Multidisciplinary Design of an Innovative Natural Draft, Forced Diffusion Cookstove for Woody and Herbaceous Biomass Fuels

User Research

Field Testing

Modeling

Design & Testing

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ETHOS
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Challenge

A sustainable way for East African’s to safely and efficiently cook food using available fuel source

Sustainable $\rightarrow$ cost, meets users needs/desires, durable, reduce deforestation, reduce impact on environment

Safely and efficient $\rightarrow$ significantly reduce emissions and fuel usage as compared to existing solution (e.g. three-stone fire)

Available fuel source $\rightarrow$ in rural Kenya this means wood
Project Goals

• Develop a Tier 4 natural draft cookstove that will meet the needs and desires of customers in rural Kenya.

• The project will deliver a manufacturable and market ready cookstove that meets the cost and usability expectations of the final users, including durability, emissions, safety, comfort, aspirational value and compatibility with local fuels, foods, and customs.
Approach

Integrated and multidisciplinary design approach that includes:

• Field based user research and focus groups (BDL)
• Empirically verified combustion, computational fluid dynamics, and heat transfer modeling (UW)
• Several natural draft stove innovations (UW, BDL)
• Lab testing (UW, BDL)
• Design for manufacturability (BDL)
• Field emission and efficiency verification (BA)
• In-home user product evaluations (BDL)
User Research
User Research Objectives

• What are potential stove user’s preferences for stove geometry, aesthetics, materials?
• What stove features do they value and are willing to accept?
• How much do they value the different aspects of stove performance?
• What are they willing to pay for the stove and for each individual feature?
• What are the characteristics of the fuel that will typically be used in the stove?
User Research Overview

- IRB and KEMRI approved
- 6 locations in Kenya (3 done, 3 more this year)
- 4 focus groups per location
- 46 participants per location (36 cooks, 10 women leaders)
- Three target market segments with income: >$71/mo, $35-71/mo, < $35/mo.
- 250+ total cook participants
- Distributor interviews
- Manufacturer interviews
- Policy influencer interviews
- Government interviews

UW/Burn and commercially available stoves used in research
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• Pre-cooking to post-cooking preferences changed substantially.
  – Pre-cooking stove preferences based on size, appearance, & weight.
  – Post-cooking, stove preferences based on perceived time to cook, ease of lighting, fuel required for cooking (efficiency), and particulate emissions.
  – Cooks willing to accept reduced visibility of flame for perceived improvement in performance
Summary of Lessons Learned

- Cooks indicated that they were willing to pay for some features (e.g. stove of preferred height)

- Cooks provide meaningful feedback on aspirations and desirability of the stove design (features, size, weight, feet, handles, stick tray, visibility of flame) and much of this feedback is based on performance (perceived time to boil, emissions, efficiency, stability) as opposed to pure aesthetics.

- Large variability in responses → adequate sample size and careful interpretation.
Computational Modeling

- Improve understanding of physical processes occurring inside cookstove.
- Can isolate effect of various parameters (geometry, fuel, etc.) on heat transfer, mixing and emissions.
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Anamol Pundle: Talk about CFD at 11:30 am today
Stove Innovations and Testing

- 23 stove prototypes and 60+ configurations
- Total number of tests: ~300
- Innovations have focused on PM and user aspirations
• Quantitative lab testing at UW and Burn: calibrated CO, CO2, temperature, real time display
• UW: Real-time gravimetric PM (TEOM) increases repeatability, increases testing rate, and facilitates a deeper understanding of cookstove performance
  • Ability to link physical actions with emissions response
  • Allows for rapid stove morphology evaluation
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Ben Sullivan: Talk about real-time PM at 10:30 am tomorrow
Baseline Stove

Baseline stove is a starting point for innovative stove features

- Geometry based on averages of existing commercial stoves
- Insulated steel construction
- Primary air swinging door
- Ashtray
- Cone deck
- Pot skirt
- Under fire primary air
- Handles
Laboratory Testing: Baseline

• CO is Tier 4

• Primary challenges are PM and efficiency

• Optimized pot standoff and skirt provide 4% increase in efficiency

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<th>Current Status</th>
<th>Benchmark</th>
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<td>Burn rate [g/min]</td>
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<td>Fire Power [Watts]</td>
<td>4850</td>
<td>3000</td>
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*Benchmark is the average of natural draft stoves in Jetter 2012
The low-emissions stoves reside in the bottom left corner of the map, indicating notably low emissions.

Forced-draft stoves, such as the Philips fan and Oorja, and the TLUD-type stoves show the ability to better correlate laboratory results with field results. Additional WBT phase-based data for MCE, OTE, and fuel use are provided in the SI.

The majority of cookstoves emit less CO and PM compared with every other stove. Charcoal stoves emit high CO levels during all three WBT phases and high PM emissions compared with other stoves. Charcoal stoves emit high PM emissions per unit volume of water per time than the 3-stone fire and lower CO and PM emissions per unit cooking energy delivered for low-moisture fuel considering the WBT high-power (cold-start) phase. UFPs are of interest in an environment where fewer accumulation mode particles tend to be found. Biological effects of UFPs are currently under investigation.

