Final Technical Report

Project Title: Thermoelectric-Enhanced Cookstove Add-on (TECA) for Clean Biomass Cookstoves

Award Number: DE-EE0006087

Recipient: RTI International

Project Location(s): Research Triangle Park, NC (RTI), Fort Collins, CO (Envirofit & CSU)

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Colorado State University

Cost-Sharing Partners: None

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Teaming Members: RTI International, Envirofit International, Colorado State University

Executive Summary:

Under the DOE Cookstove program, RTI partnered with Envirofit International and Colorado State University to develop a self-powered forced air add-on to a commercial cookstove to reduce emissions. In the course of the program we were able to advance the science of cookstove combustion in several areas, develop a clean burning self-powered prototype cookstove with low emissions, and validate the performance of the stove in the lab and in the field.

Through a thorough evaluation of exhaust gas recirculation and air injection for emissions reduction, we identified primary and secondary mechanisms that reduce emissions for rocket stove combustion. In addition, we developed a stove performance optimization approach that dramatically reduces the number and length of experiments required to adjust air injection parameters. In the area of field testing, we developed a portable tent testing approach that allows an intermediate form of field evaluation to characterized emissions performance of a stove. We demonstrated this approach with field testing in Aurangabad, India and demonstrated field performance with our enhanced stove that matched or exceed the performance in the lab.

In the end, we demonstrated a 70% reduction in emissions with our air injection add-on as compared to the baseline Envirofit M-5000 stove. This represents a 92% reduction in emissions as compared to the traditional 3-stone fire. All of these efforts have addressed the technical risks associated with developing and optimizing an air injection system for rocket stoves to reduce emissions. In addition, we have shared these lessons learned with the other DOE teams that were funded under the cookstove program and at the 2015 Ethos conference in Seattle, WA.

Out of our program, we have filed one provisional patent on the air injection approach, and have written two journal papers that will soon be submitted for publication. In addition, we have worked with Envirofit International (a U.S. small business) to develop a commercialization strategy and report. We hope to further commercialize this technology through Envirofit not only provide a clean cooking solution for the developing world, but also to expand Envirofit's role in creating US jobs and developing technology to support the bioeconomy.

Program Accomplishments:

The following is a list of the specific objectives for our program along with a description of the level to which we have achieved those goals:

- Develop an affordable add-on device to enhance biomass cookstove performance.

  Under the program, we successfully developed a prototype add-on device that reduces emissions from the Envirofit M-5000 cookstove.

- Demonstrate significant emissions reductions from the Envirofit M-5000 stove with the add-on in both the laboratory (USA) and the field (India) to approach Tier 4 standards for CO and PM2.5.

  Under the program, we demonstrated a 70% reduction in emissions for the M-5000 stove both in the lab and in our field testing in Aurangabad, India. At 1.5-2 g/MJ-delivered, the CO emission is well within the Tier 4 standard (<8 g/MJ-del). We achieved a $PM_{2.5}$ emission level at 83 mg/MJ-delivered, which puts us very close to the Tier 4 standard of <41 mg/MJ-del.

- Demonstrate field reliability and safety of the add-on device through testing a 24/7 burn lab in India.

  Under the program, we completed component-level laboratory reliability testing at elevated temperature and humidity and have begun field reliability testing that is currently ongoing. The 27/7 field reliability testing was started on June 6, 2015, and is projected to be complete by January 1, 2016.

- Demonstrate the ability to crosswalk lab and field measurements.

  Under the program, we completed field emissions testing in Aurangabad, India and compared the emissions performance of the prototype stove with the air injection add-on as compared to the standard Envirofit M-5000 stove. We demonstrated an 80% reduction in emissions with the prototype stove operated by a technician using cut fuel that closely matched the fuel used in the lab testing. With the local user and local fuel, we demonstrated a 68% reduction in emissions. In both cases this compares favorably to the 70% emissions reduction measured in the lab. We exceeded our goal of matching the field performance of the stove to the lab measurements within 15%.

- Demonstrate an innovative approach to exposure-based testing using the RTI MicroPEM™ device in a Portable Indoor Exposure (PIE) test structure that will be taken to the field (India).

  Under the program, we developed and characterized a portable indoor exposure testing approach using RTI MicroPEM™ devices and a tent. We setup the tent and MicroPEM™ devices to characterize the testing approach at RTI's facility in North Carolina. Then, we shipped the tent to Aurangabad, India and took the emissions measurement instruments there to perform the field testing.

- Develop an effective approach to bring the solution to market through a manufacturing and scale-up plan – leverage RTI's field offices and partnering manufacturing facilities in India and Kenya.

