Impact of Co-Firing a Traditional Peruvian Biomass Cookstove with Biogas on Emissions and Combustion Efficiency

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***Abstract*—This paper presents the results of an investigation of the impact of co-firing a traditional Peruvian biomass cookstove with biogas on emissions and on combustion efficiency. The impact of using a fan to increase the airflow into the combustion zone with was also assessed. The cookstove was tested (1) without co-firing and without the fan, (2) with co-firing and without the fan, (3) without co-firing and with the fan and (4) with co-firing and with the fan. Time-resolved measurements of the concentrations of CO, CO_2 and particulate matter were measured during each test. These data were used with measurement of the temperature of the water in the cooking pot and with measurement of the mass of water that evaporated during the test to calculate various cookstove performance parameters. Results obtained in this study indicate that using a fan and co-firing the cookstove with biogas improves performance. Compared to the baseline, (2), (3), and (4) reduced CO emissions by 32%, 35%, and 58%, respectively. Particulate emissions were reduced by 33%, 39%, and 71%, and the modified combustion efficiency increased by 1.3%, 1.1%, and 2.8%, respectively. These results suggest that relatively simple modifications significantly improve indoor air quality in homes where these stoves are used and reduce the impact use of this stove has on the environment.**

Keywords—Cookstoves; emissions; combustion efficiency

I. INTRODUCTION

A review of the energy access situation in developing nations was issued by the United Nations Development Program and the World Health Organization in November 2009 [1]. Statistics reported in this review indicate that slightly less than half of the earth's population (approximately 3 billon people) prepares their meals using solid fuels. It is estimated that 400 million burn coal and that the remaining 2.6 billion people burn traditional biomass fuels (wood, crop waste, and animal dung) on a daily basis. Only 27% of those who rely on solid fuels use improved, fuel-efficient, clean burning cookstoves. The remaining 73% use inefficient, highly polluting cookstoves each day. Combustion of coal and biomass in these cookstoves generally results in fuel-rich flames that spew out massive amounts of smoke, soot and toxic fumes [1, 2].

Research indicates that the incomplete combustion of solid fuels produces toxic fumes and particulate matter that damages human health by increasing the risk of cancer, damaging immune systems, irritating airways and reducing the oxygen supplied to unborn children [3]. Millions of deaths are associated with the use of solid fuels each year, and more than 99% of these deaths occur in developing nations. The death rates are particularly severe in the least developed nations and in sub-Saharan Africa [4]. The health of all household members is affected by the toxic fumes and particulate matter, but the consequences for women, infants and children – who are exposed to the poor indoor air quality for longer time periods each day – are disproportionately large.

Widespread use of solid fuels leads to other negative outcomes that also primarily impact women and children. Examples include burns from open fires and poorly designed cookstoves, exposure to risk of assault or injury while collecting fuels, and lost opportunity to attend school or engage in other activities that would result in economic or social development [4].

A vast amount of black carbon (soot) is produced in the fuel-rich conditions typically occurring in open fires and traditional cookstoves. In addition to being a leading cause of mortality in the developing world, release of black carbon into the atmosphere is a significant contributor to global climate change [5]. While suspended in the atmosphere, black carbon alters atmospheric temperatures by absorbing and scattering solar radiation. In addition, the black carbon that settles onto ice and snow has a significant impact. Since ice and snow are highly reflective and black carbon is highly absorbing of solar radiation, even a thin layer of soot on the surface of ice and snow leads to early melting of the underlying layers [6]. Through these mechanisms, black carbon can alter the amount of energy trapped in the atmosphere or absorbed by the surface of the earth, and these effects may significantly alter global temperature distributions [2].

Unlike carbon dioxide, which may remain in the atmosphere for more than 100 years, black carbon will fall from the atmosphere after a few weeks. Therefore, reducing black carbon emissions can lead to relatively quick and painless reduction in the rate of global climate change. Combined with the tremendous health and economic benefits that would accrue to developing nations, controlling the amount of black carbon released into the atmosphere is manifestly a highly desirable goal [2]. Since emission of black carbon from open cooking fires and primitive cookstoves are a significant fraction of the total black carbon emissions [7], the design, optimization, distribution, adoption and sustained used of economical, fuel-efficient, clean-burning biomass cookstoves is a moral and economic imperative for both developed and developing nations.

An interdisciplinary group of faculty and researchers at BYU is engaged in a range of projects intended to address sociological and technological issues related to development, dissemination and sustained used of clean burning biomass cookstoves. The hypothesis motivating each of these research projects is that cookstoves have fundamental and distinctive characteristics (both technical and social) that can be discovered and classified by analysis of both successful and failed cookstove implementation projects. Discovery and classification of the cookstove characteristics will enable design of regionally adaptable, clean-burning modular biomass cookstoves that will be widely adopted and sustainably used. A key element of this research is the ability to measure both the fuel efficiency and the emissions of biomass cookstoves. The objective of this paper is to describe the capabilities developed at BYU to test and analyze biomass cookstoves. These capabilities are illustrated by measuring the impact of co-firing a traditional Peruvian biomass cookstove with biogas on stove performance.

