Development Of A Unified Approach (An Index) To Study The Particulate, Carbon Monoxide Emissions And The Combustion Efficiency Using Field And Laboratory Investigations

Vidhi Singhal

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DEVELOPMENT OF A UNIFIED APPROACH (AN INDEX) TO STUDY THE PARTICULATE, CARBON MONOXIDE EMISSIONS AND THE COMBUSTION EFFICIENCY USING FIELD AND LABORATORY INVESTIGATIONS
by
Vidhi Singhal

A thesis presented to the School of Engineering of Washington University in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

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ABSTRACT OF THE THESIS


Vidhi Singhal

Master of Science in Energy, Environment and Chemical Engineering

Washington University in St. Louis, 2010

Research Advisor: Professor Pratim Biswas

About one-third of the world’s population uses biomass and other renewable sources of fuel for cooking and other heating purposes. The Biomass is not burnt efficiently which results in the release of pollutants which are the products of incomplete combustion. Previously, studies have been done to study the PM$_{2.5}$, CO, methane and non methane compounds to study the dose exposure relationships of the cookstoves. One major drawback in these studies was that they didn’t use the surface area of the particles emitted from the cookstoves. As it has been established in the previous studies, the ultrafine particles have more surface area and therefore they interact with a large area of the human lungs. Therefore, surface area monitor was used to study the surface area of the particles emitted during combustion. Although it showed low PM$_{2.5}$ concentration, high surface area was observed in some instances. Kerosene stove which appears to be a clean fuel showed low PM$_{2.5}$ but high surface area which makes a potential risk factor for tuberculosis when compared to the
biomass cookstoves. These dose parameters were then combined to get a unique index with the respect to each cookstove under a specific condition. This could be easily used to compare the different cookstoves and also help in designing new improved cookstove. Experimental studies were conducted in detail to study the effect of the size of fuel, moisture content, air fuel ratio and the sampling site. It showed that certain conditions in the improved stoves can produce harmful emissions and therefore it is essential to study the pattern of usage of a particular community to study their cooking pattern and design a stove according to their needs.
Acknowledgments

I wish to take this opportunity to express my deep sense of gratitude to my supervisor, Prof. Pratim Biswas (Department of Energy, Environment and Chemical Engineering, Washington University in St Louis) for his untiring supervision, valuable suggestions and inspiring guidance, which enabled me bring this work into the present shape.

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No word can adequately express my indebtedness to my family without their support and motivation, I would not have reached at this stage of this academic distinction.

Vidhi Singhal

Washington University in St. Louis
August 2010
Dedicated to my professor,

I would like to dedicate this thesis to my professor, V. K. Jain who has been a source of inspiration all these years.
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Chapter 1

1. Introduction

1.1 Background

Biomass burning was one of the key factors which marked the beginning of the human civilization. It is an important renewable source of energy used for cooking, heating and other domestic purposes especially in the developing countries. More than 3 billion people across the world use biomass, agriculture residues, dung and coal to meet their basic energy needs [1]. The WHO estimates that 1.5 million people annually die of gaseous and particulate emissions from cookstoves. Use of a particular type of fuel by a household depends on their total income, its availability and accessibility, its competing uses, cost of commercial and less polluting fuels like kerosene and LPG (subsidized), and poor supply of the cleaner fuels especially in the rural areas. The inherent disadvantages of the traditional stoves include strenuous and time demanding fuel collection, difficult to control combustion rates and poor efficiency [2]. Time spent for fuel wood collection has increased dramatically especially in the mountainous region in India, leading to wood poaching from the reserved forests [3]. Kerosene price has increased considerably in the past few years and is not easily available in the remote areas. Animal dung which is often used by the villagers for cooking food not only emits
high quantities of PIC’s (Product of incomplete combustion) [4] but also deprives the agricultural lands of the inexpensive and environmental friendly manure.

Biofuel combustion is responsible for emission of the particulate matter which contributes as much as 20% of the total global emissions of organic and black carbon [5]. Previous studies have studied the emissions from the cookstoves and the efficiencies and the health effects have been the function of mass concentration of particulate matter (PM$_{2.5}$ and PM$_{10}$), Carbon monoxide (CO), Carbon dioxide (CO$_2$), Organic and Elemental carbon (OC/TC), methane and other non methane hydrocarbons [6-9] etc.

