove at the same laboratory can vary between 5–25% [4].

The uncertainty analysis concluded that the thermal efficiency can be expected to have a relative uncertainty of approximately 1.5–2%. The majority of measurements used to calculate the thermal efficiency are measurements of mass, and consequently the relative uncertainty is largely impacted by the accuracy of the scale. To illustrate the effect of improving the accuracy of the scale, the Python code was modified to determine the uncertainty of a scale with 10 times greater accuracy (0.1 gram versus 1 gram). The modified code demonstrated that the uncertainty would be reduced by approximately 13.5% with the more accurate scale.

The thermal efficiency was also largely impacted by the thermocouple in the pot and the graduated cylinder used to measure the volume of ethanol. A thermocouple with 10 times greater accuracy (0.22°C versus 2.2°C) lessened the relative uncertainty by approximately 20.1%. Similarly, a device that would measure the volume of fuel with 10 times greater accuracy (0.05 mL versus 0.5 mL) would also lessen the relative uncertainty by approximately 20.1%. An uncertainty tree of the thermal efficiency can be found in figure 9 below.

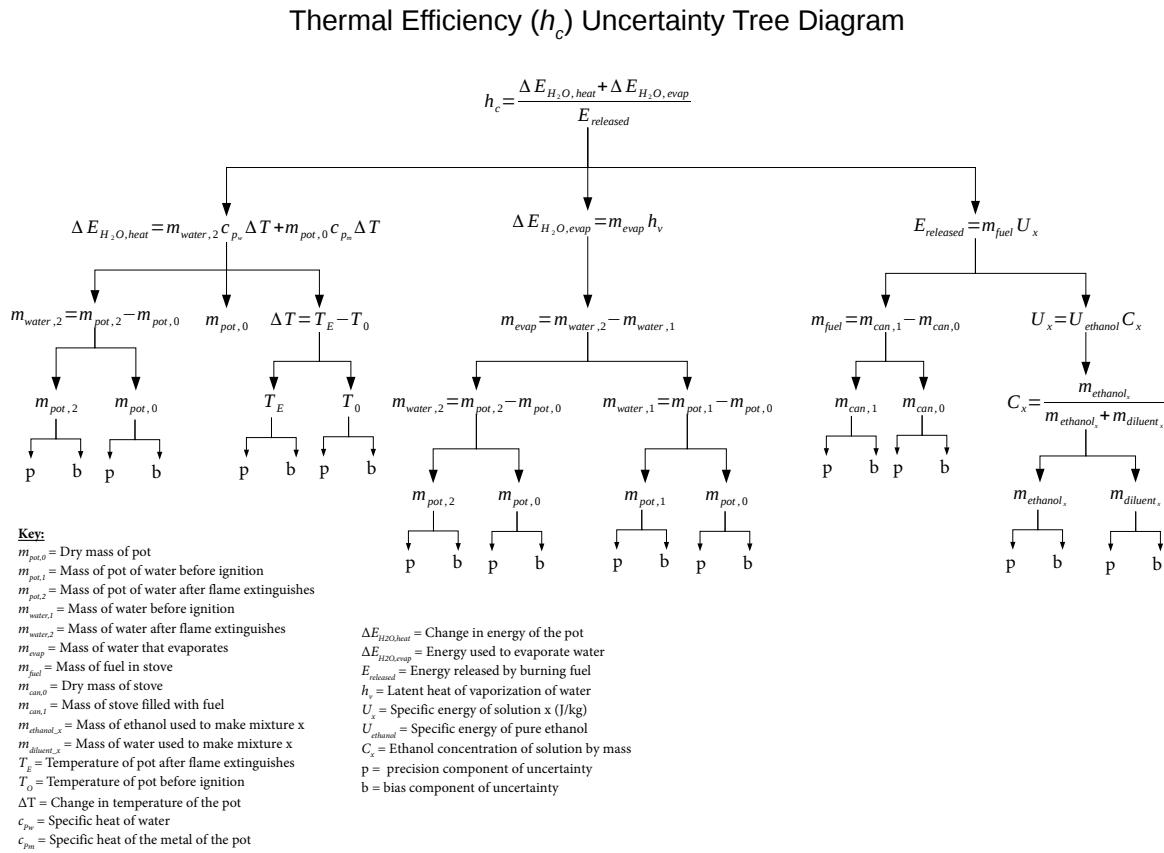
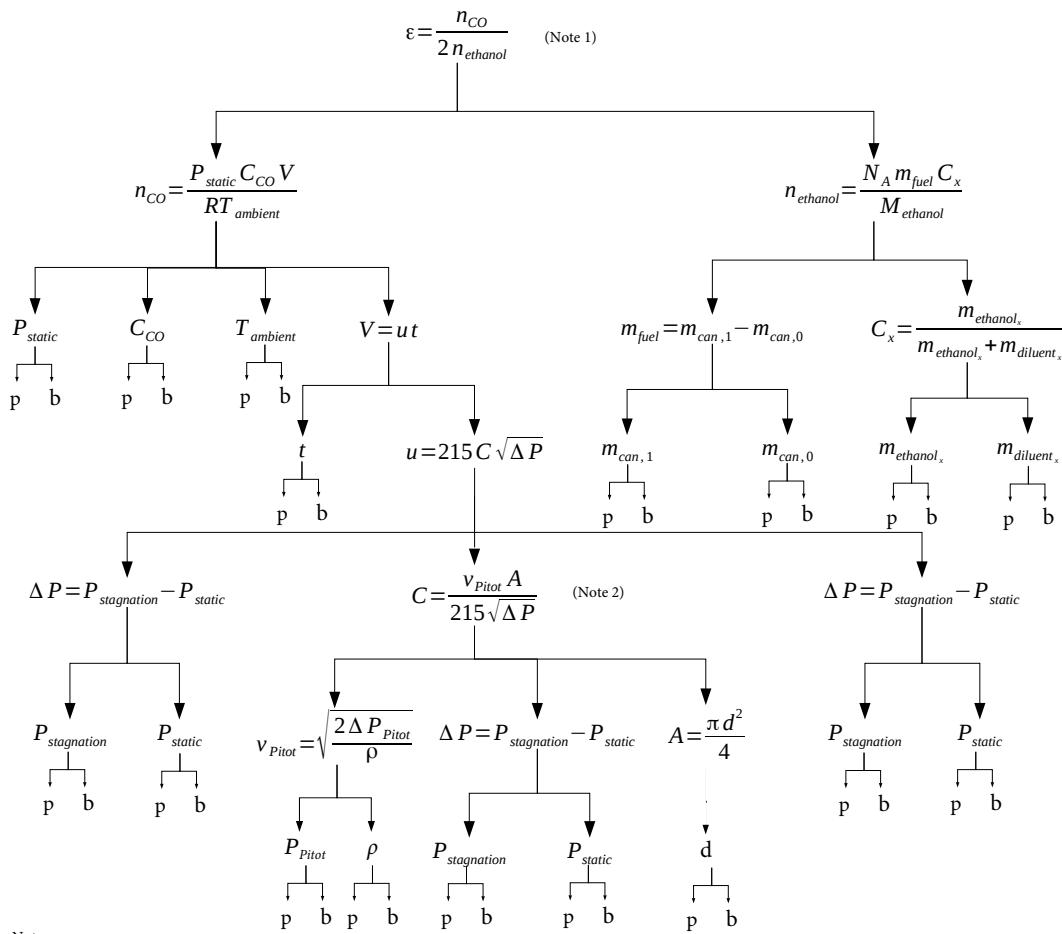


Fig. 9.

The uncertainty analysis concluded that the CO production percentage can be expected to have a relative uncertainty of approximately 5–7%. The greatest source of uncertainty for the CO production percentage was the CO sensor of the PEMS. Although the 0.5 ppm accuracy of the unit is highly sensitive for most applications, the CO production rate from the stove is very small, therefore the relative error is very large. Improving the accuracy of the CO detector by a factor of 10 would reduce the relative uncertainty by approximately 33%. Improvements in pressure, temperature, or mass measurements were found to have a smaller impact on the uncertainty. Figure 10 below depicts an uncertainty tree of the CO production percentage.

CO Production Percentage (ϵ) Uncertainty Tree Diagram



Key:

- n_{CO} = Number of molecules of CO released in test
- $n_{ethanol}$ = Number of molecules of ethanol in test
- m_{fuel} = Mass of fuel in stove
- $m_{can,0}$ = Dry mass of stove
- $m_{can,1}$ = Mass of stove filled with fuel
- $m_{ethanol,x}$ = Mass of ethanol used to make mixture x
- $m_{diluent,x}$ = Mass of diluent (water) used to make mixture x
- $M_{ethanol}$ = Molar mass of ethanol (46.06844 g/mol)
- N_A = Avogadro's number
- R = Universal gas constant
- C_x = Ethanol concentration of solution by mass
- C_{CO} = CO concentration of exhaust gas (ppm)

- $T_{ambient}$ = Ambient temperature
- P_{static} = Ambient temperature
- $P_{stagnation}$ = Ambient temperature
- ΔP = Change in pressure across the sampling tube
- ΔP_{pitot} = Change in pressure across Pitot tube
- t = Total burn time
- V = Total volume of air passed through hood during test
- C = calibration constant of sampling tube
- d = Diameter of sampling tube
- ρ = Density of ambient air
- u = Volumetric flow rate of air passed through hood during test
- p = precision component of uncertainty
- b = bias component of uncertainty

Fig. 10.

The uncertainty of CO₂ production precentage was found to range between 15–29%, often greater than the target value of 20%. This is because the PEMS was designed to be used for much larger stoves that produce much greater emissions than the personal cookstove investigated. The CO₂ production data was considered to be suspect because the nominal values often exceeded 100%, indicating that there were more carbon atoms in the CO₂ of the exhaust than there were carbon atoms in the fuel, despite correcting for background CO₂ values. For sake of completeness, a plot of the CO₂ production is included below:

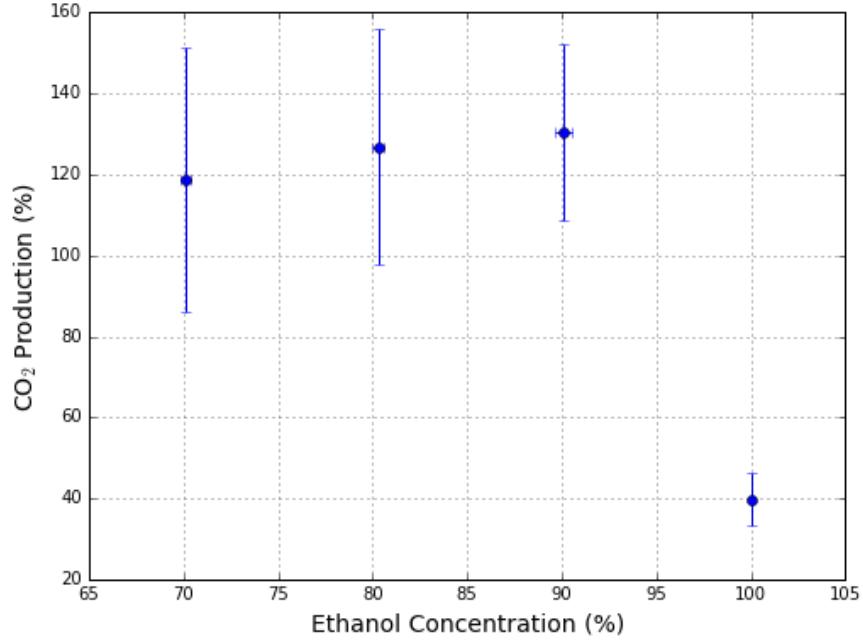


Fig. 11. CO₂ Production. The values greater than 100% indicate that the data used in this plot is suspect.

