Impacts of Diluting Ethanol on Alcohol Stove Emissions and Efficiencies

Matthew Zaiger*, Andrew Alferman†, Julia Thurber‡, and Daniel Cowan§
*CIRE Lab and Niemeyer Research Group
zaigerm@oregonstate.edu
† Niemeyer Research Group
alferma@oregonstate.edu
‡MML Humanitarian Engineering Program
thurbeju@oregonstate.edu
§ CIRE Lab
cowand@oregonstate.edu

Motivation

Traditional biomass, mainly firewood and charcoal, is currently the most common fuel used for personal cooking in many Sub-Saharan African countries. However, in recent years, scientists have pushed for cleaner fuel alternatives, such as ethanol, due to detrimental health risks associated with biomass [1]. Cleaner burning fuels such as ethanol are being implemented as an alternative fuel source. In MacCarty's research, significant improvements on emissions and energy usage have been shown [2]

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, a potential exists for greater availability and usage as the industry expands. Several countries in Africa are producing ethanol at significant scales 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 [3].

This project focuses on testing the efficiency and emissions of an ethanol-burning cook stove with varying dilutions of ethanol. The cook stove is a similar design to United States of America Patent No. 766,618 [4]. The simple personal cook stove was chosen because it can use local technology and can be produced inexpensively. This particular cook stove 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 objective of this experiment is to determine the efficiencies and emmisions of ehthanol diluted with water from 95 to 75 wieght percent ethanol.

Experiment

A. Summary of Objectives

An alcohol cookstove will be used to burn an ethanol-water dilution. The fuel will vary the mass percent of ethanol to 95%, 90%, 85%, 80%, and 75%. The experimental approach will test for fuel burn efficiency and stove efficiency of the diluted ethanol fuel. A standardized water boiling test, enabling the comparison of a wide variety of stoves, will be implemented to measure the efficiency of the stove. This test will compare the energy adsorbed by water within a pot to the energy released by the fuel. A gas analyzer will examine the CO and CO_2 contents. A stagnation style flow meter will measure the exhaust flow. By using the exhaust flow and CO and CO_2 content a fuel burn efficiency can be calculated. The CO emissions of the burn is a health concern since the stoves will be used within 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.

B. Experimental Design

For a complete understanding of the experimental design and set up, reference the flow chart found in appendixI-B. A simple personal cookstove will be constructed from aluminum beverage cans. The stove construction will feature a small fuel reservoir central to the stove axis, and will have a vaporization chamber on the sides of the stove, surrounding the reservoir. Small holes, acting as jets, will be punched or drilled near the top of the vaporization chamber for fuel vapors to escape.

Fuel concentrations will be mixed in batches (see appendix I-F. A container will be placed on a scale , and the scale will be tared. The desired water will be added to the scale, and then the calculated ethanol will will be added to the water. The water is added first because ethanol has a lower vaporization temperature. The mixed fuels will be stored in sealed containers until used.

A Pitot tube type flow meter (Nailor Industires Inc. Model: 36FMS) will measure the flow in the exhaust duct work. A differential pressure transducer (Omega PCL-1B) will measure the difference between the stagnation pressure and the static pressure. Prior to installing the flow meter, a dry test meter will be used for calibration of the meter. A thermocouple will be installed at the inside the duct to obtain the exhaust temperature.

The Portable Emissions Measurement System (PEMS), developed by the Aprovecho Research Center, will measure the constituents of the exhaust. PEMS will monitor and record emission levels, including CO and CO_2 in real time via a data acquisition system connected through a software interface.

These concentrations will be used to help calculate fuel burn efficiency.

A pot with a known mass and material will be suspended above the stove. Five hundred grams of room-temperature water will be poured into the pot. The pot will be placed on a continuous reading scale during the duration of the test. Two type-k thermocouples will be placed in the water to measure temperature raise during the burn.