### 1.2 Health Effects

Surface area concentration of the particles which is an important parameter while studying the deposition of the particles in the lungs has not been studied yet. Human respiratory system has been divided in two major regions: Tracheobronchial region (upper respiratory system) and alveolar region (lower respiratory system). The alveolar region in the human respiratory system is most vulnerable to the small particles. The larger particles deposited in the tracheobronchial or upper region of the respiratory tract can be cleared by the layer of mucus, where it is subconsciously swallowed to the gastrointestinal tract. This mucociliary system clears the upper respiratory system within hours but due to the absence of mucus membrane, insoluble particles in the pulmonary region are cleared in months. The soluble particles pass through the thin alveolar membrane into the blood stream to be engulfed by the phagocytic cells [10].
Recently, Pokhrel et al (2010) [11] found that the emission of the particles from the cookstoves was responsible for the tuberculosis in a vast region in Nepal. Though, kerosene appears to burn more cleanly as compared to the biomass smoke which attracts all the attention, it was found that kerosene as a cooking fuel is a TB risk factor whereas biomass as fuel is not. This could be attributed to the emission of high number concentration of the ultrafine particles which reach the lower respiratory regions and therefore causes respiratory health problems. Other studies reported an increase in the risk of pneumonia by a factor of 1.8 when unprocessed fuels were used [12]. Biomass health effects may include an additional risk by a factor of 1.5 to 2, causing chronic obstructive pulmonary disease, acute lower respiratory disease, lung cancer and blindness due to cataract [13].

1.3 Improved Stoves

Over the years a number of improved stoves have been introduced across the developing regions. India’s national improved chulha program (NICP) was introduced in the year 1983 disseminating more than 28 million stoves through the year 1998. The major objectives of the program were to conserve the fuelwood especially in the rural areas, prevent deforestation, reduce health hazards caused due to smoke while cooking, improve living conditions, and increase employment in the rural areas. Inspite of high numbers of improved stoves that were distributed over the years, NICP was a failure. The World Bank reported that the program was not a success due to various reasons. Lower efficiencies as compared to the lab conditions, failure to identify the stove
market, poor advertisement of the health benefits associated with the improved stoves and also their high prices were a barrier towards the adoption of clean and healthier cooking practices across the country. Moreover the life span of these stoves was no more than two years which prohibited it from becoming a success in the long term[14].

“Oorja”, was introduced by BP Energy in the year 2006, in the states of Tamil Nadu and Maharashtra, India in the year 2006. (Fig 1) This stove which cost a little over $10 has a chamber for burning fuel wood. This chamber has a mini fan which is used to blow air over the fuel increasing the efficiency of the stove. It leaves clean utensils with little or no soot after cooking and no smoke. It also reduces the fuel costs by one third as compared to other cleaner sources of fuel like LPG.

Figure 1: Improved stoves introduced by (a) “Oorja” BP energy (b) Philips

Though, it claims to be a very clean and affordable source of energy, it cannot be used to cook various food items like ‘dosa’ and ‘chappati’ in these regions. The flame is very high and also can’t be stopped in the midway like LPG or kerosene. Also, the fuel needs to burn off completely and entire ash needs to be removed before refueling. Philips
introduced the stove (Fig 2) which uses an electric motor to force the air through the combustion chamber, adjusting the air fuel ratio which it claims to reduce the fuel use by 20% and pollution caused due to smoke by 90%.

1.4 Socio-Economic Factors and Indoor Air Pollution

Energy demand across the world has been on a rise since the industrial revolution. There was shortage of fuel across the world which was not limited to the fossil fuels but also the biomass reserves in the developing countries. Biomass can be used to produce steam which in turn can be used for power generation. High prices, seasonal characteristic, sporadic availability, low density and high ash content have made them a less popular choice over the fossil fuels.

There are various technological, economic, infrastructural, cultural and social aspects that affect the diffusion of improved wood burning cookstoves. Improved stoves introduced in certain regions have received mixed response from the users. The main disadvantages as observed by the users were limited or no space heating, limited number and size of the pots that can be used, and high maintenance. The main technological factors that have prevented the large scale diffusion of the stoves have been the failure to identify the main user, the local designer and the physical elements affecting the social factors. The laboratory designed models in the developed countries are ill-adapted in these regions. Moreover, the benefits of these cookstoves are non-monetary whereas the costs incurred during their purchase or maintenance is monetary in nature.
It is also important to understand the cultural factors which affect the diffusion of stoves in a community. It can be achieved by understanding the operating technique of the user and the factors which affect the behavior and encourages the user to accomplish a task in a certain way.

