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Original Contribution

Can Currently Available Advanced Combustion Biomass Cook-Stoves Provide Health Relevant Exposure Reductions? Results from Initial Assessment of Select Commercial Models in India

Sankar Sambandam,[1] Kalpana Balakrishnan,[1] Santu Ghosh,[1]
Arulselvan Sadasivam,[1] Satish Madhav,[1] Rengaraj Ramasamy,[1] Maitreya Samanta,[1]
Krishnendu Mukhopadhyay,[1] Hafeez Rehman,[2] and Veerabhadran Ramanathan[3]

[1]*World Health Organisation Collaborating Center for Occupational and Environmental Health, Department of Environmental Health Engineering, Sri Ramachandra University, No.1, Ramachandra Nagar, Porur, Chennai 600116, India*
[2]*The Energy Resources Institute, New Delhi, India*
[3]*Scripps Institution of Oceanography, University of California, San Diego, CA*

Abstract: Household air pollution from use of solid fuels is a major contributor to the national burden of disease in India. Currently available models of advanced combustion biomass cook-stoves (ACS) report significantly higher efficiencies and lower emissions in the laboratory when compared to traditional cook-stoves, but relatively little is known about household level exposure reductions, achieved under routine conditions of use. We report results from initial field assessments of six commercial ACS models from the states of Tamil Nadu and Uttar Pradesh in India. We monitored 72 households (divided into six arms to each receive an ACS model) for 24-h kitchen area concentrations of PM2.5 and CO before and (1–6 months) after installation of the new stove together with detailed information on fixed and time-varying household characteristics. Detailed surveys collected information on user perceptions regarding acceptability for routine use. While the median percent reductions in 24-h PM2.5 and CO concentrations ranged from 2 to 71% and 10–66%, respectively, concentrations consistently exceeded WHO air quality guideline values across all models raising questions regarding the health relevance of such reductions. Most models were perceived to be sub-optimally designed for routine use often resulting in inappropriate and inadequate levels of use. Household concentration reductions also run the risk of being compromised by high ambient backgrounds from community level solid–fuel use and contributions from surrounding fossil fuel sources. Results indicate that achieving health relevant exposure reductions in solid–fuel using households will require integration of emissions reductions with ease of use and adoption at community scale, in cook-stove technologies. Imminent efforts are also needed to accelerate the progress towards cleaner fuels.

Keywords: household air pollution, advanced combustion biomass-cookstoves, exposure monitoring, $PM_{2.5}$ concentrations, CO concentrations, India

Correspondence to: Kalpana Balakrishnan, e-mail: kalpanasrmc@ehe.org.in

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Introduction and Purpose

Globally, around 2.8 billion people continue to rely on solid fuels for cooking and other household energy needs (Bonjour et al. 2013; Smith et al. 2012). As per the Indian National Census 2011, around 780 million people are estimated to use solid cooking fuels, nearly 99% of which is biomass. In the Global Burden of Disease 2010 assessment, around 1.04 million premature deaths and 31.4 million disability adjusted life years were attributed to household air pollution resulting from solid cooking fuels in India (Lim et al. 2012; Smith et al. 2014), accounting for ~6% of the national burden of disease. National exposure models developed for solid fuel using households estimate daily average $PM_{2.5}$ (particulate matter less than 2.5 µm in aerodynamic diameter) exposures of 337, 204, and 285 µg/m^3 for women, men, and children, respectively (Balakrishnan et al. 2013), greatly in excess of the current WHO air quality guideline (WHO-AQG) values (WHO 2006). Together, the exposure and disease burden estimates provide a compelling argument to intensify the momentum on intervention efforts for reducing household air pollution levels.

Previous efforts concerning household energy in India were focused on distribution of "improved" biomass cook-stoves under the National Program for Improved Chulhas (stoves). Implemented between 1985 and 2002, the program was primarily directed at increasing fuel efficiency to reduce fuel wood consumption. Most stoves were produced at the village level by artisans from the community, with limited standardization and/or laboratory pre-testing. Although more than 35 million such stoves were distributed, lack of systematic monitoring and evaluation resulted in low user adoption rates (Kishore and Ramana 2002) and the program was eventually discontinued in 2002.

More recently, with an improved understanding of the full range of health and environmental benefits associated with cleaner combustion and the launch of the newer National Biomass Cook-stove Initiative (NBCI) of the Ministry of New and Renewable Energy (MNRE), Govt. of India (MNRE 2009), a newer generation of "advanced combustion" biomass cook-stoves has become available (Venkataraman et al. 2010). Unlike the earlier "Chulha" models, the newer stoves are designed to achieve more stringent standards of emissions. These have also been primarily 'market based' in the sense that they are centrally produced, sold commercially, and based on technical and market research concerning safety, durability, and consumer support (World Bank 2011). Results from laboratory emissions testing for the newer advanced combustion cook-stove models have been reported (Bhattacharya et al. 2002a, b; Jetter et al. 2012; Mukunda et al. 2011) along with more recent studies beginning to provide an understanding of the determinants of community level uptake and adoption (Bhojvaid et al. 2014; Lewis and Pattanayak 2012; Rehfuess et al. 2014). Some models are also certified to meet the newly developed cook-stove emission standards by Bureau of Indian Standards (BIS 2013).

The progress on addressing consumer preferences, reducing fuel consumption/emissions through improvements in thermal/combustion efficiency and increasing durability in cook-stove technologies in India, has, however, not been matched by exposure assessment efforts within communities. A limited number of field measurements performed on (the earlier) "improved" cook-stove models across a few states in India have shown 30–65% reductions in area concentrations of $PM_{2.5}$ and carbon monoxide (CO) when compared with a baseline values recorded while using traditional stoves (Chengappa et al. 2007; Dutta et al. 2007; Smith et al. 2007). But these levels have consistently exceeded WHO-AQG levels and relatively little has been known about the exposure concentrations associated with the use of newer advanced combustion biomass cook-stove (ACS) technologies.