The large degree of uncertainty associated with the CO₂ concentration was one of the key factors in the decision not to calculate the CO production rate by using the ratio of CO to CO₂ concentration, as seen in the following equation:

$$\epsilon = \frac{C_{CO}}{C_{CO_2}} \quad (11)$$

in which C_{CO} is the concentration of CO in the exhaust and C_{CO_2} is the concentration of CO₂ in the exhaust. If the CO production rate had been calculated using this method instead of the method described by equation 5, the uncertainty on the measurement would have increased to approximately 18%.

As a further method of reducing the uncertainty of CO and CO₂ production, the concentration of these gases may be increased by using a larger stove or decreasing the flow rate through the fume hood. The higher concentration of exhaust gas would lower the uncertainty because the nominal readings would be relatively larger than the tolerance of the CO and CO₂ sensors.

C. Test Data

TABLE I. DATA OBTAINED FROM THE FIRST TEST

Ethanol Concentration	70	80	90	100
Thermal Efficiency	43.65%	42.83%	42.13%	N/A
Relative Uncertainty	1.91%	1.76%	1.71%	N/A
CO Production %	7.17%	7.12%	7.10%	N/A
Relative Uncertainty	5.83%	5.44%	5.38%	N/A
CO2 Production %	116.13%	98.37%	143.65%	N/A
Relative Uncertainty	28.26%	28.41%	15.10%	N/A
CO/MJ	6.74	6.82	6.91	N/A
Relative Uncertainty	5.94%	5.51%	5.41%	N/A
Time to Boil (s)	930	858	708	N/A

TABLE II. DATA OBTAINED FROM THE SECOND TEST

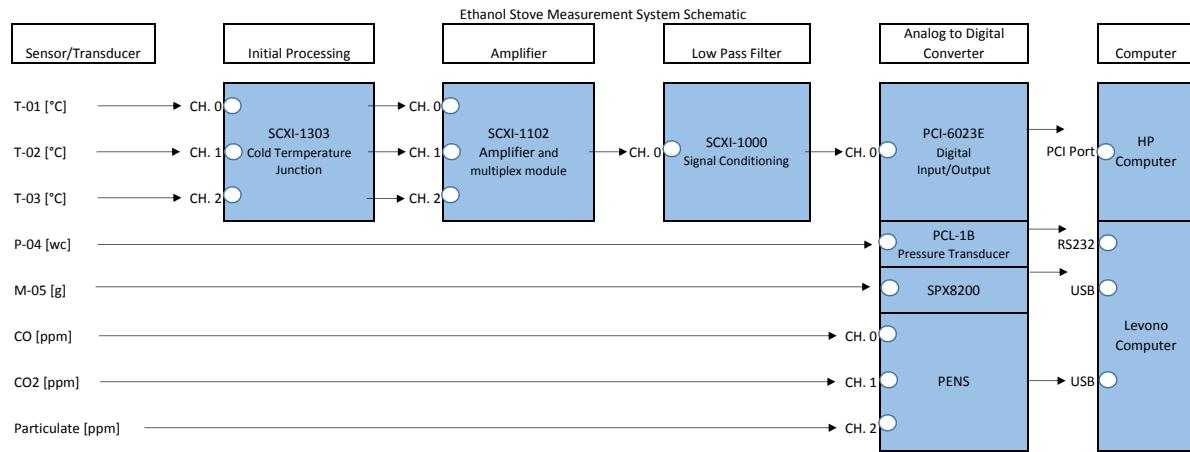
Ethanol Concentration	70	80	90	100
Thermal Efficiency	43.79%	44.27%	42.28%	38.96%
Relative Uncertainty	1.82%	1.64%	1.63%	1.56%
CO Production %	6.57%	6.56%	6.56%	5.02%
Relative Uncertainty	6.12%	5.65%	5.50%	3.67%
CO2 Production %	121.61%	155.23%	116.97%	39.83%
Relative Uncertainty	26.62%	17.58%	18.22%	15.91%
CO/MJ	6.15	6.08	6.37	5.29
Relative Uncertainty	6.20%	5.68%	5.52%	3.72%
Time to Boil (s)	1173	819	663	504

TABLE III. DATA AVERAGED FROM THE FIRST AND SECOND TESTS

Ethanol Concentration	70	80	90	100*
Thermal Efficiency	43.72%	43.55%	42.21%	38.96%
Relative Uncertainty	1.86%	1.70%	1.67%	1.56%
CO Production %	6.87%	6.84%	6.83%	5.02%
Relative Uncertainty	5.98%	5.55%	5.44%	3.67%
CO2 Production %	118.87%	126.80%	130.31%	39.83%
Relative Uncertainty	27.44%	23.00%	16.66%	15.91%
CO/MJ	6.45	6.45	6.64	5.29
Relative Uncertainty	6.07%	5.60%	5.47%	3.72%
Time to Boil (s)	1052	839	686	504

*Note that only one set of data was used for 100% ethanol.

D. DAQ Setup



E. Instruments

1) *Instrument Error List:* table IV lists the necessary instruments for the experiment. The table lists the item, the item model and the manufacturers instrument tolerance. The instruments listed in the table are described in more detail in this section of the appendix.

TABLE IV. MEASUREMENT EQUIPMENT USED

Instrument	Model	Tolerance	Tolerance (Alternative)
Thermocouples	Super OMEGACLAD XL KQXL-116E-12	+/- 1.0C	+/- 0.75%
Scale	OHAUS Scout SPX8200	+/- 1 g	
Calipers	Tritan	+/- 0.5 mm	
Differential Pressure Transducer	OMEGA PCL-1B	0.006% of span	
Differential Pressure Transducer	Dwyer Series MS MagneSense Differential Pressure Transmitter	+/- 0.005 in H ₂ O	
Sampling Tube	Nailor Industries Inc. Model 36FMS Measuring Station	N/A (Will be calibrated)	
Stopwatch	N/A	+/- 0.01 sec	
CO Sensor	Alphasense CO-AF Carbon Monoxide Sensor	+/- 0.5 ppm	
CO_2 Sensor	SainSmart MH-Z14 Sensor Module for Arduino	+/- 50 ppm	
Pitot Tube	N/A	N/A (Will be calibrated)	

2) *Particle Emissions Measurement System:* This section contains some of the images and notes on the PEMS.

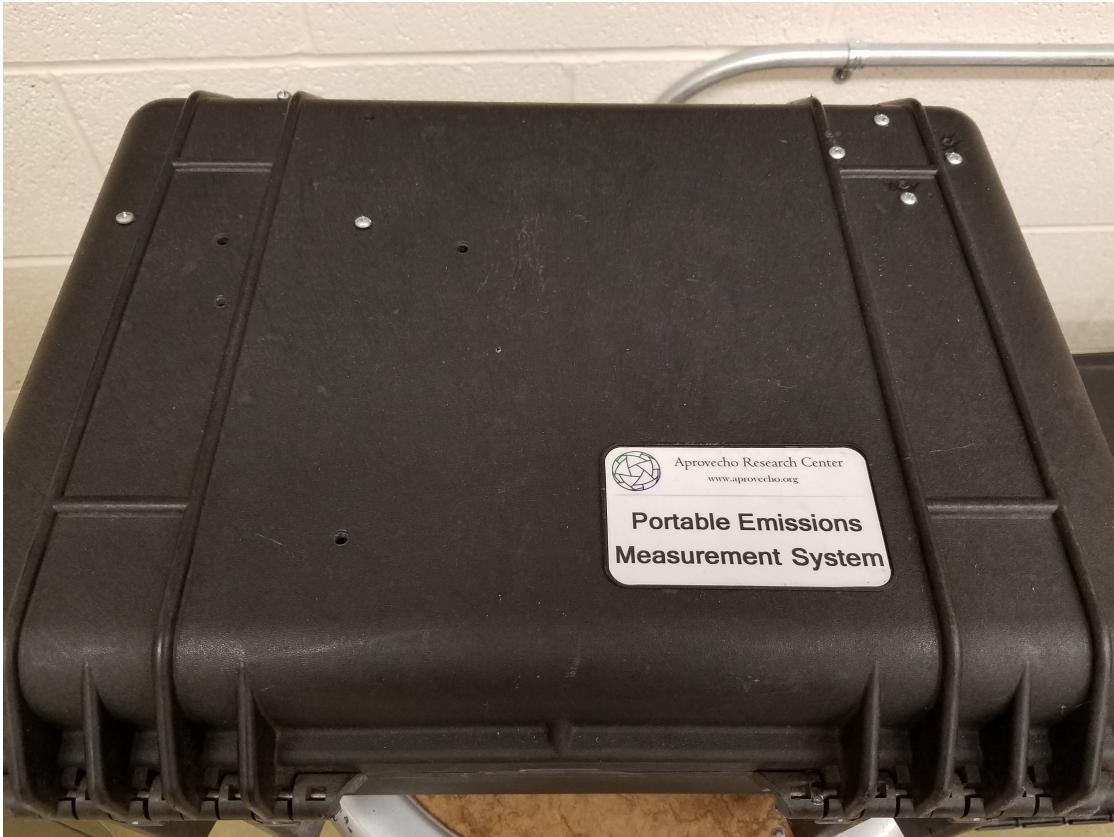


Fig. 12. PEMS case

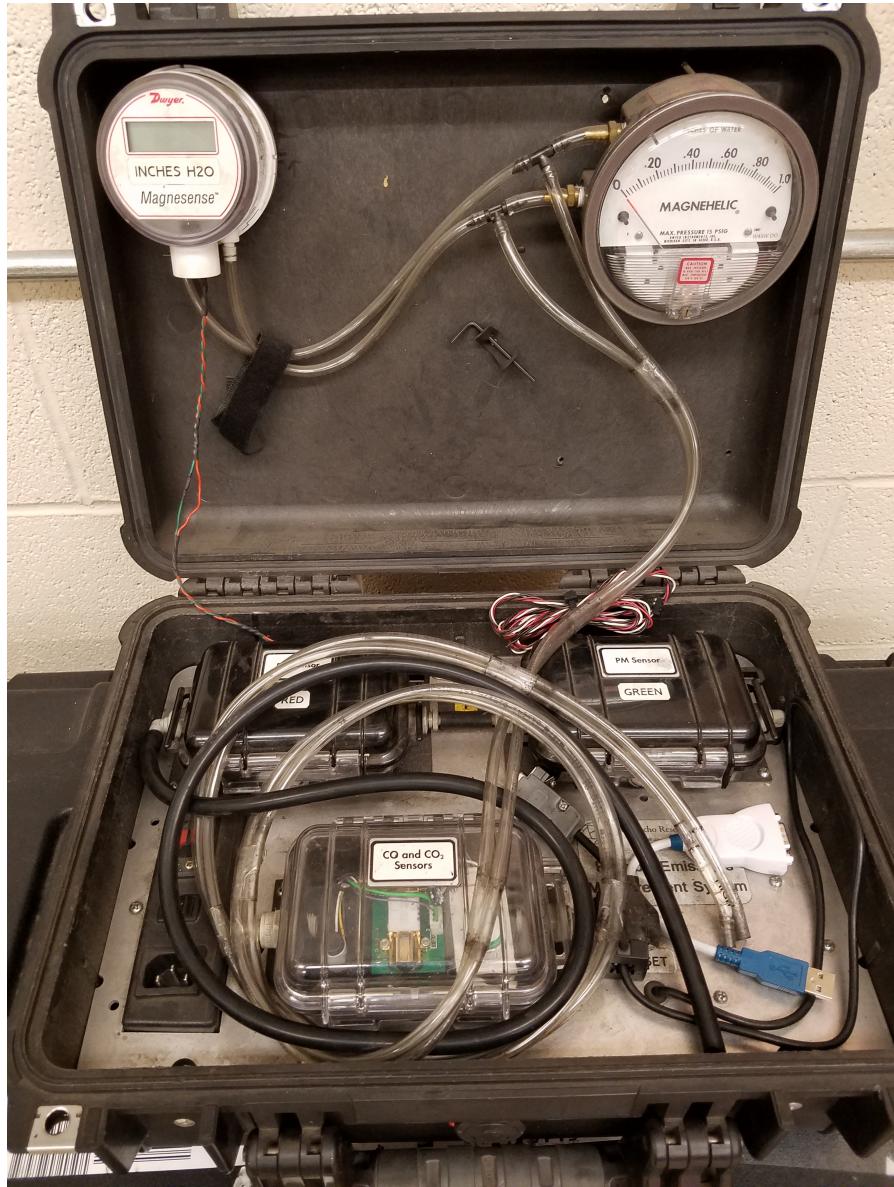


Fig. 13. PEMS case open

Instructions for Use of the Portable Emissions Monitoring System (PEMS)