The empty cookstove will be placed on a calibrated scale and its mass will be recorded. A measured volume of diluted ethanol fuel will be poured into the cookstove. The mass of the fuel will be measured. The measuring of the fuel will be preformed immediately prior to ignition in to order to reduce evaporation.

The instruments will begin to take readings 10 minutes prior to testing to ensure the sensors have steady conditions. The fuel is ignited from the reservoir. A few minutes are needed to preheat the stove prior to the jets igniting. The time taken until the jets ignite will be measured. Two thermocouples will be within the cookstove to measure the fuel temperature and the pressure chamber temperature.

The stove will be left to burn until all of the fuel is expended and the flame extinguishes. The weight of the pot and the remaining water will be measured immediately after the flame extinguishes, and the apparatus will be allowed to cool to room temperature.

The experiment will be repeated for five times at each ethanol concentration.

C. Data Analysis

The collected data will be used to determine the fuel burn efficiency and stove efficiency for each concentration of ethanol. The stove will be calculated using the following equation:

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

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 [5].

The energy released by the stove will be determined by multiplying the mass of the ethanol solution by the calorific value of the solution, 26.8 MJ/kg. Note that the water in the solution will not add to the energy released, and therefore the mass used in this calculation will vary based on the concentration, even if the same volume is used each repetition of the experiment.

The heat energy in the pot will be calculated using the data from the thermocouples in the pot using the specific heat equation:

$$\Delta E_{H_2O,heat} = m_{water} c_p \Delta T \tag{2}$$

where m_{water} is the mass of the water remaining in the pot at the end of the test, c_p is the specific heat of the water, and ΔT is the change in temperature in the water between when the fuel was ignited and when the flame was extinguished. The mass and specific heat of the pot will be taken into consideration as necessary.

The energy spent evaporating the water will be 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:

$$\Delta E_{H_2O,evap} = m_{evap} h_v \tag{3}$$

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 boil will be measured using data from the thermocouples in the pot. This time will be the time measured between ignition of the fuel and when the temperature plot reaches a plateau around 100°C.

The fuel burn efficiency will be based on how much of the carbon is released as CO. The CO content will be determined from the measured particulate count from the PENS, the volumetric flow rate, and temperature of the exhaust.

The percentage of carbon in the ethanol fuel that will be consumed in the production of CO will be calculated using the following equation:

$$\epsilon = \frac{n_{CO}}{2n_{ethanol}} \tag{4}$$

where n_{CO} is the number of molecules of CO produced and $n_{ethanol}$ is the number of ethanol molecules in the fuel. n_{CO} will be calculated using the following equation:

$$n_{CO} = \frac{N_A P_{static} C_{CO} V}{R T_{ambient}} \tag{5}$$

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, and V is the volume of air that passes through the fume hood over the course of the experiment. V will in turn be 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 will be found using the following equation:

$$u = 215\sqrt{\Delta P} \tag{6}$$

in which ΔP is the differential pressure across the pitot tube flow meter in inches of units of water. This equation for the volumetric flow rate was provided by the manufacturer of the pitot tube flow meter, and will be calibrated prior to collecting experimental data.

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

$$n_{ethanol} = \frac{N_A m_{fuel} C_x}{M_{ethanol}} \tag{7}$$

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.

The data obtained for each solution concentration will be compared to determine if any trends exist. Additionally, the data will be compared to results from literature to verify all conclusions.

I. Expected Results

It is expected that the relative flame temperature will decrease as water content increases. From [6] and [7], it is anticipated that the absolute temperature will decrease by 3% for the 85% ethanol solution compared to pure ethanol. Note, there will be a larger mass flow rate from the flame per ethanol mass because the water content in the fuel will be an increased flow rate, coupled with the lower flame temperature, allows for the combustor efficiency to remain relatively constant. This we will apply to our stove. The relative flame temperature should also affect the combustion efficiency. It is anticipated that with increased water content, the combustion will be less complete and produce more soot and carbon monoxide.