Based on this rationale, we report results from initial field assessments of six commercially available ACS models in village households from two states (Tamil Nadu and Uttar Pradesh) in India, to provide an insight into household concentration reduction potentials for these models under routine conditions of use. We also provide an analysis of user behavior and perceptions to assess implications for sustained use and achieving health relevant exposure reductions with these models.

This assessment was conducted under support from the Atmospheric Brown Cloud project of the United Nations Environment Program as part of a larger interdisciplinary study, Project Surya (www.projectsurya.org) that is examining climate and health implications of emissions from cleaner cook-stove technologies in India (Kar et al. 2012; Ramanathan and Balakrishnan 2007; Ramanathan et al. 2011; Rehman et al. 2011).

Methods

Study Location

The study was conducted in seven villages selected from three districts within the states of Tamil Nadu (TN) and Uttar Pradesh (UP) between May 2010 and December 2011. In TN, separate villages were selected to receive one of the six advanced combustion cook-stove models to minimize any discord between households receiving different types of stoves. In UP, logistic and time constraints precluded selection of six villages and hence three habitations (clusters of households) from the same village were selected to receive the six models.

Selection Criteria for the Advanced Cook-Stove Models

Only models that (a) were commercially available in India at the time of study (b) were produced by manufacturers with established consumer support services and (c) provided information in support of prior emissions and safety testing were considered. The criteria were chosen to optimize the potential applicability of study results in follow-up comparisons using objective indicators. Six portable single-burner ACS models met the above criteria for inclusion (Fig. 1). The technologies used in these models are similar to what has been described previously (Kar et al. 2012) and included three models of natural draft-rocket stoves (Envirofit-B1200, Envirofit-G3300 and Prakti-Leo), a natural draft-micro-gasifier stove (Phillips-Natural Draft) and two models of forced draft- micro-gasifier stoves (Phillips-HD4012-Forced Draft and Oorja).

Study Design and Sample Size

We designed the study as a paired before-after comparison for detecting a desired level of improvement (i.e., percent reduction between groups) as described in Edwards et al. 2007. Based on results from previous studies involving kitchen area $PM_{2.5}$ measurements in the same states (Balakrishnan et al. 2013), we estimated needing reductions in the range of 50–70% from levels measured while using traditional cook-stoves to begin approaching the 24-h WHO-Interim Target Guideline-1(WHO-ITG-1) values of 75 $\mu g/m^3$ for $PM_{2.5}$. A much larger sample size and higher field costs would have been required to detect smaller than a 50–70% reduction from a high baseline. Such reductions resulting in levels well in excess of WHO-ITG-1 levels are unlikely to be health relevant and hence could not be justified. Pilot measurements of kitchen area $PM_{2.5}$ concentrations with 4 other commercial models of advanced biomass-cook-stoves using similar technologies provided the initial basis for the expected differences between mean concentrations and the paired coefficient of variation (ranging from 0.7 to 0.9) for sample size calculations. Accordingly, we arrived at a sample size for each stove model as follows: $N = COV^2\ (1.96 + .84)^2/(\%\ \text{reduction})^2$ [Using a 2-tail test for 80% power and $P = 0.05$ where $COV = SD(ACS - TCS)/mean(TCS)$; ACS = advanced combustion cook-stove; TCS = traditional cook-stove; SD = standard deviation and COV = coefficient of variation].

The calculation resulted in a uniform sample size of 12–15 households per stove type. Although the sample size calculations were based on $PM_{2.5}$ reductions, we included measurements of carbon monoxide (CO) as an additional indicator pollutant to evaluate performance of the stove models as well as assess the extent to which the reductions in $PM_{2.5}$ and CO happened in parallel.

Household Selection and Stove Distribution

An initial visit was made to all of the selected villages to demonstrate the performance and operating procedures of the selected ACS models and to identify households willing to participate in the study. Only households using traditional cook-stoves in indoor/enclosed kitchens were considered eligible to reduce variability in measured concentrations from alternative cooking locations across households. A written informed consent was secured from the primary cook in participating households.

Phase I of the study involved performing baseline measurements while using traditional cook-stoves, following which households received the respective ACS models in the retail packaging. The households were then given 2–4 weeks to get used to the new stove before the field team returned to perform the post-ACS installation measurements (in Phase II). Measurements were performed within a 4 week period to minimize contributions from seasonal changes impacting background ambient concentrations as well as other household level variables likely to change over time. In Phase III, executed approximately 5–6 months after the provision of the ACS model, the team visited all households primarily to assess user perceptions. Measurements were also made 10% of households in this phase to

Figure 1. Advanced combustion biomass cook-stoves used in the study.

assess potential contributions from changes in other household variables, but were not included in the before–after comparisons.

Air Pollution Monitoring Methods

We measured 24 ± 2 h kitchen area concentrations of $PM_{2.5}$ and CO. Instruments were placed in the kitchen (1) approximately 100 cm from the stove (2) at a height of 145 cm above the floor and (3) at least 150 cm away (horizontally) from doors and windows, where possible. Placement of samplers was consistent across measurements within and between households (and during measurements performed with traditional or advanced combustion cookstoves).

Gravimetric $PM_{2.5}$ samples were collected using a BGI triplex cyclone (scc1.062, Waltham, MA) in portable constant-flow SKC pumps, equipped with a 37-mm diameter Teflon filter (Model 224-PCAR; filter pore size 0.45 μm; SKC, Inc., Eighty Four, PA, USA) at a flow rate of approximately 1.5 l/min. All pumps were calibrated prior to and after each sampling period using a field soap bubble meter or a rotameter (Envirotech Private Limited, India) and programmed to cover a 22–26 h sample period. Filters were weighed using either a Mettler Toledo-MT5 balance (Mettler, Greisensee, Switzerland) or a Thermo Cahn

C—34 Microbalance (Thermo Scientific, Waltham, MA, USA). All filters were conditioned in a temperature and relative humidity controlled environment before weighing. Twenty percent of the gravimetric samples were paired with field blanks (n = 14); none of the pre- and post- field blank weights differed by greater than 0.003 mg.