II. Review of Literature related to Cookstove Testing

Studies performed by Still et al. [8], MacCarty et al. [9] and by Jetter et al. [10] have quantified the energy use and emissions produced by a variety of cookstoves. MacCarty et al.[9] tested fifty stoves and classified them as simple stoves, rocket stoves, gasifier stoves, forced air stoves, charcoal stoves, and liquid/gas fueled stoves. The results of the study indicated liquid and gas fueled stoves are the most efficient and cleanest burning. However, the limited availability and/or high cost of these fuels in developing regions require the consideration of biomass-fueled stoves.

Several biomass cookstoves (rocket stoves, gasifiers, and forced air stoves) had high fuel efficiencies and low emissions [11]. However, seemingly minor changes can have a significant impact on stove performance, so these conclusions depend on the proper use and maintenance of the cookstove [12]. For example, poor fuel selection and preparation, improper lighting and tending of the fire, degradation of the insulation surrounding the combustion chamber, and incorrectly positioning the pot on the cooking surface may dramatically alter the performance of the cookstove.

Jetter et al. [10] considered cookstove systems, which were characterized by the type of stove, the type of fuel used and its moisture content, the characteristics of the thermal pathway from the flame to the object being heated (i.e. the insulation system and/or flow pattern used to channel heat to the intended location and the type of pot used) and the operating procedure (i.e. how the pot was positioned on the stove and how the fire was ignited and tended). A total of 44 cookstoves were evaluated using the water boiling test (WBT). Energy efficiency, cookstove power, and fuel use were measured during each test and several pollutants (carbon dioxide, carbon monoxide, methane, total hydrocarbons, and ultrafine particles) were measured continuously. The results of this study indicated that improved cookstoves use less fuel and emit fewer pollutants.

III. Methods

A. *Biomass Cookstove Test Facilty*

Fig. 1 shows a picture of a traditional Peruvian cookstove that is used in a remote mountain village. A replica of this type of stove was built and tested in the cookstove test facility at BYU, which is shown in Fig. 2. The cookstove was positioned in the center of a cinderblock hearth that is connected to a *Portable Emissions Monitoring System* (PEMS) [11]. A complete description of the cookstove test facility and the capabilities of the PEMS are given by Poudyal [12].

Fig. 1. Picture of a Traditional Peruvian Cookstove

Fig. 2. Picture of the Replica of a Traditional Peruvian Cookstove Used in the Biomass Cookstove Test Facility

The PEMS consists of a flow measurement system, sampling system for emissions, and a data acquisition system. The PEMS measured flue gas temperature and concentrations of of CO_2, CO, and particulate matter (PM) in the exhaust stream. PM emissions were monitored over time using a scattering photometer, and a gravimetric system was used to measure the total mass of PM emitted during the test. The concentration of CO_2 in the exhaust stream was monitored with a non-dispersive infrared sensor, and concentration of CO was monitored using an electrochemical cell [13,14]. In addition, the temperature of the water in the cooking pot was measured using a thermocouple and the mass of water in the pot was measured at the beginning and end of each test. These measurements are used to quantify emissions from the cookstove under various operating conditions and as the basis for calculating cookstove performance metrics as described in Sections IV and V.

B. *Testing Protocol*

The WBT is widely used to assess the performance of biomass cookstoves. The full WBT consists of a cold-start, high-power phase, a hot-start, high-power phase and simmering phase [15]. Since the objective of tests described in this paper was to assess the impact of co-firing the cookstove with biogas with and without a fan on emissions, only the cold-start phase of the WBT was performed. Emissions tend to be highest during this phase of the WBT [10].

A mixture of 65% CH_4 and 35% CO_2 was used to simulate the composition of biogas that would be generated from compost [16,17]. The flow rate of biogas was regulated such that a designated fraction of the total energy released during the combustion process was provided by the gas and the remainder of the total energy was provided by the biomass fuel. Biogas flow rates of 10%, 25% and 50% were used in the tests described in this paper.

In order to assess the impact of co-firing a biomass cookstove with biogas with and without a fan, tests were performed for the operating conditions listed in Table 1. Each test was repeated three times and detailed analyses of the variability and uncertainty in these results are given in [12].

TABLE I. TESTS CONDUCTED TO DETERMINE THE IMPACT OF CO-FIRING BIOMASS WITH BIOGAS WITH AND WITHOUT A FAN

Operating Set Number	Operating Parameters		
	Biomass Used	Percentage of the Total Energy Provided by Biogas	Fan On
1	Yes	0%	No
2	Yes	10%	No
3	Yes	25%	No
4	Yes	50%	No
5	Yes	0%	Yes
6	Yes	10%	Yes
7	Yes	25%	Yes
8	Yes	50%	Yes

IV. TIME-RESOLVED MEASUREMENTS

Time-resolved PM concentration measurements for each of the eight sets of operating parameters are shown in Figs. 3 – 10.