For PEMS #2022 and Newer

Aprovecho Research Center

Updated November 28, 2012



Aprovecho Research Center
Advanced Studies in Appropriate Technology Laboratory

79093 Highway 99, PO Box 1175
Cottage Grove, Oregon 97424 USA

541-767-0287
www.aprovecho.org

1. Purpose of the PEMS

The purpose of the PEMS is to quantify reductions in health-harming emissions from cooking stoves by collecting, measuring, and analyzing emissions of CO₂, CO, and PM. Collecting emissions is essential for quantifying the total amount of pollution released without the effects of ventilation and dilution within the air of a kitchen. The combustion efficiency of the stove can be understood by investigating the reported measures such as emissions per task completed (specific emissions) and emissions per kilo of fuel burned (emission factors).

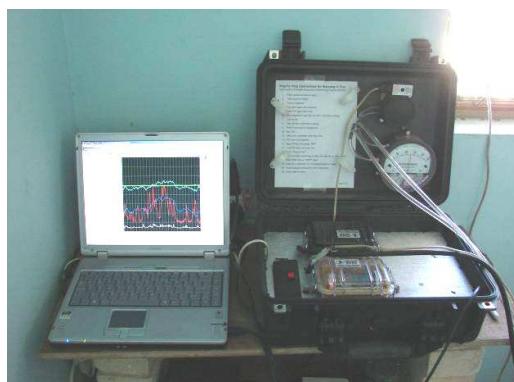


Photo 1: PEMS sensor box and computer



Photo 2: PEMS hood in use



Photo 3: PEMS sensor box, laptop, and hood in cases

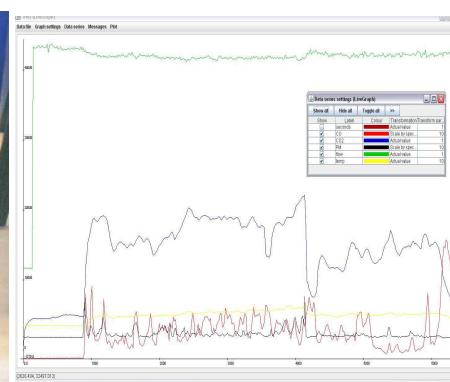


Photo 4: Live graphical readout

2. Uses of the System

2.1 Lab-Based WBT

The WBT is used to optimize stoves in the laboratory. The same fuel, pot, and tending practices are used in every test to eliminate those variables in order to focus on the stove

3) *Omega PCL-1b*: This section includes the PCL-1b catalog information.

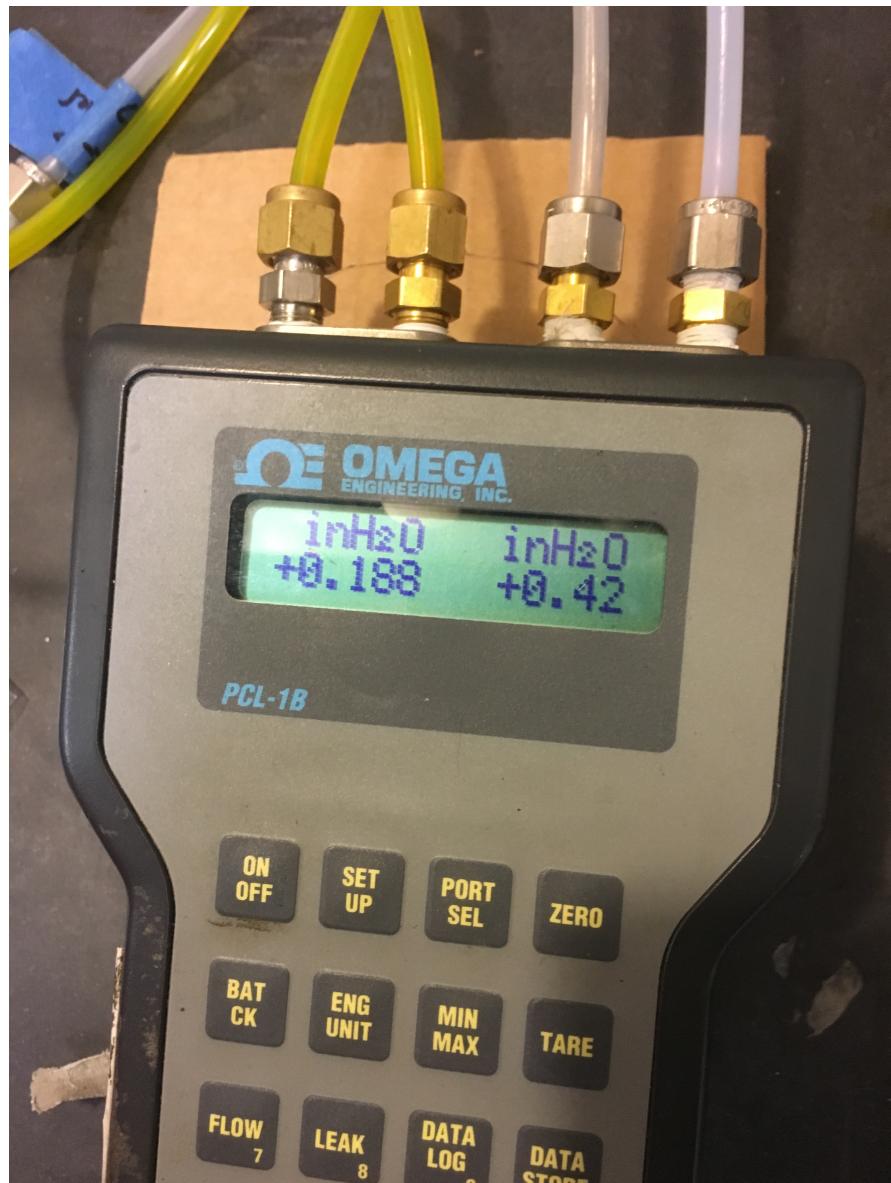


Fig. 14. PCL-1b transducer in use for calibration of flow meter

HANDHELD PRESSURE CALIBRATORS WITH INTERCHANGEABLE INPUT MODULES

A

PRESSURE INSTRUMENTS

PCL-1B Series



- ✓ Plug-In Pressure Modules Cover Ranges from 0.25 inH₂O to 7500 psi
- ✓ Dual Display Shows Applied Pressure and Transducer Output Simultaneously
- ✓ Accurate to ±0.06% Full Scale
- ✓ Measures Pressure, Temperature, Voltage, Current, Flow, and Leak Rate

The OMEGA® PCL-1B pressure calibrators are full featured handheld instruments that can measure pressure, temperature, flow, vacuum, leak, current, voltage, and change of state for switch testing—virtually all pressure measurement and test functions that an application would require.

A complete PCL-1B system consists of a base unit and 1 or 2 plug-in modules. Pressure modules are available in full scale ranges between 0.25 inH₂O and 7500 psi and in gage, vacuum, absolute, differential, and compound pressure types. Three temperature modules are available,



PCL-1B, with 2 plug-in modules, PCL-MB-030G, and PCL-MB-3KG,

for thermocouple (J, K, T, E, R, S, B, and N calibrations), and RTDs (Pt100, Ni120 and Cu120 or Pt1000 types).

When installed in the base unit, these quick-select modules not only afford unparalleled measurement flexibility; they also help protect the pressure sensor from damage. Modules can be switched in just seconds, without tools. In addition to its keypad features (see diagram on next page), the base unit can link to a computer, data acquisition system, or dumb terminal via a standard RS232 connection.

The PCL-1B can accept two removable PCL-M pressure modules, modules sold separately. Visit us online.



4) *Nailor Industry 36FMS*: The Nailor Industry 36FMS flow-meter was given to us to use by Aprovecho Research Center. This device is a 4-pt pitot tube system that averages between the points. A pressure difference is then read by Omega's PC-1b pressure transducer.