$PM_{2.5}$ concentrations were also assessed continuously for 24-h using the UCB Particle Monitor (Berkeley Air Monitoring Group; Berkeley, CA, USA), set to log concentrations at one minute intervals. UCB measurements were performed primarily to allow estimation of the ratio of cooking period versus non-cooking period concentrations, as well as provide additional information on cooking duration and number of meals (to corroborate questionnaire reported information on the same variables). CO concentrations were assessed continuously using the portable, battery-operated, data-logging Drager Pac 7000 (SKC, Inc; Eighty Four, PA, USA) set also to log at 1 min intervals.

Household Questionnaires

Information on general household characteristics and time varying household variables (such fuel quantity and composition, fuel consumption, cooking duration, number of person-meals, location of stove, time spent near the stove) was collected through questionnaires at baseline and the post-ACS installation phases. Finally, a user perception survey was administered to assess user acceptability and user behavior requirements for sustained use of the individual models.

Data Analysis

All data analysis was performed using "R" (Version 3.02). Since the distribution was skewed, concentration variables were log-transformed for analysis.

Results

Household Characteristics

General features of study households are summarized in Table 1. The households participating in the study, however, could not be drawn uniformly across the two states with nearly 2/3rd households in each arm being drawn from TN (not shown). As a result, while fixed household attributes such as location of kitchen and type of household construction were similar across the six sets of households that each received a particular brand of stove, they could not be fully matched against each other in terms of many other baseline features. Important among such features was the actual configuration of the kitchen. While only enclosed

Table 1. General Characteristics of Study Households (n = 71)

Category	Number (%)
Fuel type	
Wood	39 (54.7)
Woody stems	11 (15.3)
Dung cakes	11 (16.0)
Other (primarily coconut leaves, coconut shells)	10 (14.0)
Kitchen type	
Indoor with partition	31 (43.1)
Indoor without partition	26 (37.5)
Separate	14 (19.4)
Roof material	
Concrete	4 (6)
Thatched (leaves/straw)	49 (68.6)
Asbestos	3 (3.9)
Straw hut	12 (17.6)
Others	3 (3.9)
Wall material	
Brick/cement/clay	57 (80.3)
Mud	8 (11.7)
Others	6 (8)
Floor material	
Cement	29 (40.3)
Mud	31 (43.3)
Clay/dung/others	11 (16.4)
Fan in kitchen	
Yes	22 (30.6)
No	49 (69.4)
Additional stove	
Yes	13 (17.7)
No	58 (82.3)
Kerosene lamp use	
Yes	26 (36.2)
No	45 (63.8)
Beedi or cigarette use	
Yes	26 (36.2)
No	45 (63.8)
Incense use	
Yes	5 (7)
No	66 (93)
Mosquito coil use	
Yes	9 (12.3)
No	62 (87.7)

kitchens were selected, some were connected to the rest of the living area while others were either partitioned or separated from the rest of the living area affecting the room volume, level of ventilation and likely concentrations. Several attributes such as fuel composition, location of the stove, and number of person meals were found to vary not only across households in different stove groups but also between baseline and post-ACS installation phases (Table 2). This affected the distribution of measured concentrations with some stove groups showing a lot more heterogeneity as compared to others and reduced the power to make comparisons as described later.

Comparison of 24-h Kitchen Area Concentrations of $PM_{2.5}$ and CO Between Traditional Cook-Stoves and Advanced Combustion Biomass Cook-Stoves

Valid measurements across baseline and post-ACS installation phases were obtained in 71 of the 72 households consenting to participate in the study. The distribution of 24-h kitchen area (gravimetric) $PM_{2.5}$ and CO concentrations measured during the baseline and post-ACS stove installation phases across the six stove types are shown in Figs. 2 and 3. Percent reductions in mean and median concentrations obtained with each of the ACS models are provided in Table 3.

The mean 24-h $PM_{2.5}$ and CO concentrations recorded while using traditional cook stoves ranged from 173 to 1436 $\mu g/m^3$ and 3.6–29 ppm, respectively. The mean concentrations of 24-h $PM_{2.5}$ and CO recorded in the post-ACS installation phase were consistently lower than baseline values across all models and ranged from 153 to 750 $\mu g/m^3$ and 2.7–9.6 ppm, respectively. While the percent reductions in mean concentration ranged from 8.5 to 62.5% for 24-h $PM_{2.5}$ and 3–78% for CO, the median percent reductions ranged from 2 to 71% for 24-h $PM_{2.5}$ and 10–66% for CO (with one of the natural draft models actually showing a negative percent reduction in mean). However, only the reduction produced by the Phillips-HD 4012 Forced Draft stove was found to be statistically significant (62.7% for $PM_{2.5}$ and 78% for CO), respectively. The reductions obtained with the natural draft models were highly variable (8.5–62% for $PM_{2.5}$ and 31–67% for CO) and were not found to be significant. The Oorja-forced draft stove produced the smallest reductions for $PM_{2.5}$ ($\sim$20%) and CO ($\sim$3%). The concentrations measured across all ACS stove models consistently exceeded the highest of the recommended WHO-AQGs, i.e., WHO interim target-1 (ITG-1) values of 35 and 75 $\mu g/m^3$, respectively for annual mean and 24-h concentrations for $PM_{2.5}$ and frequently exceeded the 24-h guideline value for CO of 6 ppm.

Comparison of Real-Time Concentrations of $PM_{2.5}$ and CO During Cooking and Non-cooking Periods with Traditional and Advanced Combustion Biomass Cook-Stoves

The average 24 h household concentrations from a complex interplay of factors such as number of meals cooked, cooking duration, type of meal, type of fuel, ventilation parameters, and contributions from ambient concentrations. While every attempt was made to minimize the contributions from these variations between phases, given the small sample size feasible, it is quite likely that one or more of these factors in addition to the type of stove was responsible for the differences in observed levels between the baseline and post-ACS installation measurements in the same household. The real-time measurements allowed an understanding of at least some of these factors and the potential for contributions to variations in the measured levels.