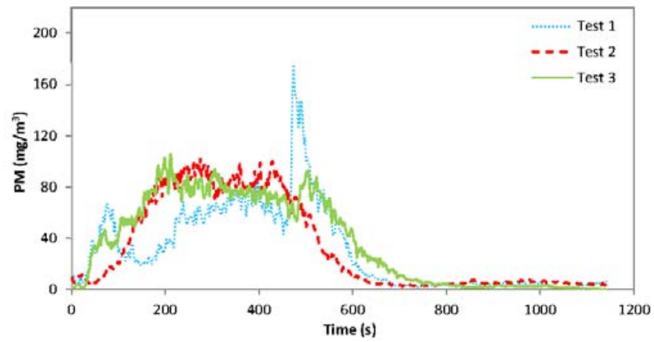

Fig. 3. Time-Resolved PM Concentration Measurements – Operating Set 1

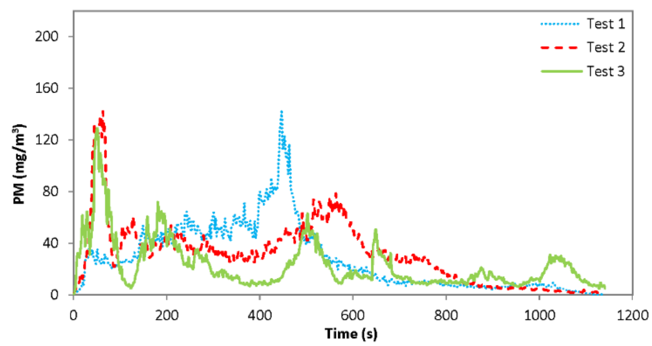

Fig. 4. Time-Resolved PM Concentration Measurements – Operating Set 2

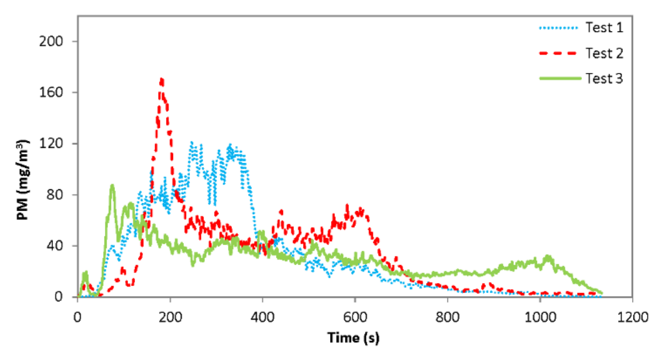

Fig. 5. Time-Resolved PM Concentration Measurements – Operating Set 3

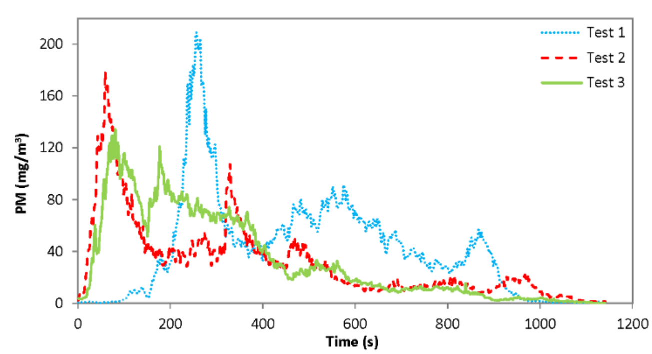

Fig. 6. Time-Resolved PM Concentration Measurements – Operating Set 4

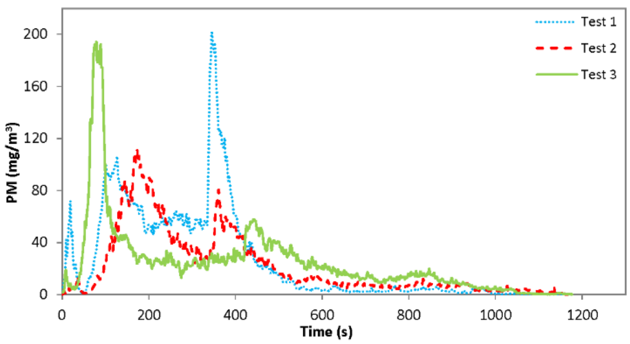

Fig. 7. Time-Resolved PM Concentration Measurements – Operating Set 5

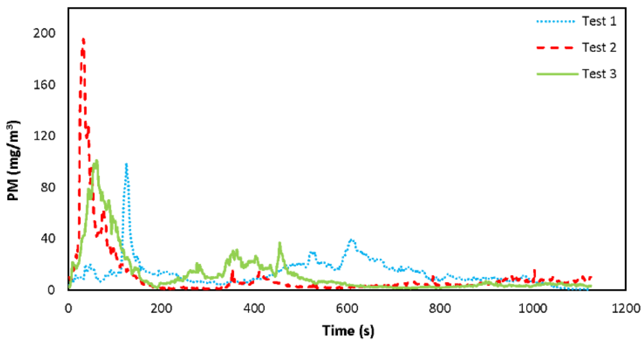

Fig. 8. Time-Resolved PM Concentration Measurements – Operating Set 6

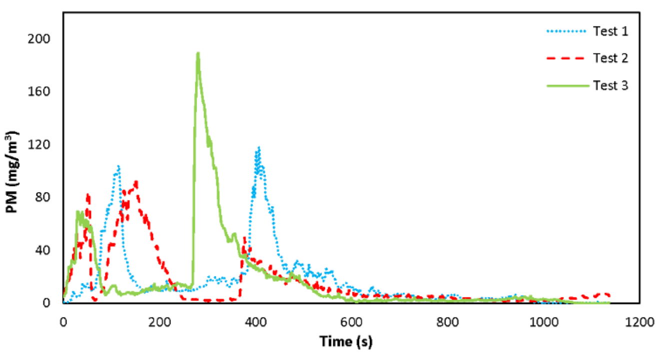

Fig. 9. Time-Resolved PM Concentration Measurements – Operating Set 7

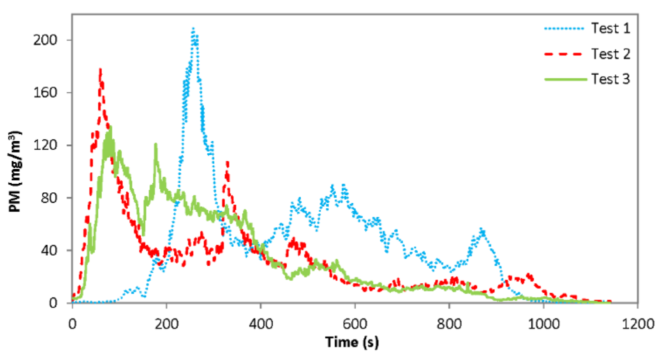

Fig. 10. Time-Resolved PM Concentration Measurements – Operating Set 8

Time-resolved CO concentration measurements for each of the eight sets of operating parameters are shown in Figs. 11 – 18.