Since water has a larger vaporization pressure than ethanol, the more diluted ethanol will need a higher temperature prior to vaporizing. This will likely result in a longer start-up flame prior to the jets igniting. The longer start up will waste more fuel and may adversely affect the efficiency of the stove. However, this loss of efficiency will be short in duration compared to the overall burn time of the stove.

References

[1] Kalpana Balakrishnan, Jyoti Parikh, Sambandam Sankar, Ramaswamy Padmavathi, Kailasam Srividya, Vidhya Venugopal, Swarna Prasad, and Vijay Laxmi Pandey. Daily average exposures to respirable particulate matter from combustion of biomass fuels in rural households of Southern India. Environmental Health Perspectives, 110(11):1069–1075, 2002.

[2] Nordica MacCarty, Dean Still, and Damon Ogle. Fuel use and emissions performance of fifty cooking stoves in the laboratory and related benchmarks of performance. Energy for Sustainable Development, 14(3):161–171, 2010.

[3] Nicolai Schlag and Fiona Zuzarte. Market Barriers to Clean Cooking Fuels in Sub-Saharan Africa: A Review of Literature. Fuel, (April):1–21, 2008.

[4] J Heinrichs. Burner, 1904.

[5] H. S. Mukunda Robert van der Plas. The Water Boiling Test Version 4.1.2. 2(January 2013):52, 2009.

[6] A. Beeton. The Calculated Performance of Ethyl Alcohol-Water Mixtures as Rocket Fuels with Liquid Oxygen The. Number 2816. Aeronautical Research Council, 1953.

[7] Baine Breaux. the Effect of Elevated Water Content on Ethanol Combustion. 2012.

APPENDIX

A. *Uncertainty Design Analysis*

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

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% and 25% [2].

The uncertainty analysis concluded that the thermal efficiency can be expected to have a relative uncertainty of approximately 5%. The majority of measurements used to calculate the thermal efficiency are measurements of mass, and consequentially the relative uncertainty is most 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 30% with the more accurate scale. An uncertainty tree of the thermal efficiency can be found in figure 1 below.

Although the accuracy of the scale had the greatest impact on the uncertainty of the thermal efficiency, the uncertainty was also notably impacted by the accuracy of the thermocouples used. Using thermocouples with 10 times greater accuracy (0.22°C verus 2.2°C) lessened the relative uncertainty by approximately 25%.