Presently, there are no USEPA standards or vehicle emissions legislation that consider UFPs. The majority of cookstoves tested show lower UFP emissions compared with those of the forced-draft Philips fan stove. Forced-draft stoves achieved lower emissions for a given cooking task at less than 0.0005 pM. These rocket stoves can thus be recommended for cooking tasks that require the lowest CO and PM emissions. The use of charcoal stoves is not recommended because of the high CO and PM emissions during the cold-start phase due to the charcoal ignition process.

Figure 4 shows the CO and PM emissions per unit energy delivered than the 3-stone fire. Two rocket stoves showed significantly lower (p = 0.018) CO emissions than during the high-power level. The two rocket stoves compared with the high-power level, the two rocket stoves achieved lower CO emissions for the StoveTec stove. These rocket stoves can thus be recommended for cooking tasks that require the lowest CO emissions. The use of charcoal stoves is not recommended because of the high CO and PM emissions during the cold-start phase due to the charcoal ignition process.

Moreover, charcoal stoves produce less surface area for condensation and growth. After ignition, charcoal stoves can produce high levels of irritating smoke compared to wood stoves and thus should be avoided.

In an environment where fewer accumulation mode particles tend to be found, gas phase nucleation may be occurring. Gas phase nucleation is of interest because they can penetrate deep into the airways of the human respiratory tract to the alveoli, where they may cause adverse biological effects. In general, nucleation rates tend to be enhanced in an environment where fewer accumulation mode particles are present. In this case, gas phase nucleation may be occurring. Gas phase nucleation is of interest because they can penetrate deep into the airways of the human respiratory tract to the alveoli, where they may cause adverse biological effects. In general, nucleation rates tend to be enhanced in an environment where fewer accumulation mode particles are present.

Intermittent malfunction of a fan speed controller likely produced highly variable UFP emissions for the TLUD stove. A natural-draft TLUD stove showed the lowest mean UFP and PM emissions per cooking energy delivered to the cooking pot for low-moisture fuel during the low-power phase (Figure 2) and lower CO and PM emissions than during the high-power (cold-start) phase of the Water Boiling Test. Again, an intermittent problem with the liquid-fuel stove burner caused high PM emissions.

Environmental Science & Technology (ES&T) 2012, 46, 10827 – 10834.

*from Jetter ES&T 2012
TallBoy Tiered Results

<table>
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<td>Time to boil [min]</td>
<td>30</td>
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<tr>
<td>Burn rate [g/min]</td>
<td>10</td>
</tr>
<tr>
<td>Fire Power [Watts]</td>
<td>2800</td>
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The stove had notably low emissions. A significant difference in forced-draft stoves (Philips fan, Oorja) and the TLUD-type ability to better correlate laboratory results with additional benefits. WBT low-power phase (Figure 4) than during the high-power emissions. Charcoal stoves emit lower PM levels during the (Figure 2) and lower CO and PM operated at medium power show higher MCE and OTE emissions.

emissions variability and possibly higher-than-expected PM emissions. Charcoal stoves emit high 0.018) was observed for the TLUD stove CO emissions compared with every other stove. Charcoal stoves emit high CO levels during all three WBT phases and high PM emissions compared with every other stove. Charcoal stoves produce less surface area for condensation and growth. An intermittent problem with the liquid-fuel stove burner caused high PM emissions.

After ignition, charcoal stoves can produce high levels of CO during the cold-start phase due to the charcoal ignition process. CO levels during all three WBT phases and high PM emissions during the cold-start phase of the Water Boiling Test. The majority of cookstoves emit less CO and PM per unit volume of water per time than the 3-stone fire base-case. Two rocket stoves are provided in the SI. Additional WBT phase-based data for MCE, OTE, and fuel use are provided in the SI. Environmental Science & Technology

**CO-PM Jetter Map**

*from Jetter ES&T 2012*
Lessons learned from lab testing

- Tier 4+ for CO, Tier 3+ for PM
- Need to further reduce PM and increase efficiency
- Secondary combustion to burn out volatiles and soot
- Improved mixing alleviates segregation of fuel and air
- Stress testing: evaluate performance with varying fuel, users, firing rate.

Standardized stress test

*Acknowledge CSU efforts in this area
Field Testing (Berkeley Air)

- **Uncontrolled Cooking Test**
  - Conducted in homes
  - CCT with uncontrolled meal and fuel
  - More variable but reflects actual use
  - Measures:
    - Fuel conditions
    - Pot size and type
    - Foods cooked
    - Lighting techniques
    - Specific fuel consumption
    - Emission factors and rates
    - Combustion efficiency
    - Firepower
    - CO, CO$_2$, PM, CH$_4$, TNMHC, BC, OC
Looking Forward (6-12 months)

- Continue user research in three locations and refine cooks needs and desires
- Improve model fidelity and validate
- Innovate to reduce PM, increase efficiency
- Refine and use stress test
- Field performance testing at two sites (Berkeley Air)
- Commercialize DOE V1 stove with BMC