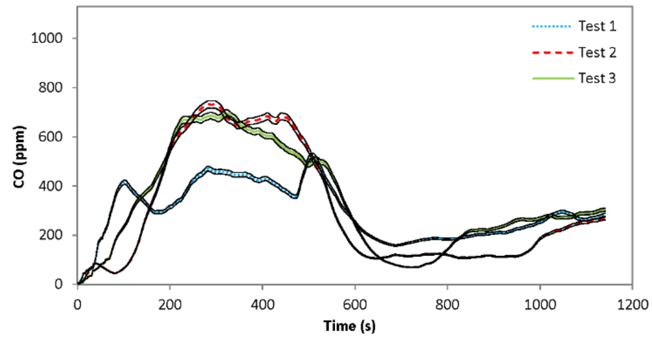

Fig. 11. Time-Resolved CO Concentration Measurements – Operating Set 1

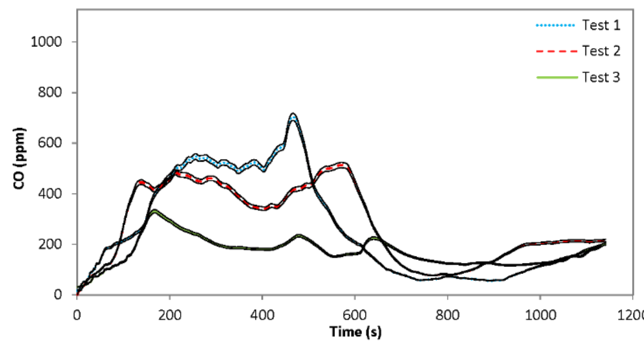

Fig. 12. Time-Resolved CO Concentration Measurements – Operating Set 2

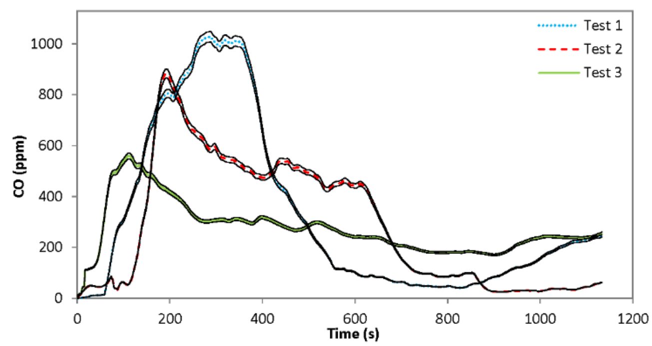

Fig. 13. Time-Resolved CO Concentration Measurements – Operating Set 3

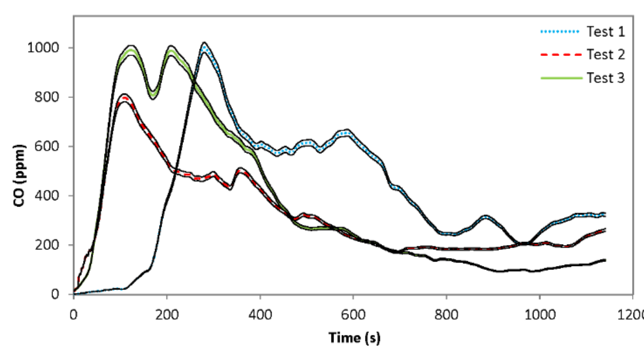

Fig. 14. Time-Resolved CO Concentration Measurements – Operating Set 4

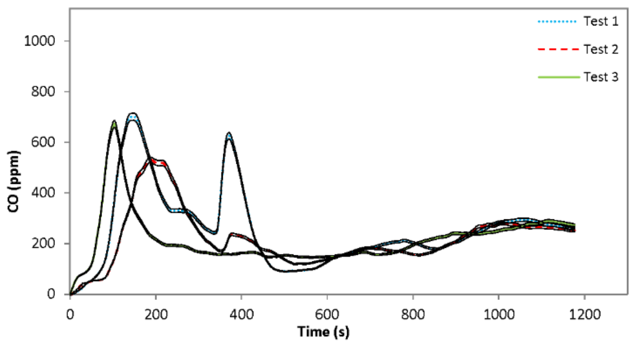

Fig. 15. Time-Resolved CO Concentration Measurements – Operating Set 5

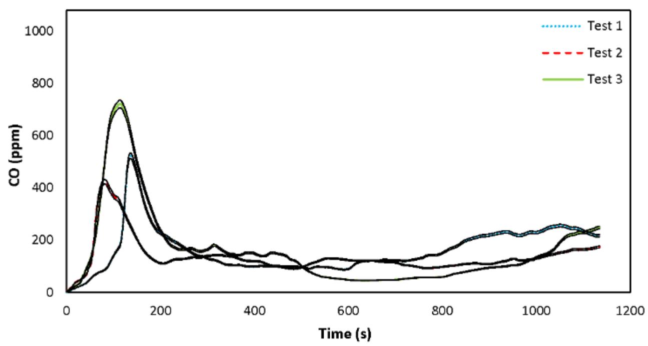

Fig. 16. Time-Resolved CO Concentration Measurements – Operating Set 6

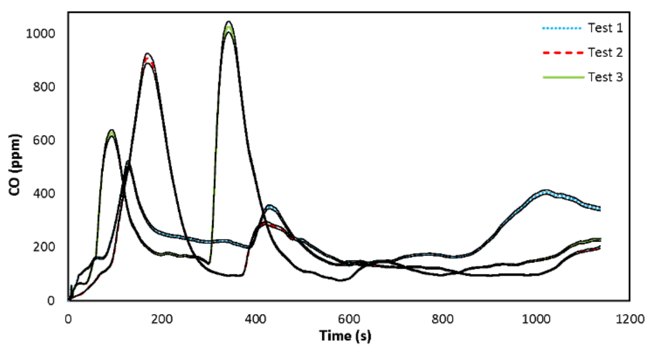

Fig. 17. Time-Resolved CO Concentration Measurements – Operating Set 7

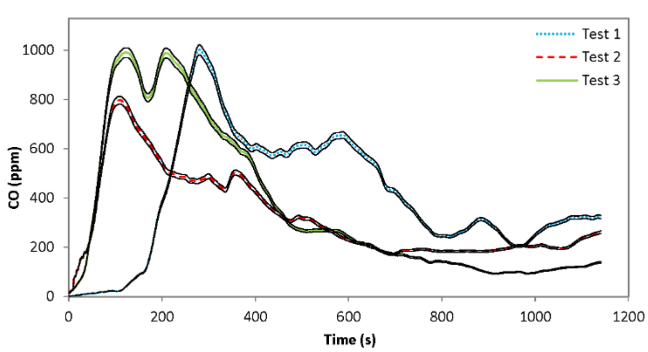

Fig. 18. Time-Resolved CO Concentration Measurements – Operating Set 8

V. Analysis of the Time-Resolved Measurements

The time-resolved measurements presented in the previous section were analyzed and the performance metrics described in the following sections were calculated.

A. *Thermal Efficiency*

The thermal efficiency of the cookstove is determined during each test by monitoring the temperature of the water in the cooking pot and measuring the mass of water that evaporated during each test [15]. The thermal efficiency of the cookstove is defined as the ratio of the energy transferred to the pot to the energy available in the fuel. The amount of energy transferred to the pot is