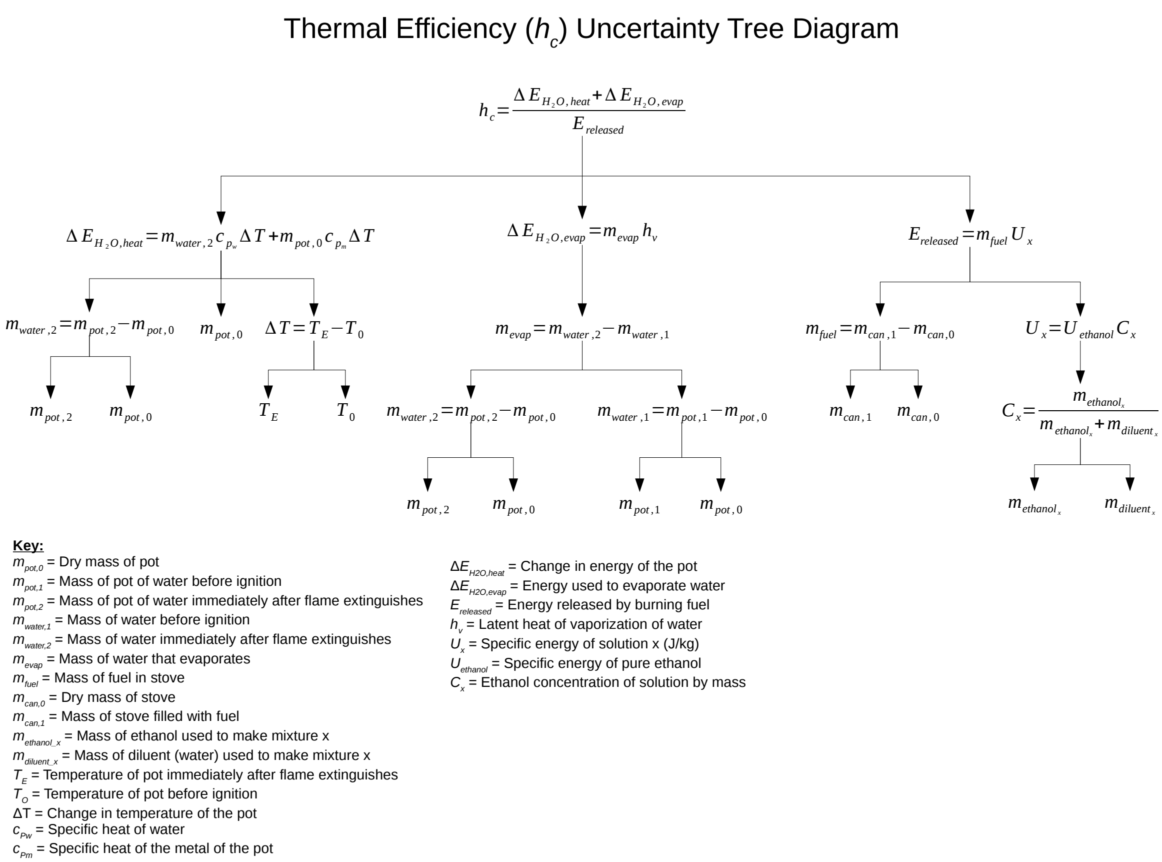
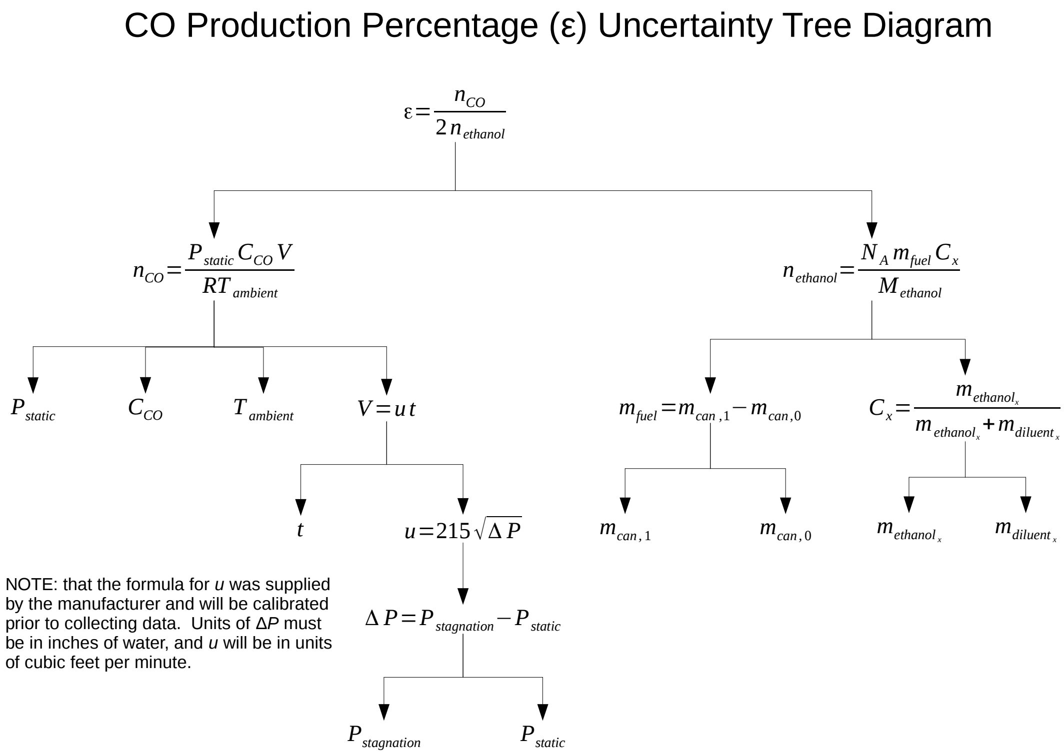


Fig. 1.