Some common features that could be discerned from the real-time monitoring are listed below

1. Most households cooked at nearly the same time and for nearly the same duration across phases except while cooking with forced draft models that often required substantially shorter cooking durations (Table 2).
2. While the $PM_{2.5}$ and CO concentrations during non-cooking periods were distinctly lower than cooking periods across phases, they varied considerably between the baseline and post-ACS installation readings for some stove types. This indicates significant potential for contributions from background ambient concentrations and/or other household sources to the 24-h concentrations within and across stove arms. The observed percent reductions across stove models could thus have been impacted variably by non-stove-related contributions.
3. Most households cooked two meals in both phases. It was, however, not uncommon to have households cook an extra meal in one of the phases, resulting in differential contributions to 24-h versus per meal reductions.
4. Levels of reductions in $PM_{2.5}$ were not always accompanied by similar reductions in CO across models. Reductions in PM or CO concentrations were also not always consistent across cooking events (meals) in a household.

Table 2. Distribution of 24-h Average Kitchen $PM_{2.5}$ and CO Concentrations from Paired Measurements Performed in Households While Using Traditional Cook Stove (TCS) and Advanced Combustion Cook Stove (ACS), Respectively

Advanced combustion cook-stove model	*n*	Median		Interquartile range		Mean (95% confidence interval)		Percent reductions in mean	Percent reductions in median	*P* value (Man Whitney)
		TCS	ACS	TCS	ACS	TCS	ACS			
24-h $PM_{2.5}$ concentrations($\mu g/m^3$) in the kitchen area										
Envirofit B1200-Natural Draft (Rocket Stove)	12	429	165	635	419	501 (280–723)	345 (108–583)	31.12	61.54	0.219
Envirofit G3300-Natural Draft (rocket stove)	12	442	353	329	242	686 (255–1117)	481 (293–669)	29.87	20.16	0.59
Prakti Leo-Natural Draft (rocket stove)	12	135	123	187	194	173 (83–262)	153 (85–221)	11.52	8.55	0.713
Philips-Natural Draft (micro gasifier)	12	227	109	609	339	585 (68–1102)	279 (60–498)	52.28	51.98	0.487
Philips-Forced Draft (micro gasifier)	12	266	99	826	162	1436 (0–3255)	750 (0–2049)	47.77	62.78	0.069
Oorja Forced Draft (micro gasifier) using Pellets	11	149	120	117	290	292 (20–564)	207 (77–336)	29.34	19.8	0.669
Natural Draft (combined)	48	285	212	508	306	486 (318–654)	315 (225–406)	35.15	25.55	0.137
24-h CO concentrations (ppm) in the kitchen area										
Envirofit B1200-Natural Draft (rocket stove)	12	10.52	3.43	12.17	12.06	9.6 (5.1–14)	6.4 (2.3–10.6)	32.71	67.39	0.219
Envirofit G3300-Natural Draft (rocket stove)	11	9.84	6.77	7.26	4.36	10.2 (4.6–15.9)	7.5 (5.2–9.8)	26.92	31.14	0.566
Prakti Leo-Natural Draft (rocket stove)	11	5.80	3.36	9.25	6.55	11.6 (1–22.1)	4.7 (1.4–8)	59.03	42.13	0.401
Philips-Natural Draft (micro gasifier)	12	3.22	3.67	5.29	3.43	3.6 (1.9–5.4)	3.2 (1.8–4.7)	11.25	−13.84	0.843
Philips-Forced Draft (micro gasifier)	11	6.12	1.32	9.41	3.84	29 (0–75.8)	9.6 (0–25.3)	66.83	78.46	0.076
Oorja forced draft (micro gasifier) using pellets	11	2.25	2.19	2.99	2.31	4.3 (0.7–8)	2.7 (1–4.4)	37.4	2.82	0.898
Natural draft (combined)	46	5.88	4.28	8.84	6.79	8.7 (5.8–11.5)	5.5 (4.1–6.9)	36.61	0.132 27.26	

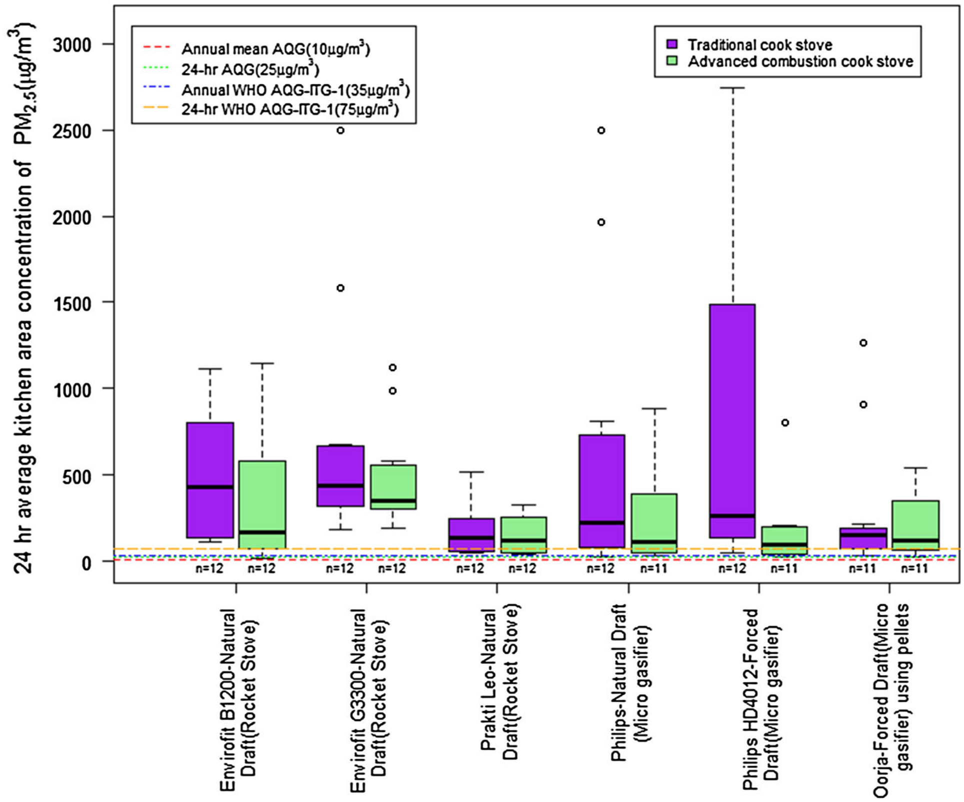

Figure 2. Distribution of paired before-after 24 h kitchen area $PM_{2.5}$ concentrations across the six advanced combustion biomass cook-stove models.