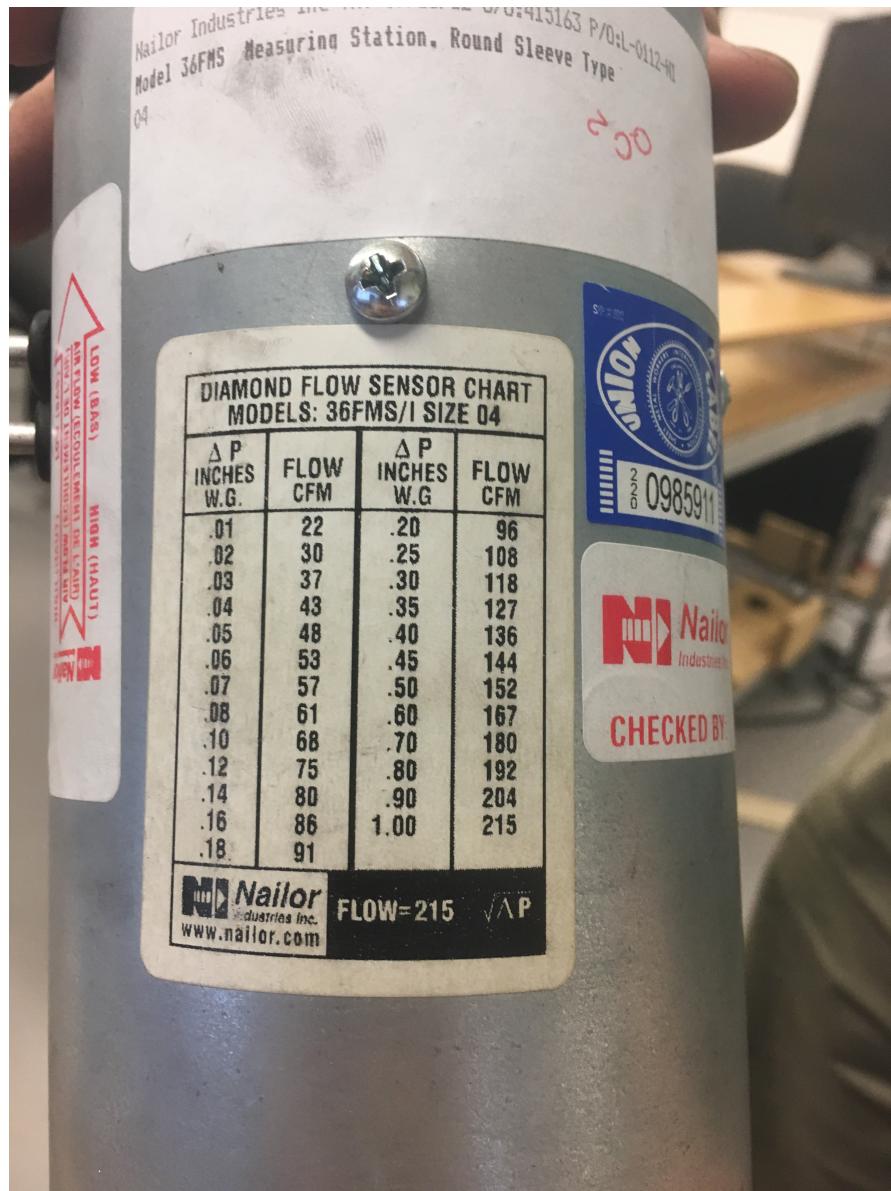
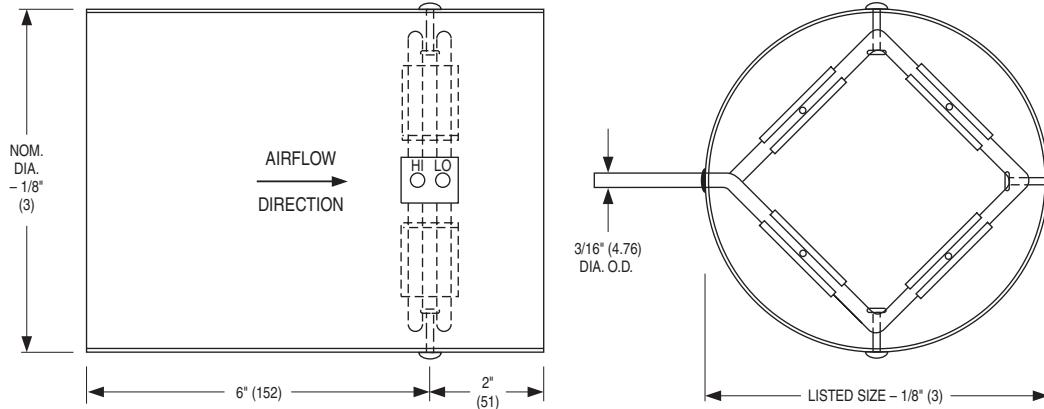


Fig. 15. Nailor series calibration curve printed on the device.



**FLOW MEASURING STATION
ROUND DUCT • SLEEVE TYPE
MODEL: 36FMS**



DESCRIPTION:

The Model 36FMS Flow Measuring Station is a multi-point averaging airflow sensor. It has been designed to provide accurate sensing by sampling air velocities in the four quadrants of a round duct. The differential pressure flow sensor provides an averaged reading at an amplification of approximately 2.5 times the velocity pressure, dependent upon nominal size.

FEATURES:

- Available to suit nominal round ductwork sizes from 4" (102) to 18" (457) diameter.
- All metal construction - no combustible materials in the air stream.
- Amplifies velocity pressure approximately 2.5 times to give a wide range of useful output signal vs. flow.
- Compact size allows easy installation in existing ductwork.
- Sensor design minimizes pressure drop and regenerated noise.
- Label provided on each unit gives airflow vs. signal differential pressure for direct reading of airflow.
- Multi-point sensing gives an accurate output signal with a maximum deviation of only $\pm 5\%$ with a hard 90 degree elbow, provided a straight inlet condition with a minimum length of two equivalent duct diameters is provided.

Unit Size	Recommended Airflow Range	
	cfm	l/s
4	0 – 200	0 – 94
5	0 – 315	0 – 149
6	0 – 450	0 – 212
7	0 – 630	0 – 297
8	0 – 860	0 – 406
9	0 – 1185	0 – 559
10	0 – 1400	0 – 661
12	0 – 1980	0 – 934
14	0 – 2795	0 – 1319
16	0 – 3650	0 – 1722
18	0 – 4800	0 – 2266

SPECIFICATIONS:

Materials: Sensor – aluminum.
Body – 22 ga. (0.85) galvanized steel.
Media: Air or other common inert gases.
Standard Tubing: 1/4" (6.35) O.D. x 0.04" (1.0) wall FR tubing (by others).

OPTIONS:

- Special Features.
Specify: _____

SCHEDULE TYPE:

Dimensions are in inches (mm).

PROJECT:

ENGINEER:

DATE **B SERIES** **SUPERSEDES** **DRAWING NO.**

CONTRACTOR:

8 - 20 - 08 **FMS** **7 - 23 - 03** **36FMS-1**

5) Ohaus Scout scale: Images and product details of the Ohaus Scout scale can be found below.



Fig. 16. ohaus scale with two 200 gram ohaus precision weights



Scout®
Portable Balances



Setting New Standards in Laboratory & Industrial Weighing— The Next Generation of Scout Balances

Ideal for laboratory and industrial applications, the OHAUS Scout comes in a slim, stackable design with large backlit LCD. Features include superior overload protection, multiple weighing units and application modes. Geared for high performance in your facility with fast stabilization time and high resolution weighing results, these portable balances set a new standard in laboratory and industrial weighing.

Standard Features Include:

- **Bright Backlit LCD & 4 Button Control Enable Efficient Operation and Ease of Use**
Combined with a simplified 4 button operation, the Scout's large backlit display increases readability in low light working conditions, and is easier to view from a distance.
- **Bolstered by Superior Overload Protection and Impact-Resistant Pan Support**
Integrated superior overload protection and impact-resistant pan support safeguard against shock and overloading the balance in rugged and demanding environments.
- **Better Performance and Higher Capacities Widen the Range of Weighing Applications**
Stabilization time as fast as 1 sec and advanced weighing technology, lead to improved productivity in your facility. Increased capacity unlocks a wider range of weighing applications.

Scout® Portable Balances

Improved Experience with Backlit Display and 4 Button Operation

Poor lighting environment is not an issue with the Scout. The large, bright backlit LCD display improves readability in conditions where lighting is poor, and makes it easy to see the results from a distance. 4 clearly marked buttons remove complexity, and guide you quickly and easily through setup, unit of measure changes, calibration and more.



Durability Guaranteed with Superior Protective Features

The Scout equipped with superior overload protection rated at 10 times the capacity of the balance, high strength stainless steel pan, impact-resistant pan support and integrated transportation/storage lock, delivers the same durable quality that you expect from OHAUS products. To complement our signature durability, we've designed the Scout to be stackable when utilizing the optional stacking and storage cover, which also protects the balance when not in use.



Most Versatile Portable Balance in its Class

With the Scout, it's all about accuracy, efficiency and possibilities! Stabilization time as fast as 1 sec means increased productivity in any facility or lab. With improved resolution, you can count on extremely precise and repeatable weighing results. Additionally, the increased capacity of the Scout gives you more flexibility in your weighing applications.



Draftshield Model Available

Scout's ingenious draftshield (1mg models only) was designed with an easy to remove top cover piece. This serves as a wind protection ring which keeps the weighing surface stable in rough environments, while maintaining weighing speed.



Built-in Application Modes

- **Weighing**—Determines the weight of items on the pan in the selected unit of measure.
- **Parts Counting**—Counts the number of pieces on the pan using a uniform weight.
- **Percent Weighing**—Measures the weight of a sample displayed as a percentage of a pre-established reference weight.
- **Check Weighing**—Compares the weight of a sample against target limits.
- **Totalization**—Measures cumulative weight of multiple items. Cumulative total may exceed balance capacity.
- **Display Hold**—Manually holds the last stable weight or the first highest stable weighing value on the display.



Draftshield

Protects the sample from external influences, increasing the speed and repeatability of measurements



Connectivity

Expanded connectivity options including RS232, USB Host, USB Device, Ethernet and Bluetooth®



Security Slot

Integrated security slot prevents theft



Large Backlit LCD Display

High contrast LCD Display displays weight and application data clearly, even in poor lighting conditions



Weigh Below Hook

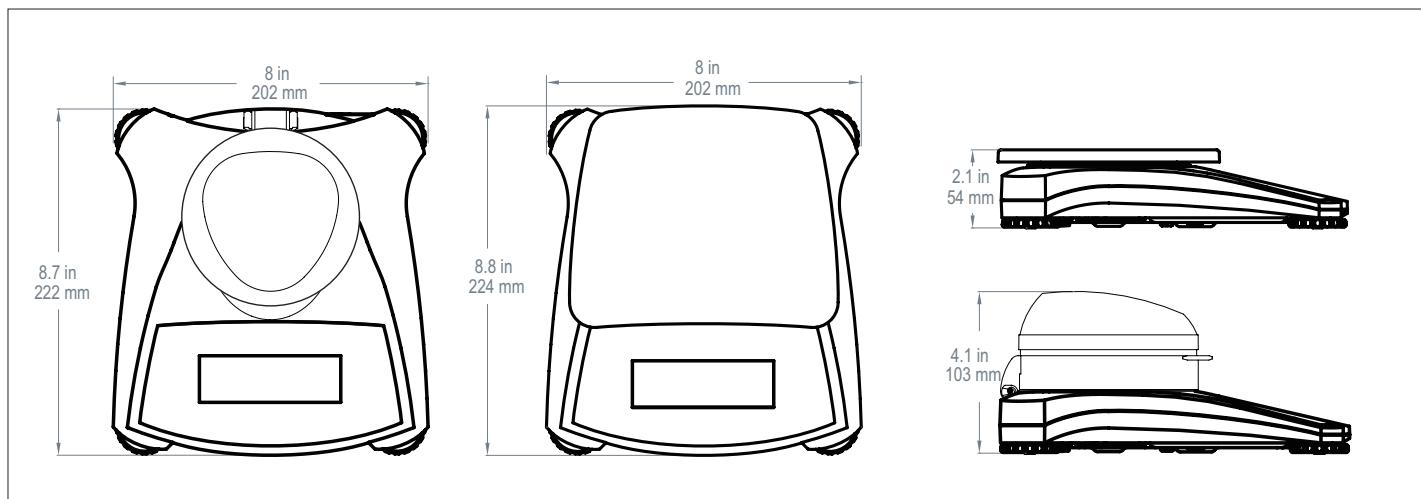
The integral weigh below hook on the bottom of the Scout allows for density determination or specific gravity calculations