The uncertainty analysis concluded that the CO production percentage can be expected to have a relative uncertainty of approximately 6%. 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 uncertaincy by approximately 40%. Improvements in pressure, temperature, or mass measurements were found to have an almost negligible impact on the uncertainty. Figure 2 below depits an uncertainty tree of the CO production percentage.

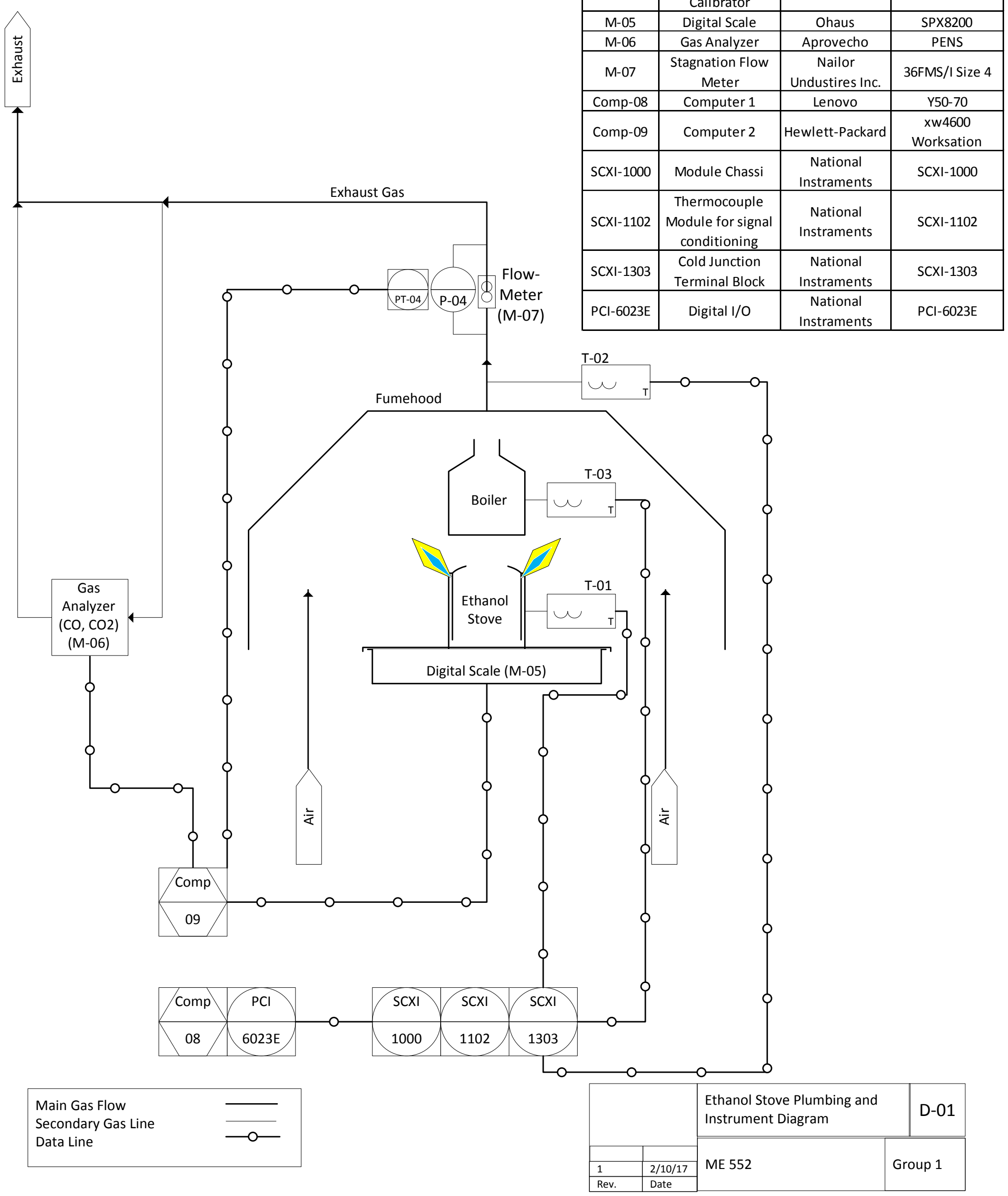


Key:
n_{CO} = Number of molecules of CO released in test