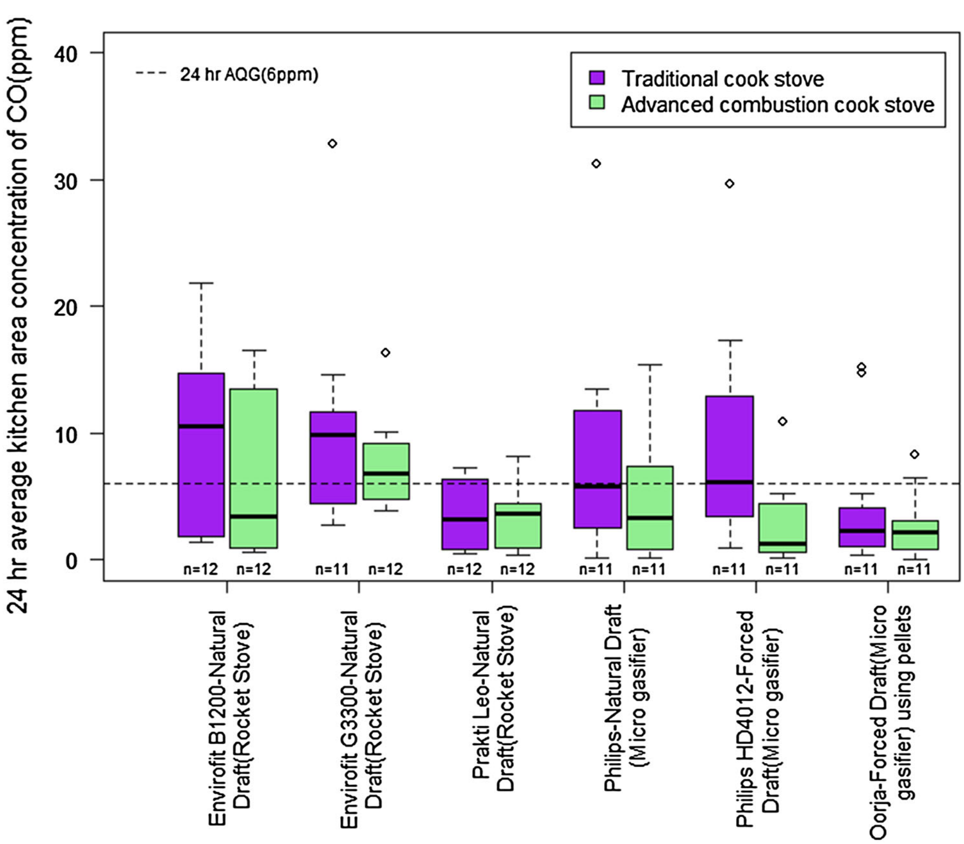

Figure 3. Distribution of paired before-after 24 h kitchen area CO concentrations across the six advanced combustion biomass cook-stove models.

Table 3. Description of Exposure Relevant Variables Recorded in the Household (Post-monitoring) Questionnaire

ACS model	*n*		Fuel quantity (kg/day)		Total cooking hours/day self-reported (UCB recorded)		Number of person meals/day		% Households reporting change in fuel mix between phases (types of change in fuel mix)	% Households reporting change in type of meal between Phases	Relative time spent near stove between TCS and ACS	Change in stove location between phases
	TCS	ACS	TCS	ACS	TCS	ACS	TCS	ACS				
Envirofit B1200-Natural Draft (Rocket Stove)	12	12	3.88	2.59	3.3 (3.9)	2.8 (4.2)	10	8	33 wood + cow dung to wood; wood to wood + agricultural residues	25	Same	No change
Envirofit G3300-Natural Draft (Rocket Stove)	12	12	3.89	3.82	3.5 (4.9)	4.1 (5.5)	13	14	33 wood + cow dung to wood; wood to wood + cow dung	42	Same	No Change
Prakti Leo-Natural Draft (Rocket Stove)	12	12	4.14	3.4	2.8 (3.6)	3.4 (4.2)	10	10	43 wood + cow dung to wood; Wood + Agri. Residue to Wood; Wood + Agri. Residue + Cow Dung to Wood	95	Same	No Change
Philips-Natural Draft (Micro gasifier)	12	11	4.96	3.04	3.0 (4.8)	3.3 (4.1)	10	13	33 wood + cow dung to wood; wood + agri.residue to wood; wood + agri.residue + cow dung to wood	33	More time spent near ACS stove to chop and load fuel	ACS stove occasionally moved outside
Philips-Forced Draft (Micro gasifier)	12	11	6.10	2.56	4.2 (4.9)	3.4 (4.1)	12	8	25 wood + cow dung to wood bits + cow dung	58	More time near ACS stove to chop and load fuel	ACS stove occasionally moved it outside
Oorja Forced Draft (Micro gasifier) using Pellets	11	11	2.71	1.94	3.3 (4.2)	3.6 (3.7)	12	9	26 wood + agri. residues + cow dung to wood + agri. residues + pellets	74	More time near ACS stove to load fuel	ACS stove frequently moved outside

Findings from Household Questionnaires

Table 3 summarizes finding from questionnaires administered during the baseline and post-ACs installation phases. Households reported significantly reduced (30–40% less) fuel consumption with the use of ACS models with the household using the Phillips (Forced Draft) stove reporting the highest reductions. However, while households self-reported somewhat shorter cooking durations, this was not borne out by the real-time records obtained from UCB monitors. Differences in fuel composition recorded, included changes proportions of wood, dung or agricultural residues in the free convection models; shifting from wood to woody stems and scrub vegetation for the Phillips (Forced Draft) stove that requires chopped pieces and pellets for the Oorja stove. With both the forced draft stoves, it was not uncommon for households to switch to fuels not recommended by the manufacturer such as dung in the Phillips (Forced Draft) stove and non-pelletized fuels in the Oorja stove.