Lockswitch

The Scout can be locked into a specific configuration using the lockswitch

Outline Dimensions



Scout® Portable Balances

Model	SPX123	SPX223	SPX222	SPX422	SPX622	SPX1202	SPX2202	SPX421	SPX621	SPX2201	SPX6201	SPX8200																					
Capacity (g)	120	220	220	420	620	1200	2200	420	620	2200	6200	8200																					
Readability (g)	0.001	0.001	0.01	0.01	0.01	0.01	0.01	0.1	0.1	0.1	0.1	1																					
Repeatability (Std. Dev.) (g)	0.002	0.002	0.01	0.01	0.01	0.02	0.02	0.1	0.1	0.1	0.1	1																					
Linearity (g)	0.003	0.003	0.01	0.01	0.02	0.03	0.03	0.1	0.1	0.1	0.2	1																					
Capacity x Readability (kg)	N/A	N/A	N/A	N/A	N/A	1.2 × 0.00001	2.2 × 0.00001	N/A	N/A	2.2 × 0.0001	6.2 × 0.0001	8.2 × 0.001																					
Capacity x Readability (lb)	N/A	N/A	N/A	N/A	1.36690 × 0.00005	2.64555 × 0.00005	4.85020 × 0.00005	N/A	1.3670 × 0.0005	4.8500 × 0.0005	13.6685 × 0.0005	18.080 × 0.005																					
Span Calibration Mass*	100 g	200 g	200 g	200 g	300 g	1 kg	2 kg	200 g	300 g	2 kg	5 kg	8 kg																					
Linearity Calibration Mass*	50, 100 g	100, 200 g	100, 200 g	200, 400 g	300, 600 g	500g, 1 kg	1 kg, 2 kg	200, 400 g	300, 600 g	1 kg, 2 kg	3 kg, 5 kg	4 kg, 8 kg																					
Stabilization Time (s)	1.5	1.5	1	1	1	1.5	1.5	1	1	1	1	1																					
Construction	ABS housing & stainless steel pan																																
Draftshield	Yes	No																															
Calibration	User-selectable external span or linearity calibration/Digital with external weight																																
Tare Range	Full capacity by subtraction																																
Weighing Units	g, kg, ct, N, oz, ozt, dwt, lb, lb:oz, grn																																
Application Modes	Weighing, Parts Counting, Percent Weighing, Check Weighing, Totalization, Display Hold																																
Power Requirement	AC adapter (included) or 4 AA batteries (not included)																																
Typical Battery Life (Hours)	80	120	80			120			80	120																							
Communication	RS232, USB Host, USB Device, Ethernet or Bluetooth® (available as an accessory)																																
Display Type	Liquid crystal display (LCD) with backlight																																
Display Size	0.78 in/20 mm digits																																
Overload Capacity	10 times rated capacity																																
Operating Temperature Range	50°F / 10°C to 104°F / 40°C at 10% to 85% relative humidity, non-condensing																																
Storage Conditions	-20°C (-4°F) to 55°C (131°F) at 10% to 90% relative humidity, non-condensing																																
Pan Size (W × D)	Ø3.7in/ 93 mm	Ø4.7in/ 120 mm			6.7 × 5.5 in/ 170 × 140 mm			Ø4.7 in/ 120 mm	6.7 × 5.5 in/ 170 × 140 mm																								
Balance Dimensions (W × D × H)	8 × 8.7 × 4.1 in/ 202 × 222 × 103 mm	8 × 8.8 × 2.1 in/ 202 × 224 × 54 mm																															
Shipping Dimensions (W × D × H)	11.8 × 9.8 × 5.1 in/ 300 × 250 × 129 mm	11.8 × 9.8 × 3.4 in / 300 × 250 × 86 mm																															
Net Weight	1 kg																																
Shipping Weight	1.5 kg																																

* Calibration weights are included with models up to 620g capacity.

Other Standard Features and Equipment

Transportation lock, stainless steel pan, menu & calibration lockout switch, slip-resistant and adjustable feet, leveling bubble, mechanical and software overload/underload protection, stability indicator, auto tare, low battery indicator, auto shut-off, user selectable printing options, user selectable communication settings

Compliance

- Product Safety: IEC/EN 61010-1; CAN/CSA C22.2 No. 61010-1; UL Std. No. 61010-1
- Electromagnetic Compatibility: IEC/EN 61326-1 Class B; FCC Part 15 Class B; Industry Canada ICES-003 Class B

Accessories

RS232 Interface Kit	30268982
USB Host Interface Kit	30268983
USB Device Interface Kit.....	30268984
Bluetooth Interface Kit	30268985
Ethernet Interface Kit.....	30268986
Stacking & Storage Cover (6 pcs)	30268987
Stacking & Storage Cover (1 pc)	30268988
Printer, Impact, SF40A, AM	30064203
Auxiliary Display Kit.....	30269019
Security Device.....	80850043
Top Loading Kit for Density Determination	30269020
Carrying Case	30269021
In-use Cover.....	30269022

OHAUS CORPORATION

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With offices throughout
Europe, Asia and
Latin America

*ISO 9001:2008
Registered Quality
Management System



6) Omega Type-K Thermocouples: the first information page on the thermocouples can be found below

Super OMEGACLAD® XL Thermocouple Probes

A Technological Advance in Temperature Measurement



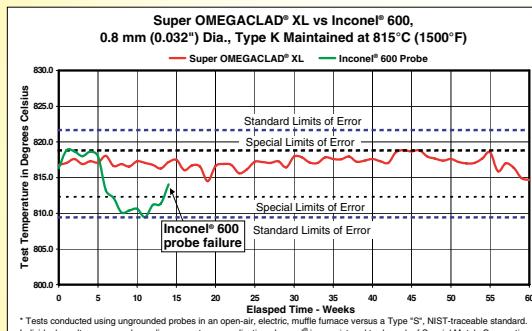
KQXL-18U-12, shown smaller than actual size.

- ✓ Thermocouple Technology from OMEGA for K and N Calibrations Only
- ✓ Super Stable Temperature Drift—Less than 2.8°C in 25 weeks
- ✓ Better Performance at a Smaller Size—0.8 mm Probe Withstands 815°C (1500°F) for 3 Years
- ✓ Probe Life Expectancy up to 10 Times Greater than Competing Devices*
- ✓ Handles Temperatures Up to 1335°C (2400°F)

High Performance!

**An Exclusive
OMEGA
Manufactured
Innovation**

OMEGA brings you the Super OMEGACLAD® XL Thermocouple Probe family, the exclusive innovation in thermocouple technology. Manufactured using state-of-the-art processes for mineral insulated (MI) thermocouple cable and finished thermocouple probe assemblies, these temperature sensors maximize performance, even at extremely small diameters. The devices resist carburization, oxidation, and chlorination in tough environments.



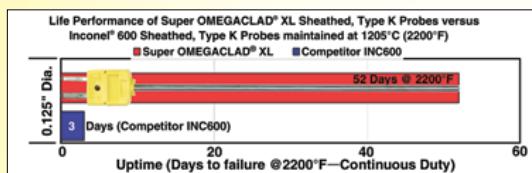
Small Size, Big Performance!

Typical 0.8 mm (0.032") Dia. Type K probes have a maximum temperature of 700°C (1260°F). Our Super OMEGACLAD® XL 0.8 mm (0.032") Dia. probe took on 815°C (1500°F) for 3 years and even reached 1000°C (1832°F) for 2 months!

0.250"
2.25 sec**
0.125"
0.55 sec**
0.062"
0.3 sec**
0.032"
~0.25 sec**

Probes shown ~50% smaller than actual size.

** Approx. response time—ungrounded in water



1204°C (2200°F) replace 17 of theirs in 52 days or just one of ours!

In life-cycle lab testing, the OMEGACLAD® XL sheathed, 0.125" Type K Probe operated continuously for 52 days at 1204°C (2200°F) while competitors' 0.125" Inconel® 600 sheathed, Type K probes lasted 3 days.†

† Results will vary on application and operating environment.

Long Life, Low Maintenance!

If your application operates at the punishing temperature of nearly 1204°C (2200°F), changing out failed thermocouples costs money in excessive maintenance, slows or cuts production, and can cause inconsistent product quality.

In head-to-head tests, Super OMEGACLAD® XL Thermocouple probes consistently post the best performance results. Our innovative temperature sensors last upwards of 10 times or longer when compared to competitors' Inconel® 600 sheathed probes of equal or larger diameters. Let OMEGA's leading edge products help engineer **your next innovation!**

Fig. 17. Omega thermocouples

F. Operating Procedures

	Task	Description
1	Start up fume hood	Start up the fume hood and ensure that air is flowing through the ducts
2	Set flow rate	Set the flow rate and record value for data processing
3	Start up emissions software	open up the emissions software package and check to see if it is gathering data.
4	Zero CO and CO2	Run for 10 minutes prior to ignition step to get an average ppm in the ambient air for a zero,
5	Measure Ambient Temperature	Measure the Ambient temperature for reference value
6	Tare scale to pot	Tare scale to wieght of the pot used to boil water
7	Wiegh water	poor the water into the pot and wiegh it till the scale stops oscillating in values, Record the value
8	Tare scale to stove	Tare scale to wieght of the stove that will contain the fuel
9	Wiegh fuel	Poor fuel into stove till it reaches the first lip. then wiegh the stove with the fuel till the scale stops oscilating. record value
10	Ignite fuel	Using a long lighter, ignite the fuel. When a visible flame sets up remove lighter.
11	Start timer	Begin timing burn.
12	Stop	Stop the timer when all fuel is consumed and the flame visible goes out. Record time
13	Export data file	Export the data file to be used in data processing.

G. Mixing Procedures

We will be diluting the ethanol by percent weight

- 1) Calculate percent weight of water and measure and weigh accordingly.
- 2) Weigh desired quantity of ethanol.
- 3) Once the ethanol weight is within +/- one percent of desired weight mix with the water and pour into a nonreactive container(plastic bottle is sufficient).
- 4) Seal the container and label it with the calculated weight percentage and that state clearly that the contents are fuel and flammable.
- 5) for clean up place all fuels in the flammables storage cabinet.

H. Code

Example code for one test run:

```
#!/usr/bin/env python3
# -*- coding: utf-8 -*-
"""
"""

Created on Thu Feb  2 10:10:13 2017
```

This program uses the uncertainties package in Python to automatically calculate and propagate the uncertainties in the equations for the ME 552 Winter 2017 Group 1 project. The method used to propagate the uncertainties is the Kline McClintock method.

```
@author: andrewalferman
"""

# Import the required packages
import scipy.constants as const
import pint
```

```
"""
This program is not configured to run automatically and solve every set of data simultaneously, so the numbers below must be manually updated for each of the different measurements.
```

```
Also note that all values will be in meters, Pa, seconds, kg, etc.
"""

# Define the universal constants
ureg = pint.UnitRegistry()
Q_ = ureg.Quantity
R = 8.3145 * ureg.joule / (ureg.mol * ureg.kelvin)
# Specific gas constant of air
R_air = 287.058 * ureg.joule / (ureg.kilogram * ureg.kelvin)
NA = (const.Avogadro / ureg.mol).plus_minus(0)
# Heat of vaporization, assumed to be constant
hv = 2258000. * ureg.joule / ureg.kilogram
# Specific heat of water at ambient temperature
cpw = 4186. * ureg.joule / (ureg.kilogram * ureg.kelvin)
# Specific heat of aluminum at ambient temperature
cpm = 910. * ureg.joule / (ureg.kilogram * ureg.kelvin)
# Energy density of ethanol
Uethanol = 29.64 * ureg.megajoule / ureg.kilogram
# Density of ethanol
Methanol = 0.04607 * ureg.kilogram / ureg.mol
# Density of 100 percent ethanol
ethrho100 = 0.78934 * ureg.kilogram / ureg.liter
# Density of 90.1 percent ethanol
ethrho90 = 0.81770 * ureg.kilogram / ureg.liter
# Density of 80.3 percent ethanol
ethrho80 = 0.84270 * ureg.kilogram / ureg.liter
# Density of 70.1 percent ethanol
ethrho70 = 0.86742 * ureg.kilogram / ureg.liter
# Molecular weight of CO
MCO = 28.01 * ureg.gram / ureg.mol

# Put all the equipment tolerances in here
thermocouples = 2.2 * ureg.kelvin # Based on Type K thermocouple documentation
thermometer = 0.2 * ureg.rankine # Based on the resolution of the thermometer
barometer = 0.5 * ureg.millibar # Based on the resolution of the barometer
caliper = 0.5 * ureg.millimeters # Based on the resolution of the caliper used
scale1 = 1.0 * ureg.gram # Based on the scale documentation
```

```

press = 0.005 * ureg.inch_H2O_39F # Based on the DP gage documentation
stopwatch = 0.01 * ureg.second # Photograph the stopwatch to achieve this
CO = 0.5 * 1.e-6 # Based on PEMS documentation
CO2 = 50 * 1.e-6 # Based on PEMS documentation
graduatedcyl = 0.5 * ureg.milliliter # Based on the resolution of the cylinder
ethtol = 0.03 * ureg.megajoule / ureg.kilogram # Based on article