the sum of the increase in the sensible heat of the water as it is brought to the boiling point and the latent heat of vaporization. The latent heat of vaporization is the product of the heat of vaporization at atmospheric pressure and the mass of water that evaporated during the test. Lower heating values are used to calculate the energy available in the fuel.

The thermal efficiency of the cookstove is shown as a function of the amount of energy provided by the biogas with and without a fan in Fig. 19. These values are the average of the results obtained in each of the three tests. Complete details regarding calculation of the thermal efficiency and a detailed description of the uncertainty analysis is given in [12].

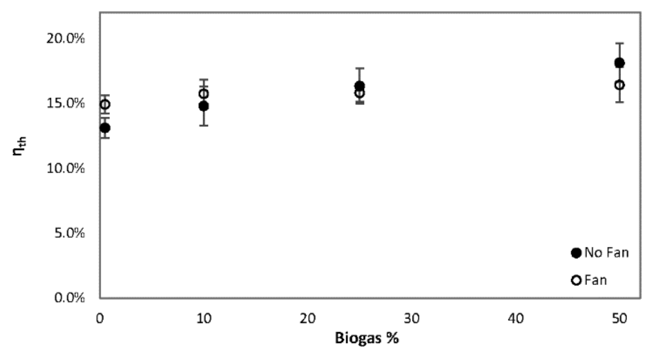

Fig. 19. Thermal efficiency of the cookstove as a function of the percent of the energy provided by biogas with and without the fan

B. *Specific Emissions*

The specific emissions of the primary pollutants (PM and CO) are obtained by integrating the time-resolved measurements and dividing the result by the total energy delivered to the cooking pot [10]. The specific emission of PM is shown as a function of the percentage of the total energy provided by the biogas in Fig. 20, and corresponding CO results are shown in Fig. 21. Again, the values shown are the average of the results obtained in each of the three tests. Complete details regarding calculation of the specific emissions and a detailed description of the uncertainty analysis is given in [12].