The nature of stove tending required with the models also changed the time spent near the stove. While the rocket stoves allowed charging the stove with the required quantity of fuel for a full meal, the Phillips and Oorja stoves required re-charging within a single meal period. This necessitated spending longer durations within the kitchen and often close to the stove (an activity that could have significant bearing on women's exposures). Finally, while the rocket stoves were found to be relatively fixed in the location (usually found placed adjacent to the traditional stove location), the micro-gasifier stoves were often moved outside. Being relatively lighter in weight may have resulted in the stove being more portable.

Findings from the User Perception Assessments

The user perceptions elicited in this study were primarily aimed at recognizing features of individual stove models that would have a bearing on regular use and consequent exposures. Although these perceptions could be indirectly reflective of stove adoption rates, these assessments were not designed to inform requirements for community level uptake and/or sustainability. The user perceptions were supplemented with observations made by the field staff during their follow-up visits to the households. Both findings are described in Table 4.

Discussion

Both natural draft and forced draft ACS models produced reductions in 24-h kitchen area concentrations of $PM_{2.5}$ and CO when compared with traditional cook-stoves, with only the Phillips-Forced Draft (HD4012) model achieving (statistically) significant reductions. There was, however, considerable heterogeneity in the reductions obtained across models under conditions of actual use. We explore reasons for the observed variability and elaborate upon the likely health relevance of reduction achieved by the ACS models used in the study. We also describe limitations of the approaches used and consequent implications for comparability/applicability of the methods in other studies concerned with cook-stove evaluations.

Variability in Household Concentrations Across and Within Stove Groups—Role of Household Level Determinants and Ambient Concentrations

The baseline values across stove groups varied considerably both on account of the stoves being distributed to six different sets of households and unequal representation from the two states. Values recorded in households selected to receive the Phillips-Forced Draft (HD4012) stove were for, e.g., much higher than households selected to receive other models. The distribution of several household level determinants of area concentrations has been shown to heterogeneous across states (Balakrishnan et al. 2013) with levels in UP reported to be 1.5- to 3-fold much higher than TN. This set of households had the highest proportion of UP households, feature that may have been responsible for the higher baseline.

Further, use of different combinations of biomass, changes in location of the stove, type and number of meals cooked, and use of multiple stoves changed the conditions between baseline and post-ACS installation phases variably across the six sets of households. Although the paired before-after design would have allowed a comparison of the percent reductions achieved across models, this could not be reliably made on account of multiple factors contributing to variability across and within arms. However, it provided important insights into what may be determinants of significant exposure variability under actual field conditions and the implications of such variability for long-term exposure.

It is also important to recognize the potential contributions from background outdoor concentrations to indoor concentrations in solid fuel using communities. Continuous $PM_{2.5}$ (UCB monitor) records indicate that concentrations during the non-cooking period range from 45 to 105 $\mu g/m^3$ in Tamil Nadu and 85–207 $\mu g/m^3$ in Uttar

Table 4. Summary of User Perception and Field Observations on Stove Use and Acceptability

Location	Type of Stove provided	User perceptions	Observations by field staff
Gudapakkam, Thirupachur, Nandambakkam, Puduvallur, Koppur, Poothandalam (Tamil Nadu) Puredigarz, Nayapuroah, Purvezpurr, (Uttar Pradesh)	Traditional stove (available and not provided)	Flexibility to use any combination of fuels, little or no fuel processing requirements, ability to cook large and varied combinations of meals, little or no costs incurred in procuring fuel and relative durability (often over years) were cited as favorable features of traditional stoves	Using the traditional stove was a customary part of the household routine and posed no specific challenges to women. Some households reported being aware of ACS models but had no direct experience of use. All women were familiar with LPG and kerosene stoves. Several households within the same communities used LPG as the primary cooking fuel (especially in Tamil Nadu)
Gudapakkam, (Tamil Nadu) Puredigarz, Nayapuroah, Purvezpurr, (Uttar Pradesh)	Envirofit B1200-natural draft (rocket stove)	Women reported being comfortable with the stove. Reduction in fuel consumption and ease of use cited as favorable features. Cracking of the refractory chamber was the most common complaint registered (usually resulting from women pushing the fuel too far ahead or from stuffing the chamber)	High levels of cooperation from participating households and during village level interactions. Fuel mixtures were quite variable and included thick wood, fencing bush, dung cakes and agricultural wastes. Stoves found operational for 6 months after distribution with some support by field team. Good service backup was available from manufacturer especially in Tamilnadu. Two stoves requiring replacement were promptly attended by manufacturer
Thirupachur, (Tamil Nadu) Puredigarz, Nayapuroah, Purvezpurr, (Uttar Pradesh)	Free Convection Envirofit G3300-Natural Draft (rocket stove)	Women reported being comfortable with the stove. Many however expressed the need for an additional pot. Reduction in fuel consumption and the ability to use any combination of biomass available cited as the major reason for wanting to use the stove	Good level of cooperation at household and village level. Same fuel mixtures found being used as in Gudapakkam. Stove found operational for 6 months after distribution with limited support by field team. Since both model 1 and 2 were supplied by the same manufacturer, the service levels were comparable
Nandambakkam, (Tamil Nadu) Puredigarz, Nayapuroah, Purvezpur, (Uttar Pradesh)	Prakti Leo-Natural Draft (rocket stove)	Comparable in acceptance and similar user perceptions as reported for the Envirofit Models. Users reported slow but less smoky cooking. The increased cooking time was perceived to be an important disadvantage despite the reduction in fuel consumption. Several users also reported difficulty with cleaning leftover ash	Good level of cooperation at household and village level. The manufacturer was rather supportive and very interested in hearing about user perception. Not much in terms of maintenance was required but manufacturer was actively in touch with the field team and willing to assist users if required. Lack of a double pot model, together with somewhat slower cooking made it unsuitable for larger families