Indoor air pollution (IAP) is not only responsible for the poor health of the individuals but also is a potent factor responsible for affecting the economic well being of the household. Studies suggest that increase in the IAP brings down the productivity level and therefore one woman with poorest health is expected to cook which further deteriorates her health. It also affects the health of the children and their continuous absence from school which affects their studies and their overall development.

Various policies have been designed to counter the problem of high IAP in these countries. Government has introduced better and expensive fuels at subsidized rates in these areas. Electric stoves have been used to replace the old traditional biomass stoves. Other strategies have been the development and replacement of the old traditional stoves with the new improved counterparts. This has proved to be successful in many areas and led to the emission of lesser pollutants and better health. It has been found out that increasing the ventilation in these areas can also reduce the IAP resulting in the reduction of the smoke exposure.
1.5 Indices

‘Index’ in economics is usually defined as a single number calculated from the set of prices or quantities. They help us to analyze and compare the values between the given set of data. Every country has established indices for the ambient air quality commonly known as the ‘air quality index’, which helps in characterizing the quality of air at a given place. Similarly, Human Development Index (HDI) is the normalized measure of life expectancy, literacy, education, and Gross domestic Product (GDP) per capita worldwide. It essentially measures the development of a country. As per United Nations development program (UNDP), it is referred as the process of widening the options by giving them greater opportunities for education, health care, income, employment, etc.

Fossil fuel Sustainability Index (FFSI) was designed with an overview of effective management of the fossil fuel resources in the present energy system (Ediger et al., 2006). The three parameters defining FFSI were based on the Oil Sustainability Index (OSI), Natural Gas Sustainability Index (GSI), and Coal Sustainability Index (CSI) corresponding to the availability of oil, natural gas and coal. The field measurements (environmental, health and socio-economic) for the emissions from the cookstoves usually produces a large data set of information. To effectively analyze and correlate the data, different indices were designed to incorporate the issues related with the burning of fuels in the stoves. The indices allow comparison of different stove designs, households (for example, with different ventilation patterns) and eventually correlating to health effects. The indices will also enable guide development and design of
improved stoves that will result in reduced health and energy impacts. The aim of the study is to design ‘Inverse energy efficiency index’ and ‘Cookstove respiratory air quality index’ which along with other socio-economic parameters will help us design an ‘Integrated air quality’ index allowing us to do comparison studies between the stoves in the rural environment.

1.6 Objective of the Study

The aim of the study is to design ‘Inverse energy efficiency index’ and ‘Cookstove respiratory air quality index’ which along with other socio-economic parameters will help us design an ‘Integrated air quality’ index allowing us to do comparison studies between the stoves in the rural environment. We also study the effect of the monsoon (wet wood) on the emissions from the traditional and the improved biomass stoves. To study the effect of wind speed (air circulation) on the emissions from the stove, a battery operated fan was used to simulate the conditions and study the PM and the surface area concentration of the particles in the room.

The other objective of the study is to conduct parametric study of stoves in the laboratory conditions. These parameters would include the size of the fuel, moisture content in the fuel, height from the cookstoves and the type of the stove. This would be combined to form an integrated index which will help us provide a number to compare the stoves not only on the basis of combustion efficiency but also on the emission factors. The parameters that will be measured are the PM2.5, surface area concentration, number concentration, CO concentration and efficiency of the cookstoves to study the
overall impact of the emissions on the human body. This will be extension of the previous work and be used to compare the data between the field and the laboratory conditions.