$n_{ethanol}$ = Number of molecules of ethanol in test
m_{fuel} = Mass of fuel in stove
$m_{can,0}$ = Dry mass of stove
$m_{can,1}$ = Mass of stove filled with fuel
$m_{ethanol\_x}$ = Mass of ethanol used to make mixture x
$m_{diluent\_x}$ = Mass 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
t = Total burn time
V = Total volume of air passed through hood during test
u = Volumetric flow rate of air passed through hood during test

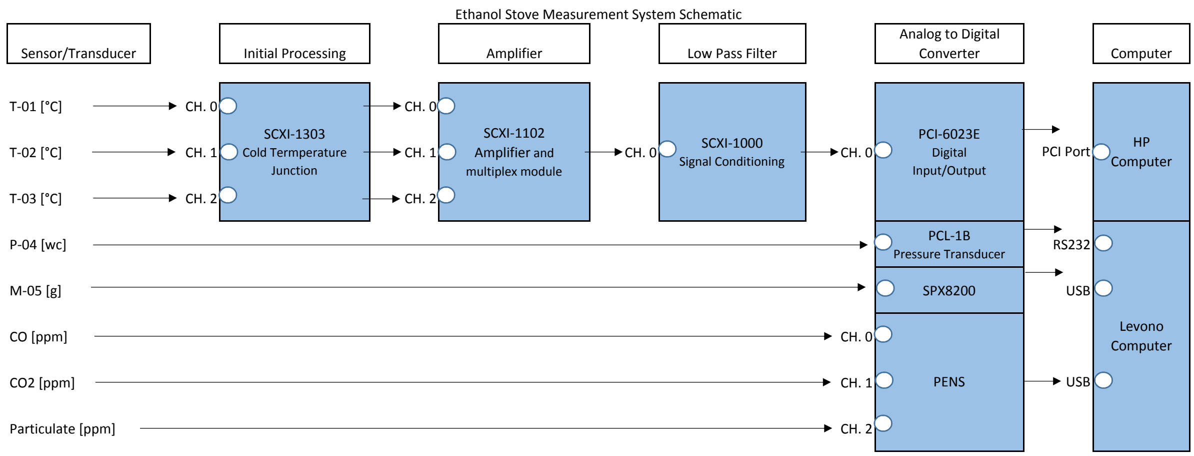
Fig. 2.