Table 4. continued

Location	Type of Stove provided	User perceptions	Observations by field staff
Puduvallur, (Tamil Nadu) Puredigarz, Nayapuroah, Purvezpurr, (Uttar Pradesh)	Philips-Natural Draft (micro gasifier)	Women were not happy with the stove. Felt the ACS to be considerably more smoky, resulting in more intense blackening of vessels which in turn necessitated a bigger effort for cleaning. Most households used it only during the monitoring period with limited enthusiasm to use it regularly	Poor level of cooperation at the household and village level. No stoves were found operational 6 months after distribution. Poor level of service support was available from the manufactures for accompanying maintenance issues. This model unlike the rocket stoves required fuel chopping and tending during cooking resulting in the same movement constraint as reported for forced draft stoves
Koppur, (Tamil Nadu) Puredigarz, Nayapuroah, Purvezpurr, (Uttar Pradesh)	Philips-Forced Draft (micro gasifier)	Women expressed immense enthusiasm for the look of the stove initially. In UP where all models were used in same habitation, most women preferred to receive this model on account of the exterior looks. Upon use however, they found fuel chopping and feeding to be a major nuisance. Although cooking duration was significantly shorter, and all users reported little or no smoke, continuous feeding made it difficult for them to move away during cooking. This movement constraint increased their total time in close proximity to the stove and reduced the time available to do other household chores. Many users complained about the lack of stability while placing large vessels and fragility of the plastic under casing (provided for base support)	Repeated electrical and electronic faults with the stoves especially with the rechargeable battery. No support provided by the manufacturer to maintain the stoves. Software access for downloading the stove use data was not provided by the manufacturer despite multiple requests. Women often did not find the time to process fuel ahead of when they start cooking and without such preparation, many are not able to cook with the ICS. Postural discomfort while operating the ICS, noticed for many women, who could neither sit nor stand comfortably during the cooking period. Despite all these glitches nearly all households were found using them in Phase 3 although only irregularly so

Table 4. continued

Location	Type of Stove provided	User perceptions	Observations by field staff
Poothandalam (Tamil Nadu) Puredigarz, Nayapuroah, Purvezpur', (Uttar Pradesh)	Oorja Forced Draft (micro gasifier) using Pellets	Nearly all women were dissatisfied with the pellet requirement in terms of having to purchase it and pack it before cooking. Not being able to use other types of commonly available unprocessed biomass was perceived to be most important disadvantage	Very low level of cooperation at the household and village levels. Use of unprocessed fuel although not endorsed by manufacturer was very common. Nearly all households added other unprocessed fuels to supplement pellets making the fuel visibly more smoky. Stoves were not found being used in Phase 3. Manufacturer was willing to supply pellets but the burn time afforded by packing it once was not sufficient for the average cooking time needed by families. Feeding in between was both inefficient and inconvenient
Gudapakkam, Thirupachur, Nandambakkam, Puduvallur, Koppur, Poothandalam (Tamil Nadu) Puredigarz, Nayapuroah, Purvezpurr, (Uttar Pradesh)	LPG (Not provided but perceptions recorded)	Universally perceived by households as the desirable stove "if only, it could be paid for". All households reported cost and not access as the central issue that precluded LPG use	Several households in every village used LPG as the primary but not exclusive fuel. A traditional stove was available indoors or in many cases outdoors as a backup for the periods an LPG cylinder refill could not be procured by the family. Many villages in Tamil Nadu were covered under the Government LPG stove distribution schemes but were not observed using LPG routinely

Pradesh. Although, we did not have ambient air quality data in this study, previous studies in the same area have shown indoor concentrations to relax to outdoor concentrations within a few hours after cooking (Rehman et al. 2011) as well as differential contributions from other sources through medium-range transport to outdoor concentrations (Praveen et al. 2012; Ramanathan and Balakrishnan 2007). In densely populated habitations, the ambient background may thus contribute significantly to household concentrations, diminishing reductions achieved through the use of the advanced combustion cook-stoves. Indeed, in such communities household concentrations may exceed AQG levels even with use of clean fuels such as LPG (Balakrishnan et al. 2014).

Implications of User Acceptability for Long-Term Exposure Reductions

Traditional biomass cook-stoves were perceived in this study to be the easiest to use (Table 4). Any stove that makes routine use more complicated or cumbersome is thus not likely to be used on a sustained basis. The natural draft (rocket stove) models merited favorable user perceptions for ease of use, but the concentration reductions recorded in the field were at best modest. The forced draft models used in the study have been reported previously to perform exceedingly well in the laboratory (Jetter et al. 2012; Mukunda et al. 2011) with some of the highest emission reductions and considerably enhanced efficiency when compared to traditional cook-stoves but their reported ease of use was among the lowest. While electricity availability and fuel processing posed a challenge for the Phillips stoves, lack of supply of pellets posed the biggest challenge for the Oorja stove. Several households using Oorja, reported adding wood or other fuels to the chamber designed to burn only pellets (see Table 3), making it difficult assess potential concentration reductions for this model under conditions of appropriate use. With all models tested currently being available only in a single-pot configuration, the need for an additional stove was often reported and also resulted in simultaneous traditional stove use to fulfill specific meal requirements. The current configurations of these stove models, therefore, appear to be poorly suited for sustained use by households. Although reductions in emissions are a pre-requisite for achieving reductions in exposures, without appropriate levels of user acceptance, any gains made in the laboratory may thus run the risk of being lost under actual field-use conditions. Interestingly, all households responded affirmatively to LPG stoves being the single best solution if only "it could be paid for".