1.7 References


Chapter 2

2. Development of Emissions Indices for Cookstoves in Rural India

2.1 Abstract

Although mass-based measures of cookstove particulate emissions concentrations (e.g. PM$_{2.5}$) are standard, particle surface area deposition in the tracheobronchial (TB) and alveolar (A) regions of the human lung is a crucial but - to our knowledge – an under studied dose parameter in the investigation of emissions from cookstoves. Using theoretical and empirical methods, it was found that PM$_{2.5}$ is not a sufficient proxy for surface area concentration; correlation coefficient for PM$_{2.5}$ vs. surface area concentration in TB region = 0.38, for PM$_{2.5}$ vs. surface area concentration in A region = 0.47. Novel cookstove emissions indices are developed that allow for comparison of cookstove with a 0 to 1 score (0 is the lowest and 1 is the highest). Field sampling of cookstove emissions was performed in two regions of rural India, wherein PM$_{2.5}$, particulate surface area concentration in both TB and A regions, and carbon monoxide (CO) were measured in 120 households and two roadside restaurants. The emissions indices are applied to compare several household and commercial cookstoves. It was found that several household cookstoves have high levels of particulate surface area
concentration emissions while their PM$_{2.5}$ emissions are comparatively low, supporting our argument that surface area concentration is an important dose parameter.

2.2 Introduction

Over 2 billion people presently use biomass to cook, boil water, for heating, and myriad of other household needs (1, 2), and this number is expected to increase over the next decades (3). This enormous scale of household biomass energy use demands attention from the public health and development communities given the known adverse impacts of the emissions from biomass cookstoves (4-15). For decades, governments and NGOs have attempted to disseminate improved household stoves in developing nations in order to facilitate more efficient and less harmful household cooking practices (6). In this effort, alterations have been made to traditional biomass cookstoves commonly used in rural areas, and new, non-biomass using stoves have also been offered. In the case of India, it is recognized that the disseminated improved stoves have not met their efficiency or emissions objectives (7), and a very low fraction has been adopted for use (8).

Extant research on cookstoves has analyzed several emissions types to investigate their negative health effects. Regarding cookstove particle emissions, mass-based dose parameters have been most prevalent, especially PM$_{2.5}$ (9,10). Small particles usually have low mass compared to large particles but have large surface areas and, therefore, their concentrations are not accurately reflected in the mass concentration of the particles. Several studies of particle emissions from non-cookstove sources indicate that
the surface area of smaller particles deposited in the lungs may be a more relevant dose parameter in determining the health effects of cookstove particle emissions than mass (11, 12, 13). Park et al., (2009) evaluated the exposure metrics by classifying them into ranks based on the different aerosol concentrations measured during cooking in kerosene or liquefied petroleum gas in residences in India. Their analysis indicates that exposure ranking by mass and surface area was similar but ranking were different when number concentrations were used, which undermines the importance of selecting exposure metric most relevant in evaluating adverse health impact (14). Ultrafine particles with diameters between 10-400 nm, where the deposition curves (International Commission on Radiological Protection (ICRP) model) exhibit their maxima, are of particular interest in studying health effects (15). To our knowledge, surface area has not been studied as a dose parameter for biomass cookstove particle emissions.

Field measurements of cookstove efficiency and emissions often produce a large set of disparately parameterized data. Indices can standardize these disparate factors or quantities for easier comprehension or comparison. There are presently no indices for the efficiency and emissions from the cookstoves. The development of cookstove indices would be useful in two clear ways. First, raw data for cookstoves can be standardized in order to create a clear “score” that would easily communicate a high or low efficiency or emissions level for cookstoves. Secondly, indices could help to compare the total emissions of a cookstove by standardizing and combining the levels of particulate, CO, and other types of emissions within a single “score.”
The central aim of the study is to design an energy efficiency index and several cookstove emissions indices that will allow holistic comparison studies between the stoves in rural areas of developing nations. A significant gap in the knowledge of particulate emissions from rural cookstoves and respiratory health is narrowed by examining the surface area concentration of particulate emissions and comparing this to a more common measure, PM$_{2.5}$ concentration. These novel indices are used to compare the emissions of several rural cookstoves used in India in order to make recommendations for dissemination interventions in this context.