C. *Modified Combutsion Efficiency*

Combustion efficiency is defined as the ratio of the energy released during a combustion process to the energy available in the fuel. A combustion process is said to be complete when all the carbon and hydrogen in the fuel combines with oxygen to form CO_2 and H_2O. Complete combustion releases all of the energy available in the fuel, so a combustion process that is complete has a combustion efficiency of 100%. If the amount of oxygen in the combustion zone is insufficient to react with all the carbon and hydrogen released by the fuel, the combustion process will be incomplete. Conditions in which the amount of

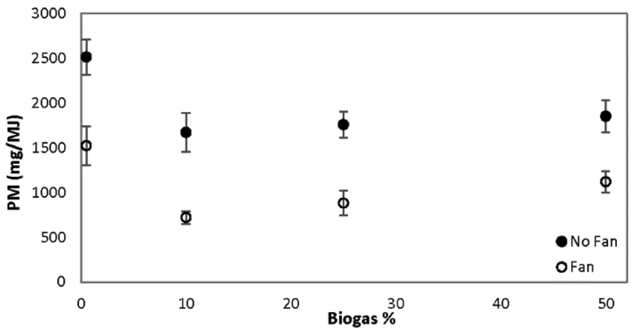

Fig. 20. Specific Emission of PM (mg/MJ) as a function of the percent of the energy provided by biogas with and without the fan

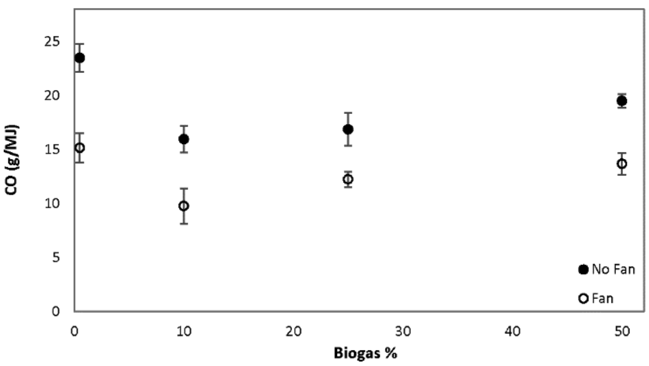

Fig. 21. Specific Emission of CO (g/MJ) as a function of the percent of the energy provided by biogas with and without the fan

fuel exceeds the amount of oxygen are referred to as fuel rich conditions. If there is unburned carbon (PM) or CO in the exhaust stream, it is clear that the combustion process is incomplete, and the combustion efficiency will be less than 100%. Determining the total amount of carbon and hydrogen in a solid fuel is difficult, so determining the combustion efficiency is challenging. However, measurement of CO and CO_2 concentrations in the exhaust stream is relatively simple, so the ratio of the CO_2 concentration to the sum of the CO and CO_2 concentrations, which is defined as the modified combustion efficiency (MCE), is generally used as a proxy for the combustion efficiency [18].

The average MCE is shown as a function of the percentage of the total energy provided by the biogas in Fig. 22. Details regarding calculation of the MCE and a detailed description of the uncertainty analysis is given in [12].

VI. Discussion

A. Time-Resolved Measurements

When biomass was burned alone (operating set 1), the time-resolved PM and CO increase steadily from the time of ignition until approximately 200 s. Both PM and CO concentrations are relatively flat between 200 and 600 s and drop off after 600 s, which is the time at which most of the biomass has been consumed. After this time, the PM concentration decreases as fire burns out, but the CO concentration increases slightly. Due to uncontrolled variations in the composition of the fuel and to randomness inherent in the combustion process, there are significant variations in each of the three tests.

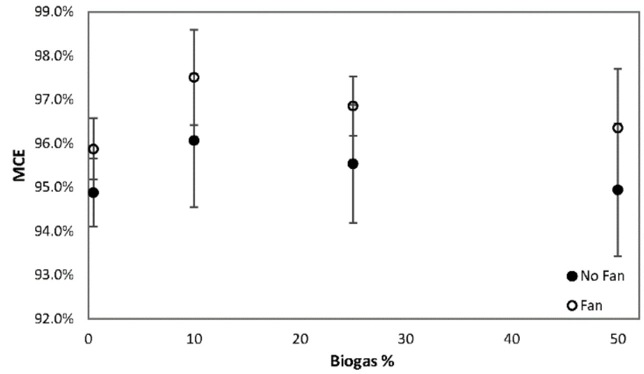

Fig. 22. The modified combustion efficiency as a function of the percent of the energy provided by biogas with and without the fan

Although there are significant run-to-run variations, some general trends may be observed in the time-resolved PM and CO concentration measurements when the cookstove was co-fired with biogas and the fan was not used (operating sets 2 – 4).