```

"""

MEASUREMENT VALUES START HERE

"""

```

# Add in all of the measured masses
fuelmass = 41.2 * ureg.gram # Measured value
potmeasurement = 99.3 * ureg.gram # Measured value
watermassmeasurement = 590 * ureg.gram # Measured value
ethanolmass = 318 * ureg.gram # Measured value
bottletotal = 396 * ureg.gram # Measured value
hotwatermass = 440 * ureg.gram # Measured value

# Poured volume of fuel in liters
fuelvolume = 50 * ureg.milliliter # Measured value

# Temperature measurements
starttemp = 296.25 * ureg.kelvin # Measured value
tempreading = Q_(75.7, ureg.degF) # Measured value
ambienttemp = tempreading.to(ureg.kelvin) # Convert to kelvin
finaltemp = 365.65 * ureg.kelvin # Measured value

# Add in the pressure measurements of the sampling tube
# Will be input and output in inches of water
pressurediff = 0.455775 * ureg.inch_H2O_39F # Measured value

# Absolute pressure in Pascals
barpressure = 1024. * ureg.millibar # Measured value

# Exhaust gas constituent measurements
# Points 40 to 621 were measured
COlevel = 12.3252 * 1.e-6 * ureg.mol/ureg.mol # Measured value
CO2level = 291.7894 * 1.e-6 * ureg.mol/ureg.mol # Measured value

```

Add in burn time, in seconds

```

minutes = 28. * ureg.minute # Measured value
seconds = 42. * ureg.second # Measured value

```

"""

CALCULATION STARTS HERE

"""

```

# Add uncertainties to all of the measured values
fuely = fuelvolume.plus_minus(graduatedcyl)
methanol = ethanolmass.plus_minus(scale1)
mbottle = bottletotal.plus_minus(scale1)
mpot0 = potmeasurement.plus_minus(scale1)
mpot1 = watermassmeasurement.plus_minus(scale1)
mpot2 = hotwatermass.plus_minus(scale1)
deltaP = pressurediff.plus_minus(press)
Pabsolute = barpressure.plus_minus(barometer)
COppm = COlevel.plus_minus(CO)
CO2ppm = CO2level.plus_minus(CO2)
burntime = (minutes + seconds).plus_minus(1.).to(ureg.second)
T0 = starttemp.plus_minus(thermocouples)
Tambient = ambienttemp.plus_minus(thermometer)

```

```

TE = finaltemp.plus_minus(thermocouples)
Uethanol = Uethanol.plus_minus(ethtol)

# Plug in each of the equations and solve. The bottom of the tree is computed
# first in order to allow computation of the higher level tolerances.
mfuel = (fuelv * ethrho80).to(ureg.kilogram)
rho_air = (Pabsolute / (R_air * Tambient)).to(ureg.kilogram / ureg.meter**3)
mwater1 = (mpot1 - mpot0).to(ureg.kilogram)
mwater2 = (mpot2 - mpot0).to(ureg.kilogram)
mevap = (mpot1 - mpot2).to(ureg.kilogram)
Cx = methanol / mbottle
Ux = (Uethanol * Cx).to(ureg.joule / ureg.kilogram)
Ereleased = (mfuel * Ux).to(ureg.joule)
EH2Oevap = (mevap * hv).to(ureg.joule)
deltaT = (TE - T0).to(ureg.kelvin)
N = (215. * (ureg.ft**3) /
      (ureg.minute*(ureg.inch_H2O_39F**0.5))).plus_minus(0)
Vdottube = (N*(deltaP**0.5)).to(ureg.meter**3 / ureg.second)
C = (1.5998468653396583 * ureg.meter/ureg.meter).plus_minus(
      0.02159726001744998) # Calibrated value
Vdot = Vdottube * C
V = (Vdot * burntime).to(ureg.meter**3)
COpartial = Pabsolute * COppm
CO2partial = Pabsolute * CO2ppm
nco = ((NA * COpartial * V) / (R * Tambient)).to('')
nco2 = ((NA * CO2partial * V) / (R * Tambient)).to('')
nethanol = NA * mfuel * Cx / Methanol
EH2Oheat = mwater2*cpw*deltaT + mpot0*cpm*deltaT
hc = (EH2Oheat + EH2Oevap) / Ereleased
epsilon = nco / (2 * nethanol)
epsilon2 = nco2 / (2 * nethanol)
sigma = ((nco * MCO / NA) / (EH2Oevap +
                               EH2Oheat)).to(ureg.gram / ureg.megajoule)

print('CONCENTRATION: {:.1f}%'.format(Cx.n * 100))
print('Sunday Value')
print('_____')
print('THERMAL-EFFICIENCY_(h_c)')
print('Nominal_value: {:.2f}%'.format(hc.n * 100.))
print('Relative_uncertainty: +/- {:.2f}%'.format(hc.rel * 100.))
print('_____')
print('CO_PRODUCTION')
print('Nominal_value: {:.2f}%'.format(epsilon.n * 100.))
print('Relative_uncertainty: +/- {:.2f}%'.format(epsilon.rel * 100.))
print('_____')
print('CO2_PRODUCTION')
print('Nominal_value: {:.2f}%'.format(epsilon2.n * 100.))
print('Relative_uncertainty: +/- {:.2f}%'.format(epsilon2.rel * 100.))
print('_____')
print('NORMALIZED_EMISSIONS')
print('Nominal_value: {:.2f}'.format(sigma.n))
print('Relative_uncertainty: +/- {:.2f}%'.format(sigma.rel * 100.))

```

Example code output:

- CONCENTRATION: 80.3%
- Sunday Value
- THERMAL EFFICIENCY (h_c)
 - Nominal value: 44.27%
 - Relative uncertainty: +/- 1.64%
- CO Production
 - Nominal value: 6.56%

- Relative uncertainty: +/- 5.65%
- CO2 Production
 - Nominal value: 155.23%
 - Relative uncertainty: +/- 17.58%
- NORMALIZED EMISSIONS
 - Nominal value: 6.08
 - Relative uncertainty: +/- 5.68%

Example code for reading PEMS file and producing plots:

```
#!/usr/bin/env python3
# -*- coding: utf-8 -*-
"""
Created on Sat Mar 11 13:38:45 2017

@author: andrewalferman
"""

"""
Reader file for the ME552 Winter 2017 Group 1 Term Project
This file grabs all of the raw data from the csv files that the portable
emissions measurement system (PEMS) software generates, and processes it into a
more user friendly file. It also generates plots of all of the data, if
desired.

The file is currently configured to not process some of the data from the files
due to missing data from the PEMS output.
"""

import os as os
import numpy as np
import csv as csv
import pylab as pyl
import pint

def concentrations(CO,CO2,**mod):
    if ('startpoint' in mod):
        CO = CO[mod['startpoint']:]
        CO2 = CO2[mod['startpoint']:]
    COtotal = 0.
    CO2total = 0.
    for i in range(len(CO)):
        COtotal += float(CO[i])
        CO2total += float(CO2[i])
    COtotal = (COnumber / len(CO)) - float(CO[0])
    CO2total = (CO2number / len(CO2)) - float(CO2[0])
    return COnumber, CO2number

def avgval(vals):
    total = 0.
    for i in range(len(vals)):
        total += float(vals[i])
    return total/len(vals)

"""

If all goes well, you should only need to update the portion of the code
between these two commented lines.
"""

# Enter the filename that you want to parse. Don't add in the ".csv"
filename = '90_11mar2017_1401'
```

```

# Make this a 1 if you want to save the data or plot the data
savefile = 0
plotfigs = 0

"""
"""

# Get the current path to add to the filename
currentpath = os.getcwd()

# Need to look at each file and determine which row has the multipliers , and
# which row is the last row of column headers .
multiplierrows = {'70_12mar2017_1': 4, '80_12mar2017_1': 5,
                  '90_12mar2017_1': 5, '100_12mar2017_1': 4,
                  '70_11mar2017_1530': 4, '80_11mar2017_1440': 5,
                  '90_11mar2017_1401': 4
                  }

# Use this dictionary for all of the starting point values for emmission avg
starts = {'70_12mar2017_1': 0, '80_12mar2017_1': 40, '90_12mar2017_1': 120,
           '100_12mar2017_1': 140, '70_11mar2017_1530': 80,
           '80_11mar2017_1440': 159, '90_11mar2017_1401': 40
           }

# Initialize lists to append the corrected data to
sec = []
CO = []
CO2 = []
PMred = []
flow = []
fluetemp = []
ThermoCo = []
PMgreen = []
FlowGrav = []
COtemp = []
gastemp = []
rlas = []
temp = []
rboxtemp = []
glastemp = []
gboxtemp = []
#gashboxRH = []
#PMgrenRH = []
chiptemp = []

# Read the data
with open(currentpath + '/Data/' + filename + '.csv', 'r', newline='') as f:
    reader = csv.reader(f, delimiter=',')
    # Iterate accross the rows, and use a counter to grab the information
    rownum = 1
    for row in reader:
        # Grab the multipliers
        if rownum == multiplierrows[filename]:
            COMult = float(row[1])
            CO2mult = float(row[2])
            PMredmult = float(row[3])
            flowmult = float(row[4])
            fluetempmult = float(row[5])
            ThermoComult = float(row[6])
            PMgreenmult = float(row[7])
            FlowGravmult = float(row[8])

```

```

COtempmult = float(row[9])
gastempmult = float(row[10])
rlasmult = float(row[11])
tempmult = float(row[12])
rboxtempmult = float(row[13])
glastempmult = float(row[14])
gboxtempmult = float(row[15])
#gasboxRHmult = float(row[16])
# This if statement cuts off all the info at the top of the file
if rownum > multiplierrows[filename] + 3:
    # Convert all of the data from strings to floats
    row = [float(e) for e in row if e]
    # Test to see if the row contains most of the useful information
    try:
        test = row[8]
        realrow = True
    except IndexError:
        realrow = False
    # Append all of the useful data from the larger rows
    if realrow == True:
        sec.append(row[0])
        CO.append(row[1])
        CO2.append(row[2])
        PMred.append(row[3])
        flow.append(row[4])
        fluetemp.append(row[5])
        ThermoCo.append(row[6])
        PMgreen.append(row[7])
        FlowGrav.append(row[8])
        COtemp.append(row[9])
        gastemp.append(row[10])
        rlas.append(row[11])
        temp.append(row[12])
        rboxtemp.append(row[13])
        glastemp.append(row[14])
        gboxtemp.append(row[15])
        #gasboxRH.append(row[16])
    # Append the data from the smaller rows
    else:
        #PMgrenRH.append(row[-2])
        chiptemp.append(row[-1])
else:
    pass
# Be sure to progress the counter
rownum += 1

# Incorporate the multiplier on each of the lists , as applicable
CO = [x * COmult for x in CO]
CO2 = [x * CO2mult for x in CO2]
PMred = [x * PMredmult for x in PMred]
flow = [(x - 10550.)/41000. for x in flow]
fluetemp = [x * fluetempmult for x in fluetemp]
ThermoCo = [x * ThermoComult for x in ThermoCo]
PMgreen = [x * PMgreenmult for x in PMgreen]
FlowGrav = [x * FlowGravmult for x in FlowGrav]
COtemp = [x * COtempmult for x in COtemp]
gastemp = [x * gastempmult for x in gastemp]
rlas = [x * rlasmult for x in rlas]
temp = [x * tempmult for x in temp]
rboxtemp = [x * rboxtempmult for x in rboxtemp]
glastemp = [x * glastempmult for x in glastemp]
gboxtemp = [x * gboxtempmult for x in gboxtemp]