  Under the program, RTI's commercialization team collaborated with Envirofit's expertise in product development and deployment to draft a commercialization strategy and report. Both RTI and Envirofit have facilities in India and Kenya that can ultimately support the marketing, manufacturing, and scale-up of the developed prototype.

- Demonstrate auxiliary power production from the TECA device to power a light or recharge a cell phone to make the enhanced cookstove more attractive for long-term user acceptance and use.

  As part of our lab and field testing, we demonstrated the availability of auxiliary power output from the prototype stove in the form of a USB charging port. This feature was also presented to three focus groups in Aurangabad, India to gauge user acceptance and preferences.

The following tables summarize the target milestones and deliverables and the current status in meeting those milestones. Every deliverable has been completed, and all but one milestones have been met. The field reliability testing didn't begin until June 6, 2015 and will not be complete until January 1, 2016.

Milestone	Status
TECA prototype complete	Completed
Lab testing complete	Completed
Component reliability testing complete	Completed
Field reliability testing complete	Started June 6, 2015 Projected to complete by January 1, 2016
Field testing complete	Completed

Deliverables	Status
Fully integrated prototype TECA device	Completed
Demonstration of field emission performance	Completed
Detailed manufacturing plan with quotes for component costs	Completed
Publication/presentation of the program results	Completed

Project Activity Summary:

The project was broken in the following tasks:

Task A – TECA Device Development
Task B – Emissions Reduction Design (air injection)
Task C – Laboratory Emissions and Exposure Characterization
Task D – TECA Component Level Reliability Testing
Task E – Prototype Field Reliability Testing
Task F – Lab-Field Crosswalk Emissions and Exposure-Based Testing
Task G – Manufacturing and Scale-up
Task H – Project Management and Reporting

The project was based on the following hypotheses:

- Biomass cookstove emissions from a rocket stove can be reduced by careful injection of air into the combustion chamber.

- Electric power to drive the fan or blower can be generated from the combustion heat using a thermoelectric (TE) device.
- A new portable indoor air emissions measurement methodology will help to more accurately predict the field emissions performance for a cookstove.

At the start of the program we developed a sub-hypothesis that employing exhaust gas recirculation (EGR) might provide the best improvement in emissions by allowing incompletely combusted species to be passed back through the flames in the combustion chamber to be fully burned. In the course of the emissions reduction design and testing (Tasks B and C), we developed an EGR emissions reduction system, but did not arrive at the target emissions reductions that we had expected. This set us back in our development timeline, but we decided to examine the emissions reduction approach further.

We then explored an alternate sub-hypothesis that the injection of fresh air could improve the emissions further. From our design and experiments in Tasks B and C we concluded that the injection of fresh air did further reduce emissions beyond the reduction that EGR could provide. This was contrary to the general understanding that the enhanced turbulent mixing was the most significant mechanism for reduced emissions for fan stoves of this type. The high natural draft of rocket stoves provides an ample volume of fresh air for the combustion chamber beyond the ideal stoichiometric levels; however, in our experiments we found that the extra oxygen injected at just the right position in the combustion chamber did lead to more complete combustion and provided the necessary oxygen in the flame region where it was needed. This was an unexpected result and provided new insight into biomass stove combustion.

The emissions reduction design and testing tasks were expanded beyond our original timeline, but it produced a more complete understanding of enhanced combustion in a rocket stove and lead to the development of our prototype that was able to reduce emissions from the baseline stove by 70%.

Product Development Summary

Several developments have come out of the work completed in this program. This includes the development of a prototype cookstove add-on device that effectively reduces emissions, control electronics for a self-powered cookstove add-on, a commercialization plan, a new field testing methodology, a patent for the air injection approach for emissions reduction, and a number of publications and presentations.

The following is a list of the specific publications and presentations that have come from the program:

Master's Thesis

- Kevin Dischino, Colorado State University, "Methods for particulate matter emissions reduction in wood burning Cookstoves"

Conference Presentations:

- David Stokes, RTI International, "Thermoelectric Energy Harvesting for Developing-World Applications," 2015 10th Energy Harvesting Workshop, Blacksburg, VA
- David Stokes, RTI International, "Thermoelectric-Enhanced Cookstove Add-on (TECA) for Clean Biomass Cookstoves," 2015 Ethos Conference, Seattle, WA
- Kevin Dischino, Colorado State University, "Experimental Optimization of Forced Draft for PM 2.5 Emissions Reduction," 2015 Ethos Conference, Seattle, WA

