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 signifant health risks. A push for cleaner burning fuels, such as ethanol, is occurring, but creates market and cost challenges. To ease this cost burden, ethanol diluted with water is considered as an alternative to distilled ethanol. However, diluted ethanol could reduce the combustion efficiency, lowering its viability as an alternative cooking fuel. This study will use a simple alcohol stove to compare the impacts of diluent on emissions and efficiencies. It is expected that increasing diluent will result in reduced emissions and minimal change in cooking efficiencies. These measurements will be determined according to the standard Water Boiling Test protocol with a Portable Emmissions Measurement System, and the data collected from this experiment will be compared to the literature.**

I. Introduction

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].

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 that are used for fuel must have a greater ethanol content than solutions produced by fermentation alone, so the fermented solution must be distilled. Increasing the ethanol content further must be accomplished by using various dehydration methods described by Breaux [4]. Note, Raoults Law does not allow for ethanol to be perfectly distilled from a water/ethanol mixture. As reported by Brewster et al, the absolute maximum that ethanol can be distilled to is 95.57% [5]. To receive pure ethanol, Madson et al states that an additional technique is needed that requires around 14,000 to 17,000 BTU per gallon of ethanol [6].

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.

Studies on hydrous ethanol have been performed for some combustion applications. For example, homogeneous charge compression ignition (HCCI) is an emerging technology that runs on hydrous ethanol. This particular engine design can run on fuels containing ethanol as low as 35%, decreasing energy required for distillationOverall, this is a net 34% energy gain when using 35% ethanol. Howevever, Landisch et al 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 [7].

Other studies performed by Breaux 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%. A stable flame was achieved with 35% diluent. This study showed that the exhaust heat rate was not affected with up to 20% diluent. It was found that ethanol with up to 20% water content was found to be a practical fuel for continuous flame application. Additionally, 85% ethanol would result in a 25% life cycle energy savings, when compared to 100% ethanol [4], and the global heat release is reduced as much as 60% with the addition of 20% water.

Furthermore, in Breaux's research, flame temperatures were recorded. For 100% ethanol at an equivalence ratio of one, the average low flame temperature was around 1155 K. For 80% ethanol, the low flame temperature was around

1130 K. The reduction in low flame temperature was around 2.2% for an addition of 20% water content. This is comprable to a study looking at diluted ethanol as a rocket fuel that burned diluted ethanol with liquid oxygen [4]. Another study preformed by Beeton et al found that the max combustion temperature for pure ethanol when burned with liquid O_2 was 3,285 K, and the max combustion temperature for 85% ethanol was 3,200 K. This represents a 2.6 % decrease in temperature for an addition of 15% water content [8].

The relative light intensity decreased between 100% ethanol and 90% ethanol, but appeared to be relatively constant between 90% ethanol and 80 % ethanol [4]. This is mentioned because there is a concern for burns by low visibility flames when cooking.

Results showed that combustion efficiency and combustor thermal efficiency were not negatively affected by elevated water content between 80% to 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 [4].

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 [9]. 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.

II. Experiment

A. Experimental Design

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.

The empty cookstove will be placed on a calibrated scale in a chemical hood and its mass will be recorded. A pot with a known mass and material composition will be suspended directly above the stove. Thermocouples will be placed in the pot. The Portable Emissions Measurement System (PEMS), developed by the Aprovecho Research Center, will be placed adjacent to the pot to monitor the constituents of the flame exhaust. PEMS will monitor and record emission levels, including CO, CO_2, and soot, in real time via a data acquisition system connected through a software interface. PEMS, originally designed for use with large biomass stoves, will need to be calibrated for the lower emissions of a personal alcohol cookstove. A visual camera will be used to find comparative light intensities with different ethanol dilutions.

A measured volume of room-temperature water will be poured into the pot. A measured volume of ethanol solution will be placed in the cookstove. After starting the visual camera and data acquisition system, and verifying that all instruments are functional, the ethanol solution in the central preheat area (fuel reservoir) will be ignited. The time taken until the jets ignite and the temperature and pressure of the pressure chamber will be measured. 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.

A thermocouple will be placed with a fixed position in the flame above the stove. This thermocouple will be used to provide relative flame temperatures between different fuel dilutions.

There will be a port with a pressure transducer on the side of the cookstove measuring pressure and a port with a thermocouple to measure temperature of the pressure chamber. This will give insight into what temperature is needed to vaporize the fuel prior to flamelet ignition. The pressure transducer will allow for the monitoring of different pressures within the chamber caused by different dilutions.

The experiment will be repeated for several solutions with different ethanol concentrations.

B. Data Analysis

The collected data will be used to determine the power output and efficiency of the cookstove for each concentration of ethanol. The thermal efficiency of 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 [10].

The energy released by the stove will be calculated 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.

Specific fuel consumption of the stove will be calculated using the following equation:

$$SC = \frac{f_{cd}}{w_{cr}} \tag{4}$$

where SC is the specific fuel consumption, f_{cd} is the mass of fuel burned, and w_{cr} is the mass of the water boiled. f_{cd} and w_{cr} will be measured using output from the scale when the water first reaches boiling point. Specific fuel consumption can be thought of as the amount of fuel required to produce a given output (boiling water in the case of this experiment) [10].

The time for the water to boil will be measured using data from the thermocouples in the pot. This time will be the time measured between a point in which the temperature plot begins to rise above ambient and when the plot reaches a plateau at 100°C.

In addition to the above calculations, the emission constituents, CO, CO_2, will be measured using a PEMS and related software, for both emission factors and total emissions. 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.

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

$$\epsilon = \frac{n_{CO}}{2 n_{ethanol}} \tag{5}$$

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:

$$n_{CO} = \frac{N_A P_{static} C_{CO} V}{R T_{ambient}} \tag{6}$$

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:

$$u = 215\sqrt{\Delta P} \tag{7}$$

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:

$$n_{ethanol} = \frac{N_A m_{fuel} C_x}{M_{ethanol}} \tag{8}$$

wherem_{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.

A description of the uncertainty analysis performed on the thermal efficiency and the CO production percentage can be found in appendix

III. Expected Results

It is expected that the relative flame temperature will decrease as water content increases. From [8] and [4], 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.

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