B. Experiment Flow Chart

Equipment Call-out	Mesurement Device	Manufacture	Part Number
T-01	Type-k Thermocouple	Omega	KQXL-116E-12
T-02			
T-03			
P-04	0-10 inches of Water Column Pressure Guage	Omega	PCL-MA-10WC
PT-04	Pressure Calibrator	Omega	PCL-1B
M-05	Digital Scale	Ohaus	SPX8200
M-06	Gas Analyzer	Aprovecho	PENS
M-07	Stagnation Flow Meter	Nailor Undustires Inc.	36FMS/I Size 4
Comp-08	Computer 1	Lenovo	Y50-70
Comp-09	Computer 2	Hewlett-Packard	xw4600 Worksation
SCXI-1000	Module Chassi	National Instraments	SCXI-1000
SCXI-1102	Thermocouple Module for signal conditioning	National Instraments	SCXI-1102
SCXI-1303	Cold Junction Terminal Block	National Instraments	SCXI-1303
PCI-6023E	Digital I/O	National Instraments	PCI-6023E



C. DAQ Setup



Ethanol Stove Measurement System Schematic
Sensor/Transducer
Initial Processing
Amplifier
Low Pass Filter
Analog to Digital Converter
Computer
T-01 [°C]
T-02 [°C]
T-03 [°C]
P-04 [wc]
M-05 [g]
CO [ppm]
CO2 [ppm]
Particulate [ppm]
CH. 0
CH. 1
CH. 2
SCXI-1303
Cold Termperature Junction
SCXI-1102
Amplifier and multiplex module
SCXI-1000
Signal Conditioning
PCI-6023E
Digital Input/Output
PCL-1B
Pressure Transducer
SPX8200
PENS
PCI Port
RS232
USB
HP Computer
Levono Computer

D. Instrument Error List

Instrument	Model	Tolerance	Tolerance (Alternative)
Thermocouples	Super OMEGACLAD XL KQXL-116E-12	+/- 2.2C	+/- 0.75%
Scale	OHAUS Scout SPX8200	+/- 1 g	
Pressure Transducer	OMEGA PCL-1B	+/- 0.006% of span	
Sampling Tube	Nailor Industries Inc. Model 36FMS Measuring Station	N/A (will be calibrated)	
Dry Test Meter	Singer DTM-200	+/- 0.01 cfm	
Stopwatch	N/A	+/- 0.01 s	
CO Sensor*	Alphasense CO-AF Carbon Monoxide Sensor	+/- 0.5 ppm	
CO2 Sensor*	SainSmart MH-Z14 Sensor Module for Arduino	+/- 50 ppm	+/- 5% reading value
Differential Pressure Transmitter*	Dwyer Series MS Magnesense DP Transmitter	+/- 1% of reading (assumed to be 50 Pa)	
Temperature Sensor*	National Semiconductor LM35 Precision Centigrade Temperature Sensors	+/- 0.5C	
Differential Pressure Gage*	Dwyer Magnehelic Differential Pressure Gage	+/- 2% of full scale (1 in H2O)	

*Part of portable emissions measurement system and subject to change

E. 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 abient 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.

F. 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 flamable.
5) for clean up place all fuels in the flammables storage cabinet.