The following is a list of the patents, technologies, and prototypes that have come from the program:

Patents:

- Provisional patent filing by CSU on air injection approach

Technologies:

- Portable indoor air field emissions testing methodology – provides a means to predict performance of a cookstove before going to the field and to validate the emissions in country
- Rocket stove air injection methodology – significantly reduces emissions from rocket stoves
- Air injection optimization methodology – significantly reduces the complexity and number of experiments
- Control electronics for a self-powered air injection system – provides means for controlling air flow and balancing power generated and used

Prototypes:

- Developed working prototype add-on device for an Envirofit M-5000 cookstove that reduces PM emissions by 70%

Photos, Tables, and Graphs Highlighting Outcomes of the Program

The following is a photo of the Envirofit M-5000 prototype with the air injection add-on device:

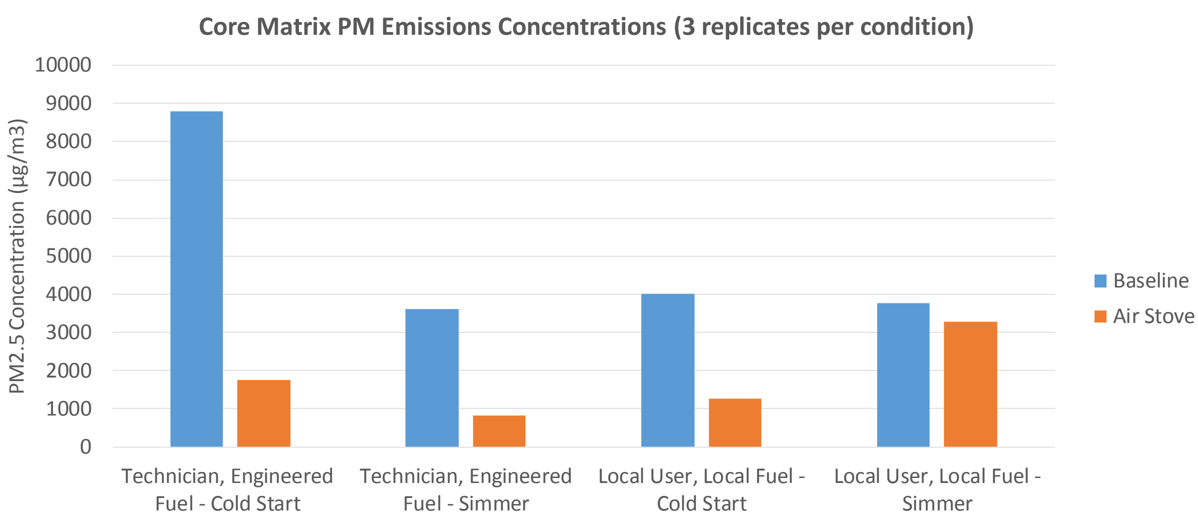
The following photo shows the standard Envirofit M-5000 stove (on the left) and the prototype stove on the right for comparison.

The following photos show the field reliability testing data acquisition system and the prototype stove under testing.

We completed a matrix of tests outlined in the table below. The stove performance results showed significant reduction in the emissions in the field under all conditions in the range of 67-87% reduction with the air stove as compared to the standard Envirofit M-5000. This compares favorably to the 70% reduction measured in the lab.

Field Emissions Test Matrix:

Fuel	Standard M-5000	Enhanced M-5000 with RTI TECA
Engineered Wood (pine)	1) Technician operated (3 replicates)	2) Technician operated (3 replicates)
Indian Wood (Neem sticks)	3) Local user operated (3 replicates) 5) Technician operated (1 sample)	4) Local user operated (3 replicates) 6) Technician operated (1 sample)



Test Condition	Test Phase	Location 1 (1.5 m) Average PM2.5 (µg/m3)	Location 2 (1m) Average PM2.5 (µg/m3)	Location 3 (0.3m) Average PM2.5 (µg/m3)	Personal Average PM2.5 (µg/m3)	Overall Average PM2.5 Reduction
Technician, Engineered Fuel	Cold Start	82%	76%	83%	52%	73%
	Simmer	77%	77%	79%	71%	76%
Local User, Local Fuel	Cold Start	66%	70%	69%	63%	67%
	Simmer	0%	18%	28%	39%	21%
Technician, Local Fuel	Cold Start	60%	53%	VOID	11%	41%
	Simmer	63%	46%	56%	57%	56%
Technician, Engineered Fuel	Cold Start	86%	89%	90%	82%	87%
	Simmer	87%	86%	89%	84%	87%