PM emissions tend to spike during the ignition stage. Although there are random spikes in PM concentrations following the ignition stage, the time-resolved PM measurements indicate that, on average, co-firing reduces the PM concentration from approximately 80 mg/m^3 to approximately 40 mg/m^3 during the post-ignition stage (roughly 200 – 600 s). The spikes in the PM concentration in the post-ignition stage are probably associated with randomly occurring micro-explosions that occur when the pressure of the heated water vapor and gases trapped in the wood causes the wood to rupture. These micro-explosions are the source of the popping and crackling commonly heard in wood fires. Video and audio recordings of future tests will be used to correlate these events with the spikes in the measured PM concentrations.

Co-firing the cookstove with 10% biogas had relatively little effect on the CO concentration levels, but co-firing with higher levels of biogas, on average, increases the emission of CO. These results show that fuel-rich conditions exist in the stove under these operating conditions and there is insufficient oxygen available to allow for complete combustion.

The run-to-run variations were also significant when the fan was used without co-firing (operating set 5), but some general trends may be observed by comparing Fig. 7 with Fig. 3 and Fig. 15 with Fig. 11. Since the fan brought more oxygen into the combustion zone, conditions were less fuel-rich under these operating conditions. Therefore, the ignition stage was shorter, and PM and CO concentrations in the exhaust were reduced.

The time-resolved PM concentration measurements obtained when the cookstove was co-fired with biogas and the fan was used are shown in Figs. 8 – 10, and corresponding CO measurements are shown in Figs. 16 – 18. Again, the run-to-run variations are significant, but some general trends may be observed.

PM emissions tend to spike during the during the ignition stage, and except for the randomly occurring spikes that are probably associated with the previously described micro-explosions, the PM concentration levels are relatively low. It is hypothesized that these reductions are largely due to fact that conditions are less fuel-rich when the fan is used, which results in a more complete combustion process. Recall that PM is largely created by unburned carbon, and the amount of unburned carbon is reduced as the oxygen supply increases. Comparison of Figs. 8 and 7 indicates that co-firing with 10% biogas leads to a reduction in PM emissions following the ignition stage.

However, further increasing the flow of biogas level appears to increase the amount of PM emitted. Comparison of Fig. 9 with Fig. 8 indicates that the PM emissions with 25% biogas are greater than the PM emissions observed with 10% biogas. However, the number of spikes in the PM emissions observed in the post-ignition stage of the runs performed with 25% biogas may confound this conclusion, since these spikes are likely primarily due to uncontrolled variations in the composition of the solid biomass fuel. Therefore, the amount of biogas may not have played a dominate role in the amount of PM generated in these particular tests. Comparison of Fig. 10 with Figs. 8 and 9 indicates that the baseline level of PM emissions does increase when the cookstove is co-fired with 50% biogas. Since the fan operated at the same speed in all the tests, it is likely that use of excess biogas created more fuel rich operating conditions, which lead to a less complete combustion process with a resulting increase in the amount of PM generated.

Comparison of Fig. 16 with Fig. 15 indicates that co-firing the cookstove with 10% biogas when the fan is used reduces CO emissions, but co-firing with 25% or 50% biogas increases CO emissions. Again, use of higher biogas flow rates likely increases the extent to which fuel-rich conditions exist in the combustion zone, which results in less complete combustion and an increase in CO emissions as well as PM emissions.

Considering the time-resolved measurements of PM and CO concentrations together indicates that the use of the fan reduces the extent to which fuel rich conditions exist in the combustion zone, which results in a combustion process that is more complete. These measurements also indicate that an optimal level of co-firing with biogas also exits. Since biogas ignites easily and energy released by combustion of the biogas promotes complete combustion of the solid fuel during the ignition stage, PM and CO emissions are reduced early in the combustion process. However, an excess flow of biogas increases the fuel to oxygen ratio in the post-ignition stage, which leads to less complete combustion and an increase in the emission of PM and CO. More tests in which the fraction of the total energy is varied between 0 and 25% are required to determine the optimal level of co-firing.

B. *Time-Averaged Measurements*

It is interesting to note that the variations in the integrated results – thermal efficiency, specific emission of PM, specific emission of CO and MCE – are much less than the variations seen in the time-resolved measurements.

Recall that the thermal efficiency is defined as the ratio of the rate heat is transferred to the pot to the rate is energy released during the combustion process. Therefore, the thermal efficiency depends on how well the stove channels the heat generated in the fire to the pot and the extent to which the heat lost to the surroundings is minimized. The thermal efficiency also depends on the rate fuel is burned. Since these parameters were not varied, the thermal efficiency should not vary with the amount of biogas used or depend on whether the fan was used. As shown in Fig. 19, the measured thermal efficiency of this traditional Peruvian cookstove is approximately 15%, and it is independent of the amount of biogas used or whether the fan was used. The fact that the measured thermal efficiencies are independent of the combustion process may see uninteresting at first, it should be noted that this consistency is an indication that despite the high degree of variation in the time-resolved measurements, the experiments were performed consistently.