```

```

#gasboxRH = [x * gasboxRHmult for x in gasboxRH]

# Put headers on each of the rows (which will be converted to columns)
sec = np.hstack((('seconds', sec)))
CO = np.hstack((('CO', CO)))
CO2 = np.hstack((('CO2', CO2)))
PMred = np.hstack((('PMred', PMred)))
flow = np.hstack((('DP', flow)))
fluetemp = np.hstack((('fluetemp', fluetemp)))
ThermoCo = np.hstack((('ThermoCo', ThermoCo)))
PMgreen = np.hstack((('PMgreen', PMgreen)))
FlowGrav = np.hstack((('FlowGrav', FlowGrav)))
COtemp = np.hstack((('COtemp', COtemp)))
gastemp = np.hstack((('gastemp', gastemp)))
rlas = np.hstack((('rlas', rlas)))
temp = np.hstack((('temp', temp)))
rboxtemp = np.hstack((('rboxtemp', rboxtemp)))
glastemp = np.hstack((('glastemp', glastemp)))
gboxtemp = np.hstack((('gboxtemp', gboxtemp)))
#gasboxRH = np.hstack((('gasboxRH', gasboxRH)))
#PMgrenRH = np.hstack((('PMgrenRH', PMgrenRH)))
chiptemp = np.hstack((('chiptemp', chiptemp)))

# Putting it like this so that we can easily forego columns
A = np.array([sec,
              CO,
              CO2,
              PMred,
              flow,
              fluetemp,
              ThermoCo,
              PMgreen,
              FlowGrav,
              COtemp,
              gastemp,
              rlas,
              temp,
              rboxtemp,
              glastemp,
              gboxtemp,
              #gasboxRH,
              #PMgrenRH,
              chiptemp
              ])
# Need to transpose the data for it to be written in a csv, if desired
A = np.transpose(A)

# Find the region of interest based on where we have values for ThermoCo
imin = 9999
imax = 0
for i in range(1, len(ThermoCo)):
    # 6553.6 chosen because that's the value that is returned when the
    # thermocouple is disconnected
    if float(ThermoCo[i]) != 6553.6 and i < imin:
        imin = i
    if float(ThermoCo[i]) != 6553.6 and i > imax:
        imax = i

# Save the data in a csv file, if desired
if savefile == 1:
    with open(filename + '_corrected_flow.csv', 'w', newline='') as f:
        writer = csv.writer(f)

```

```

writer.writerow(A)

# Plot the data, if desired
if plotfigs == 1:
    # Plot only the data we want
    xmin = float(sec[imin])
    xmax = float(sec[imax])
    size = (6, 4.5)
    fs = 14
    dots = 900
    # Start at 1 because seconds vs. seconds is useless
    for i in range(1, len(A[0,:])):
        pyl.figure(i-1, figsize=size, dpi=dots)
        pyl.plot(sec[imin:imax], A[imin:imax,i])
        pyl.xlabel('Time_(Seconds)', fontsize=fs)
        pyl.grid(True)
        pyl.xlim(xmin, xmax)

    # Add the figure specific labels and settings
    # Keep in mind that it is not configured to plot gasboxRH or PMgrenRH
    # currently
    pyl.figure(0)
    pyl.ylabel('CO_Concentration_(ppm)', fontsize=fs)
    pyl.ylim(0,)
    pyl.figure(1)
    pyl.ylabel('CO2_Concentration_(ppm)', fontsize=fs)
    pyl.figure(2)
    pyl.ylabel('PMred_Value', fontsize=fs)
    pyl.figure(3)
    pyl.ylabel('DP_Value', fontsize=fs)
    pyl.figure(4)
    pyl.ylabel('Flue_Temp_Value', fontsize=fs)
    pyl.figure(5)
    pyl.ylabel('Pot_Temperature_(\$^\circ C)', fontsize=fs)
    pyl.figure(6)
    pyl.ylabel('PMgreen_Value', fontsize=fs)
    pyl.figure(7)
    pyl.ylabel('FlowGrav_Value', fontsize=fs)
    pyl.figure(8)
    pyl.ylabel('CO_Temp_Value', fontsize=fs)
    pyl.figure(9)
    pyl.ylabel('Gas_Temp_Value', fontsize=fs)
    pyl.figure(10)
    pyl.ylabel('RLAS_Value', fontsize=fs)
    pyl.figure(11)
    pyl.ylabel('Temp_Value', fontsize=fs)
    pyl.figure(12)
    pyl.ylabel('Rbox_Temp_Value', fontsize=fs)
    pyl.figure(13)
    pyl.ylabel('GLAS_Temp_Value', fontsize=fs)
    pyl.figure(14)
    pyl.ylabel('Gbox_Temp_Value', fontsize=fs)
    pyl.figure(15)
    pyl.ylabel('Chip_Temp_Value', fontsize=fs)

# Show the goods
pyl.show()

# Display the average CO and CO2 concentrations as well as the average DP
COavg, CO2avg = concentrations(CO[imin:imax],
                                 CO2[imin:imax],
                                 startpoint=(starts[filename]-imin + 1))

```

```

        )

# Some fluctuations in one file that we want to fix
if filename == '100_12mar2017_1':
    imin += 4

# Find the temperature of the water at the start and stop of the WBT
ureg = pint.UnitRegistry()
Q_ = ureg.Quantity
Tempmin = Q_(float(ThermoCo[imin]), ureg.degC)
Tempmax = Q_(float(ThermoCo[imax]), ureg.degC)

# Find the time that it takes to boil
boilthreshold = 98.0
for i in range(starts[filename]+1, len(ThermoCo[imin:imax])):
    if float(ThermoCo[i]) >= boilthreshold:
        boilnum = i
        break
    elif i == imax - 1:
        boilnum = False
if boilnum != False:
    boiltime = float(sec[boilnum]) - float(sec[starts[filename]+1])

print(filename)
print('First_point: {}' .format(starts[filename]))
print('Last_point: {}' .format(imax))
print('CO_Average: {:.4f} ppm' .format(COavg))
print('CO2_Average: {:.4f} ppm' .format(CO2avg))
print('DP_Average: {:.6f} inH2O' .format(avgval(flow[1:])))
print('Start_Temp: ' + str(Tempmin.to(ureg.kelvin)))
print('Final_Temp: ' + str(Tempmax.to(ureg.kelvin)))
if boilnum != False:
    print('Boil_time: {} seconds' .format(boiltime))
else:
    print('Water_did_not_reach_{} degC' .format(boilthreshold))

```

I. Images



Fig. 18. Prototype stove used in preliminary test

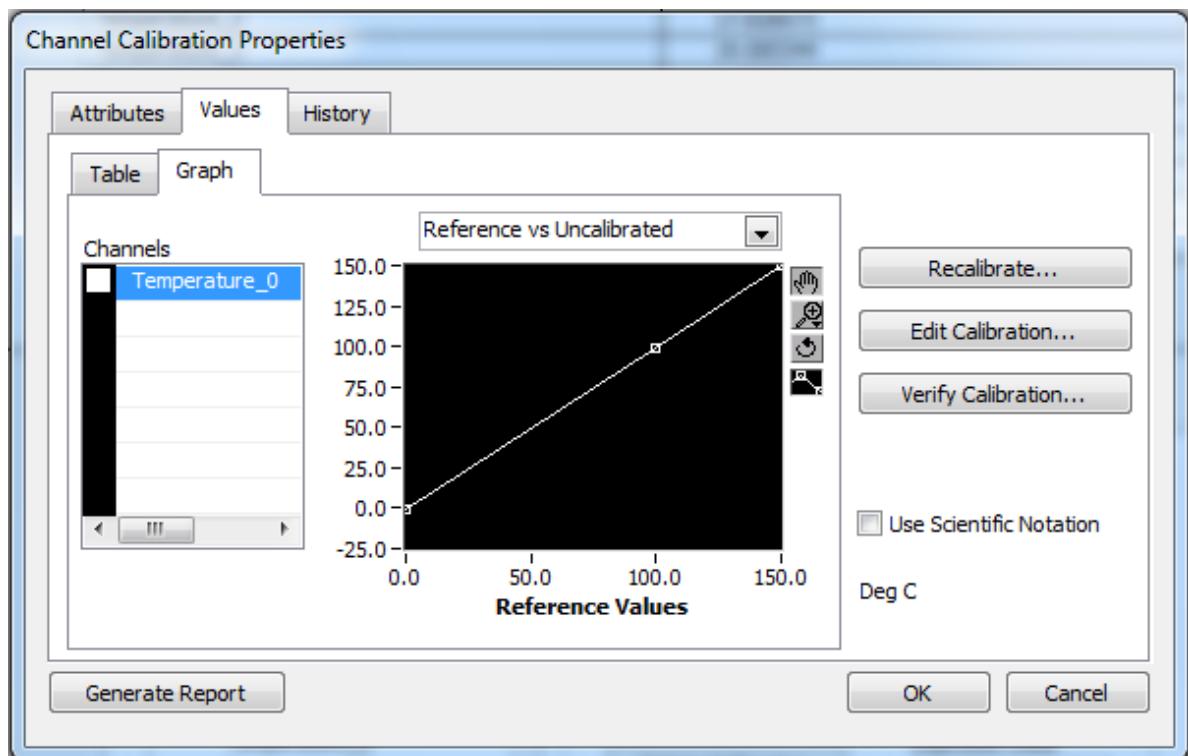


Fig. 19. 2 point calibration curve using a $0.0C^\circ$ ice bath and a $100C^\circ$.