2.3 Methods and Analysis

2.3.1 Study Area

Emissions sampling was conducted in two geographical regions of India. The state of Orissa (eastern India), and a contiguous region of Andhra Pradesh and Karnataka (southern India) were chosen to compensate for the dearth of evidence from these regions (16), and also to capture variation in geographical and political contexts, which determines household cooking technology use to a significant degree. A small number of households were purposively chosen in Orissa in order to cover the entire range of cookstoves used in that area, whereas in Andhra Pradesh and Karnataka, a stratified, random sample of 110 households were chosen to get an accurate representation of the household cooking technology used, which included stoves disseminated by large-scale interventions such as biogas stoves and improved chulhas.
Several different types of stoves are used in the rural areas of India based on the ease of availability and the cost of the fuels. Rural households in India in these areas predominantly use biomass stoves because of the inexpensively available fuel wood and for their ease of maintenance. Furthermore, they can also be replaced at almost no cost. Many tree and shrub species are used by households as fuel, usually several at a time. Some households also use kerosene to fuel the stoves. The various stoves tested in this study are described in Table 2.1 and shown in Figure 2.1B

### 2.3.2 Emissions Measurements and Characterization

Real time PM$_{2.5}$ emissions concentrations were measured under different operating scenarios using a personal aerosol monitor (TSI SidePak AM510, St. Paul, Minnesota, USA). The real time lung deposited surface area concentration of the particles deposited in the tracheobronchial (TB) and alveolar (A) regions of the lung was measured by a nanoparticle aerosol monitor (TSI AEROTRAK™ 9000, St. Paul, Minnesota, USA). Carbon monoxide was measured using a Langan Model T15n monitor (Langan products, San Francisco, USA). For evaluating the stove performance, a water boiling test (WBT) was conducted by taking a fixed amount of water (~2500g) in an aluminum pot that is used in the rural areas for cooking food. The time required for boiling water (i.e. time to reach 100 °C from the room temperature) when the stove is in steady state burning conditions, was recorded to calculate the efficiency of the stoves. (See Appendix I)
Table 2.1. Description of sampled cookstoves

<table>
<thead>
<tr>
<th>Stove type</th>
<th>Fuel</th>
<th>Construction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traditional biomass <em>chulha</em></td>
<td>Wood from trees and shrubs collected or bought locally</td>
<td>Earthen/clay, U-shaped opening on front</td>
</tr>
<tr>
<td>Outdoor stove</td>
<td>Wood from trees and shrubs collected or bought locally</td>
<td>Similar to above, &lt; 5 m from house</td>
</tr>
<tr>
<td>Kerosene stove</td>
<td>Kerosene purchased from local markets</td>
<td>Pressure-type, iron-frame, fuel in side-tank</td>
</tr>
<tr>
<td>Traditional coal <em>chulha</em></td>
<td>Coal produced &amp; purchased from local markets</td>
<td>Similar in make to traditional biomass <em>chulha</em></td>
</tr>
<tr>
<td>Improved <em>chulha</em></td>
<td>Wood from trees and shrubs collected or bought locally</td>
<td>Design varies by region: in Orissa, metallic frame; in Karnataka, concrete with metal flue</td>
</tr>
<tr>
<td>3-stone stove</td>
<td>Wood from trees and shrubs collected or bought locally</td>
<td>3 stones resting on ground aligned at 120° to each other</td>
</tr>
<tr>
<td>Biogas plant/stove</td>
<td>Methane gas produce by “plant” constructed near to owner’s home</td>
<td>Deenbandhu model; underground masonry structure produces methane gas that is carried to stove by rubber tube</td>
</tr>
<tr>
<td>LPG</td>
<td>Liquid petroleum gas purchased from local markets</td>
<td>Liquefied petroleum gas stored in canister, carried to stove by tube</td>
</tr>
<tr>
<td>Commercial biomass <em>bhati</em></td>
<td>Wood from trees and shrubs collected or bought locally</td>
<td></td>
</tr>
<tr>
<td>Commercial coal <em>bhati</em></td>
<td>Coal produced &amp; purchased from local markets</td>
<td></td>
</tr>
</tbody>
</table>
Figure 2.1: (A) Illustration of the schematic of a rural household in India and emissions sampling locations from a stove (Dotted line represents separation of kitchen from sleeping room in some households) (B) Different types of stoves tested during field sampling in India (i) Three stone (ii) Traditional (wood fired) (iii) Traditional (coal fired) (iv) Improved (Orissa) (v) Kerosene (vi) Biogas (vii) Commercial (wood fired) (viii) Commercial (coal fired)
2.3.3 Experimental Test Plan