Health Relevance of Observed Reductions in $PM_{2.5}$ Concentrations

The study was designed to assess if the levels of reduction achieved by the advanced combustion cook-stoves would likely result in 24-h exposure concentrations of $PM_{2.5}$ comparable to 24-h WHO-ITG-1 values for $PM_{2.5}$ of 75 µg/m^3 as limited exposure–response information was available at the time of the design of the study. Recent progress in the development of Integrated Exposure Response Curves (Burnett et al. 2014) over a continuous range of $PM_{2.5}$ concentrations in relation to ambient air pollution, household air pollution, passive and active smoking have allowed comparisons of excess risks for a range of health endpoints (including ischemic heart disease, stroke, COPD, lung cancer, acute lower respiratory infections). The exposure–response functions are strikingly non-linear at levels of $PM_{2.5}$ below an annual mean of 100 µg/m^3, with the most discernible risk reductions beginning to appear around the annual mean WHO-ITG-1 values of 35 µg/m^3.

Although, we could not monitor personal exposures to $PM_{2.5}$, previous studies have shown a high level of correlation between personal exposures and 24-h kitchen area concentrations for women in India (Balakrishnan et al. 2004). Despite the wide variability in the level of reductions accomplished across the ACS models, with the mean 24-h kitchen area concentrations ranging from 150 to 750 µg/m^3 across models and limited evidence of sustained use, the results from this study indicate that the currently available ACS models may not accomplish health relevant exposure reductions under current conditions of field use and expected level of adoption within the community.

Limitations of Study Methods and Implications for Applicability in Other Settings

The study was designed at a time when field level information on the models chosen was quite sparse. Consequently, there were limitations imposed by the choice of study methods in extending the applicability of results to other settings. First, the phenomenon of stove stacking or using both the traditional and advanced combustion cook-stove was not apparent in questionnaire responses until results from half the measurements indicated continued high levels, prompting a more detailed interview with household members to understand underlying reasons. Single-pot configurations and requirements for fuel processing in the ACS models also compromised the ability to displace traditional stove use in these communities. Provision of multiple new stoves as per family requirement, provision of fuel processing facilities, better manufacturer support, and additional training to emphasize the need to discontinue the use of traditional stoves could each enhance the performance of the stoves in other settings.

Second, the paired before-after measurements without a control group compromises abilities to make comparisons of stove performance over time especially seasonal contributions. Although we tried to minimize seasonal influences by monitoring within a month of stove distribution, it would be very important to understand the relative contributions from ambient concentrations across seasons. Monitoring of stove use using the newly developed Maxim IC's iButton technology (Ruiz-Mercado et al. 2012) could also significantly improve understanding of long-term user behavior and consequent implications for exposure variability. Monitoring of ambient air quality, measures of stove use, and addition of control groups could thus add valuable information in cook-stove evaluations.

Finally, we could not perform personal monitoring in this study. Although personal monitoring may not be feasible in routine monitoring efforts, understanding the relationship between personal exposures and kitchen area concentrations is important for using available exposure–response functions. Routine assessments would benefit from personal exposure monitoring in a sub-sample.

Conclusions

The recently launched NBCI of the MNRE in India is focused on developing the next-generation cleaner biomass cook-stoves and has set itself the lofty aim of providing energy services comparable to clean sources such as LPG (Venkataraman et al. 2010). While MNRE has initiated several steps to progress toward such a goal including revising the standards for emissions efficiency (through the revised Bureau of Indian Standards), certifying select commercial models, and providing facilities for laboratory testing, limited information has been available thus far on benchmarking these stoves against health criteria. By choosing six most widely marketed ACS models in India that included the range of commonly deployed stove technologies, the pilot results have established the levels of exposure reductions likely to be achieved with these models. While the median percent reductions in 24-h $PM_{2.5}$ and CO concentrations ranged from 2 to 71% and 10–66%, respectively, concentrations consistently exceeded WHO-AQG values across all models raising questions regarding the health relevance of such reductions. Most models were also perceived to be sub-optimally designed for routine use often resulting in inappropriate and inadequate levels of use. Household concentration reductions also run the risk of being compromised by high ambient backgrounds from community level solid–fuel use. The results of the study have thus provided initial evidence that the performance of all models is complicated by insufficient levels of "improvement" (i.e., reduction in exposures), by mixed levels of sustained use (i.e., varying levels of user acceptability) and the stove "staying improved" (i.e., sustained field performance) to achieve desired levels of exposure and consequent health benefits. This remains the single biggest challenge for being able actually label the models tested as "improved" or "advanced" using available health benchmarking criteria.

MNRE has planned a series of monitoring and evaluation exercises for commercial cook-stove roll outs across multiple states in India. Results from this study provide a framework for the careful design and conduct of such studies. They also point to the need for further research to enhance the performance of the stoves to meet health relevant criteria before engaging in large scale implementation. Results from a large body of field based assessments will be critical in informing future revisions in cook-stove standards by NBCI.

Globally, a growing number of studies are reporting results from exposure assessments in relation to household air pollution and cook-stove evaluation efforts (Anenberg et al. 2013; Clark et al. 2013). These assessments can play strategic role in household air pollution research including cook-stove evaluation efforts and offer an expeditious modality to assess if potential health benefits are likely before investment of major resources for interventions. Such information is needed to supplement the more widely available laboratory level information on such technologies. Advocacy for positive user behavior changes can clearly not be made if technologies perform poorly on the count of emissions/exposure reductions or are ill-suited for user requirements.

Finally, although the study represents results from initial assessments of advanced biomass cook-stoves, the modest exposure reductions achieved with the ACS models indicate the need for alternative ways of exploring cleaner fuel choices. A recent assessment reports less than 1% of World Bank lending being devoted to addressing household energy issues between 2000 and 2008 (Barnes et al. 2010; World Bank 2011). Greater levels of advocacy are, therefore, needed to both raise the concern with current biomass cook-stove technologies and find feasible mechanisms for providing access to uniform clean energy solutions for all populations across global regions.

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