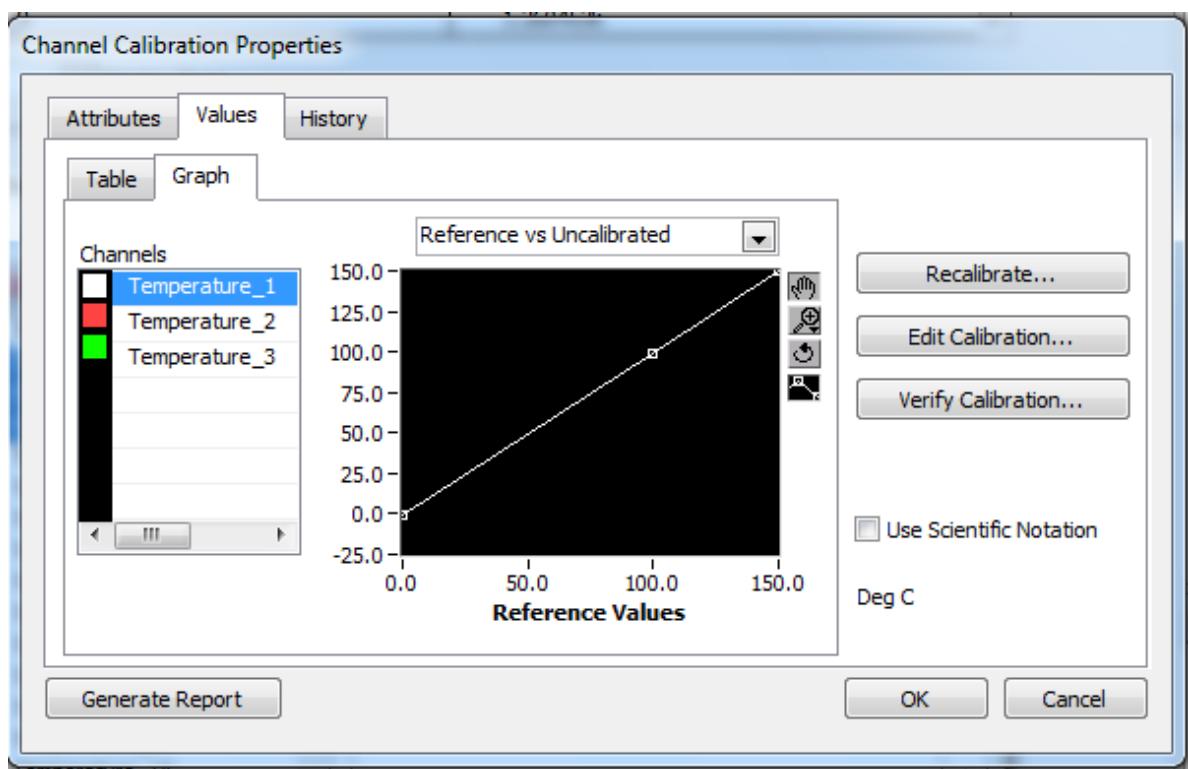


Fig. 20. 2 point calibration curve using a $0.0C^\circ$ ice bath and a $100C^\circ$.

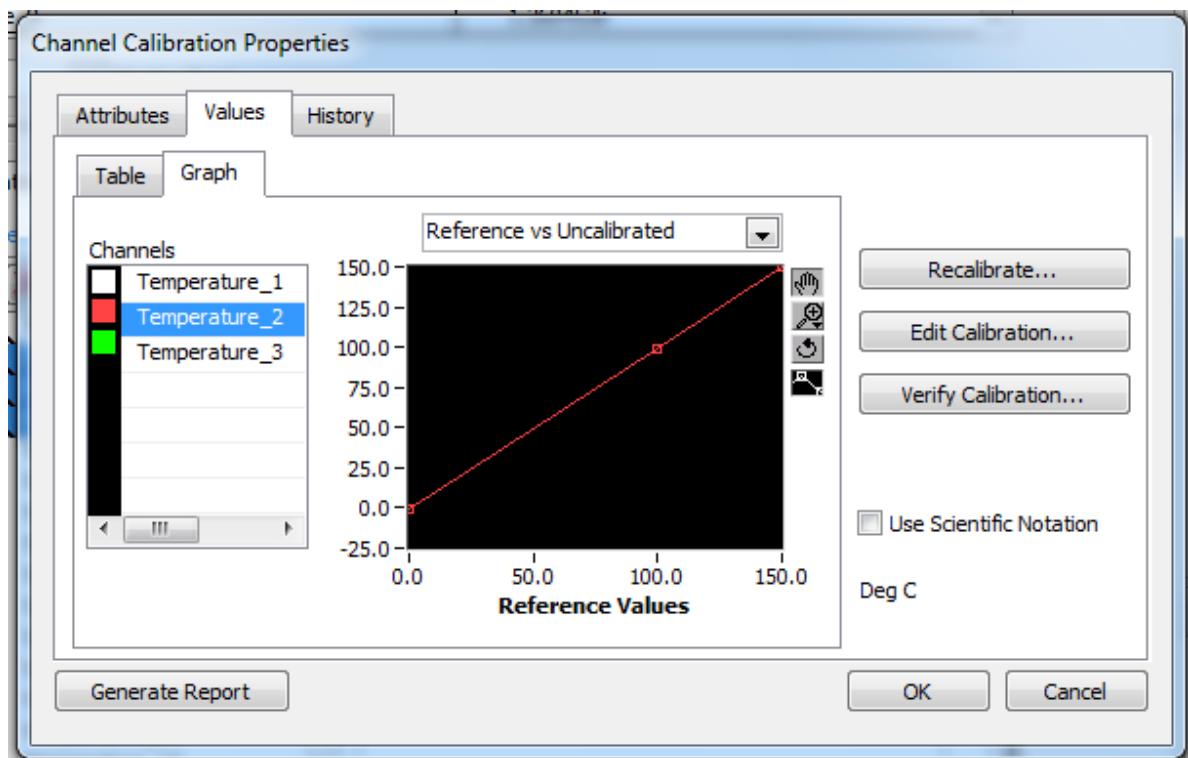


Fig. 21. 2 point calibration curve using a $0.0C^\circ$ ice bath and a $100C^\circ$.

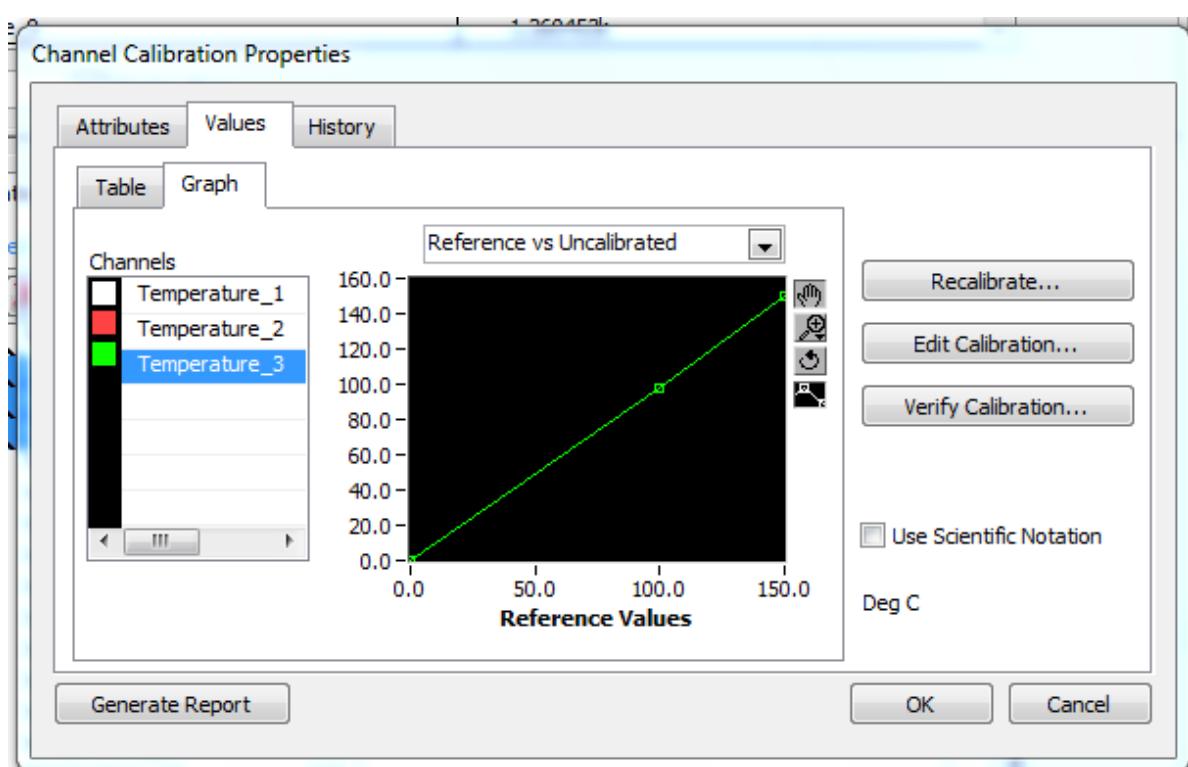


Fig. 22. 2 point calibration curve using a $0.0C^\circ$ ice bath and a $100C^\circ$.

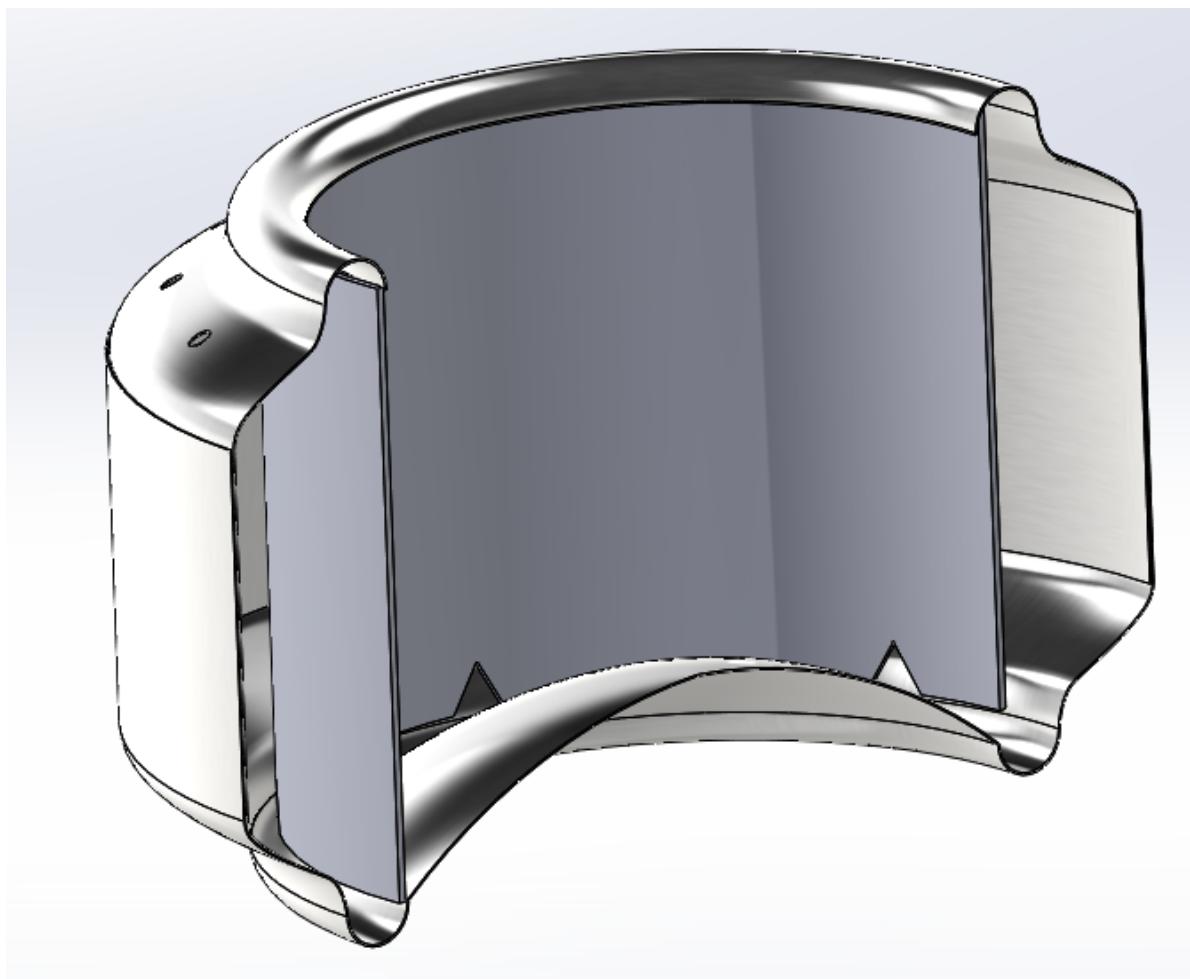


Fig. 23. Cookstove Cross Sectional View from SolidWorks Model to Show Pressure Chamber Ring.