G. Code

```python
#!/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 uncertainties as unc
import scipy.constants as const

"""
The following parameters are for experiment 1.  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
R = 8.3145 # J/mol*K
NA = const.Avogadro
hv = 2258000. # J/kg
cpw = 4186. # J/kg
cpm = 490. # J/kg*K
Uethanol = 26400000. # J/kg
Methanol = 0.04607 # kg/mol

# Conversion factors for handy dandy use later, if needed
intom = 0.0254 # Inches to meters
psitopa = 6894.76 # psi to Pascals
psioffset = 14.7 # psig to psia
cftocm = 0.0283168 # cubic feet to cubic meters
inwtopa = 248.84 # Inches of water to Pascals
cfmtocms = 0.000471947 # Cubic feet per minute to cubic meters per second

# Put all the equipment tolerances in here because it's the cool thing to do
thermocouples = 2.2 # degrees C, but could be 0.75% reading
scale1 = 0.001 # 1 gram accuracy
scale2 = 0.0001 # If we can get 0.1 gram accuracy out of the better scale
pressscale = 10. # Assume that the range will be 10 inches H2O
press = 0.00006 * pressscale
dtm = 0.01 # Dry test meter, in cfm
stopwatch = 0.01 # Photograph the stopwatch to achieve this
CO = 0.5 # parts per million
CO2 = 50 # parts per million, may be 5% of reading though
dpt = 50 # Pascals, if we even use this
tempsensor = 0.5 # Deg C, if we use this
dpgage = 1.*0.02*inwtopa # If we even use this gage from the PEMS

# Add in all of the measured masses
# All units will be in kg
mcan0 = unc.ufloat(0.010, scale1) # Similar to values found at Aprovecho
mcan1 = unc.ufloat(0.050, scale1) # Similar to values found at Aprovecho
```

```
methanol = unc.ufloat(0.95, scale1) # Assuming 95% concentration
mdiluent = unc.ufloat(0.050, scale1) # Assuming 95% concentration
mpot0 = unc.ufloat(0.5, scale1) # Assuming the pot will weigh around 0.5 kg
mpot1 = unc.ufloat(1.0, scale1) # Assuming 0.5 kg / 0.5 L water added
mpot2 = unc.ufloat(0.995, scale1) # Assuming we lose 5g of water due to boiling

# Add in the pressure measurements of the sampling tube
# Will be input and outputin inches of water
Pstag = unc.ufloat(0.1, press) # The one meter went up to 1 in, so 0.1 in
                               # sounds at least somewhat reasonable.
Pstat = unc.ufloat(0, press)    # This should be 0 psig.

# Absolute pressure in Pascals
Pabsolute = unc.ufloat(101300, 0.0007 * 101300)

# Add in the CO and CO2 readings
COppm = unc.ufloat(10., CO)
CO2ppm = unc.ufloat(200., CO2)

# Add in burn time, in seconds
burntime = unc.ufloat(15.*60., stopwatch) # Assuming that it will burn 15 min

# Add in the temperature measurements
# Input and output in Kelvin
T0 = unc.ufloat(292.23, thermocouples) # This value was what we had in lab 1
Tambient = T0 # Should equilibriate to this.
TE = unc.ufloat(373.15, thermocouples) # Assuming boiling point at sea level


# 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.
mwater1 = mpot1 - mpot0
mwater2 = mpot2 - mpot0
mevap = mwater1 - mwater2
mfuel = mcan1 - mcan0
Cx = methanol / (methanol + mdiluent)
Ux = Uethanol * Cx
Ereleased = mfuel * Ux
EH2Oevap = mevap * hv
deltaT = TE - T0
deltaP = Pstag - Pstat
Vdot = 215.*(deltaP**0.5) * cfmtocms
V = Vdot * burntime
COpartial = Pabsolute * COppm / 1.e6
CO2partial = Pabsolute * CO2ppm / 1.e6
nco = (NA * COpartial * V) / (R * Tambient)
nco2 = (NA * CO2partial * V) / (R * Tambient)
nethanol = NA * mfuel * Cx / Methanol
EH2Oheat = mwater2*cpw*deltaT + mpot0*cpm*deltaT
hc = (EH2Oheat + EH2Oevap) / Ereleased
epsilon = nco / (2 * nethanol)

print('————————————————————————')
print('THERMAL EFFICIENCY (h_c)')
print('Nominal value: {:.2f}%'.format(hc.n * 100.))
print('Relative uncertainty: +/- {:.2f}%'.format((hc.s / hc.n) *100.))
print('————————————————————————')
print('CO PRODUCTION')
print('Nominal value: {:.2f}%'.format(epsilon.n * 100.))
print('Relative uncertainty: +/- {:.2f}%'.format(
        (epsilon.s / epsilon.n) *100.))
```

Code Output:

THERMAL EFFICIENCY (h_c)
Nominal value: 19.82%
Relative uncertainty: +/- 5.28%

CO PRODUCTION
Nominal value: 0.73%
Relative uncertainty: +/- 6.19%

H. Images

Fig. 3. Prototype stove used in preliminary test