The thermal efficiency of the cookstove is low, but these values are typical for unimproved cookstoves [10,18]. These results highlight the fact that the thermal coupling between the combustion chamber and the pot are poor in traditional cookstoves, and increasing the effectiveness of the processes used to transfer heat from the fire to the pot will lead to significant improvements in cookstoves.

Compared to the combustion of biomass without using the fan, co-firing with 10% biogas reduced CO emissions by 32% and PM emissions by 33%. Using the fan without co-firing with biogas reduced CO emissions by 35% and PM emissions by 39%. Using both co-firing with 10% biomass and the fan reduced CO emissions by 58% and PM emissions by 71%.

Use of 10% biogas and the fan also resulted in improved MCE. These results suggest that relatively simple modifications significantly improve indoor air quality in homes where these stoves are used and reduce the impact use of this stove has on the environment.

REFERENCES

[1] Legros, G., Havet, I., Bruce, N., and Bonjour, S., 2009. "The energy access situation in developing countries," UNDP and the World Health Organization, http://content.undp.org/ go/cmsservice/stream/asset/ ?asset_id=2205620 , Accessed February 14, 2013.

[2] V. Ramanathan and G. Carmichael, "Global and regional climate changes due to black carbon," *Nature Geoscience*, vol. 1, no. 4. pp. 221–227, 2008.

[3] M. Dherani, D. Pope, M. Mascarenhas, K. R. Smith, M. Weber, and N. Bruce, "Indoor air pollution from unprocessed solid fuel use and pneumonia risk in children aged under five years: a systematic review and meta-analysis.," *Bull. World Health Organ.*, vol. 86, no. 5, pp. 390–398C, 2008.

[4] World Health Organization, "Indoor Air Pollution and Health," 2013.

[5] B. DeAngelo, C. Schneider, and J. Moss, "Black Carbon and Its Implications for Climate Change and Public Health," *Environmental and Energy Study Institute*, Washington, D.C., 2010.

[6] R. E. Kopp and D. L. Mauzerall, "Assessing the climatic benefits of black carbon mitigation.," *Proc. Natl. Acad. Sci. U. S. A.*, vol. 107, no. 26, pp. 11703–8, Jun. 2010.

[7] T. C. Bond, D. G. Streets, K. F. Yarber, S. M. Nelson, J. H. Woo, and Z. Klimont, "A technology-based global inventory of black and organic carbon emissions from combustion," *J. Geophys. Res. Atmos.*, vol. 109, 2004.

[8] D. Still, N. MacCarty, D. Ogle, T. Bond, and M. Bryden, "Test Results of Cook Stove Performance," http://www.pciaonline.org/resources/test-results-cook-stove-performance, Accessed July 18, 2014.

[9] N. MacCarty, D. Still, and D. Ogle, "Fuel use and emissions performance of fifty cooking stoves in the laboratory and related benchmarks of performance," *Energy Sustain. Dev.*, vol. 14, no. 3, pp. 161–171, 2010.

[10] J. Jetter, Y. Zhao, K. R. Smith, B. Khan, T. Yelverton, P. Decarlo, and M. D. Hays, "Pollutant emissions and energy efficiency under controlled conditions for household biomass cookstoves and implications for metrics

useful in setting international test standards," *Environ. Sci. Technol*., vol. 46, no. 19, pp. 10827–10834, 2012.

[11] N. L. Panwar, "Design and performance evaluation of energy efficient biomass gasifier based cookstove on multi fuels," *Mitig. Adapt. Strateg. Glob. Chang.*, vol. 14, no. 7, pp. 627–633, Aug. 2009.

[12] C. A. Ochieng, S. Vardoulakis, and C. Tonne, "Are rocket mud stoves associated with lower indoor carbon monoxide and personal exposure in rural Kenya?," *Indoor Air*, vol. 23, no. 1, pp. 14–24, Feb. 2013.

[13] Aprovecho Research Center, "Emissions Equipment", http://aprovecho. org/lab/emissionsequip, Accessed July 18, 2014.

[14] Poudyal, M. *Co-Firing Biomass with Biogas in a Cookstoves with a Fan*, MS Thesis, Department of Mechanical Engineering, Brigham Young University, 2014.

[15] Aprovecho Research Center, "Testing," http://aprovecho.org/lab/pubs /testing, Accessed July 18, 2014.

[16] A. Ounnar, L. Benhabyles and S. Igoud, "Energetic Valorization of Biomethane Produced from Cow-Dung" *Procedia Engineering*, vol. 33, pp. 330-334, 2012.

[17] R. Arthur, M. F. Baidoo and E. Antwi, "Biogas as a potential renewable energy source: A Ghanaian case study", *Renewable Energy*, vol. 36, no. 5, pp. 1510-1516, 2011.

[18] M. Johnson, R. Edwards, V. Berrueta and O. Masera, "New Approaches to Performance Testing of Improved Cookstoves," *Environ. Sci. Technol.*, vol. 44, no. 1, pp. 368-374, 2010.