Field tests were conducted in Orissa in June 2008 and in Andhra Pradesh and Karnataka between June and August 2008. The experimental plan and test conditions are summarized in Table 2.2. Several types of cookstoves were tested in each location. In Andhra Pradesh and Karnataka (Test 1), 110 households were sampled, including traditional biomass chulhas with and without chimney, improved chulhas, kerosene stoves, and biogas stoves for emissions measuring PM$_{2.5}$ and particulate surface area concentration, as the central focus of this research is on particulate emissions. In Orissa (Test 2), traditional biomass chulha, traditional coal chulha, improved chulha, kerosene stove, LPG stove, and biogas stoves were sampled for emissions measuring PM$_{2.5}$, particulate surface area, and CO concentrations. The emissions sampling was conducted for 10-15 minutes continuously during the different operating scenarios considered in this study. Many of the tests described below were conducted only in the Orissa field location, as the broader purpose of this phase of the research was to obtain data on a wide variety of cookstove parameters from a small set of purposively selected households, while the broader purpose of the Andhra Pradesh and Karnataka phase was to see the impact of emissions of household cookstoves in a generalizable way, entailing the need for a large household sample.

Emissions sampling was conducted at three locations within the household. (See Figure 2.1a) Location 1 (L1), or the breathing zone, approximated the position of a person using the stove and was always within 0.5 m of the stove. Location 2 (L2) represents the emissions experienced by people working on other household tasks while the stove...
is burning, a common practice in our study areas, and also for children who are near their mother while she is operating the stove. In Orissa, L2 was typically between 1-3 m away from the stove, and in Andhra Pradesh and Karnataka, L2 was between 1-5 m away from the stove. L2 was chosen based on the location in the household where the aforementioned activities took place as opposed to a precise distance from the stove, and it varies by household accordingly. Location 3 (L3) was between 3-5 m away from the stove, depending on the particular household, and represents the emissions experienced by other household members sitting or sleeping in another part of the house. In Orissa (Test 2) each stove was sampled for emissions at L1, L2, and L3. However, in Andhra Pradesh and Karnataka (Test 1) only L1 and L2 were sampled.

Various cookstove operating conditions were tested in Orissa. Two stove operating phases were considered: start-up and steady state (Tests 2 & 3). Start-up refers to the time directly after the stove is ignited, and steady state refers to the normal operating phase, after the start-up phase has finished. These two phases of cookstove use are important to measure separately because the non-ideal combustion process at start-up (e.g. moisture in the wood) impacts emissions levels, and emissions levels may change after this phase. Examining the potential divergence between start-up and steady state conditions also provides an opportunity to exemplify the benefit of cookstove emissions indices. If raw cookstove emissions data vary considerably between these two phases, having a standardized metric of emissions levels across time of use will be useful in communicating this information more simply and effectively to decision
makers. All of the household cookstoves in the Orissa sample were tested at start-up phase in L1, and in steady-state phase at L1, L2, and L3.

The impact of air-fuel ratio on cookstove efficiency and emissions levels was tested for traditional stove and measurements were taken at breathing zone using a hand-held fan to improve air-fuel mixing during fuel combustion (Test 3). In addition to the household stoves, commercial stoves, or *bhatis*, were also sampled for emissions (Test 4). This test includes both biomass and coal *bhatis* from roadside restaurants, which were sampled for PM$_{2.5}$, particulate surface area, and CO emissions at L1 and L2 in the steady-state phase for normal air-fuel ratio. The definition of L1 is consistent between the household and commercial stove tests, although L2 in the commercial stove tests is defined as 3-5 m from the stove, the location where restaurant patrons would sit and be impacted by emissions. Finally, cookstove efficiency was tested for household cookstoves in Orissa using the water-boiling test (WBT) (Test 5).
### Table 2.2. Experimental test plan

<table>
<thead>
<tr>
<th>Test #</th>
<th>Study Area</th>
<th>Stoves Tested</th>
<th>Parameters Measured</th>
<th>Measurement Location</th>
<th>Stove Operating Condition</th>
<th>Air/Fuel</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Andhra Pradesh &amp; Karnataka</td>
<td>Traditional biomass <em>chulha</em></td>
<td>PM2.5, Surface area</td>
<td>L1, L2</td>
<td>Steady state Normal</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>Traditional biomass <em>chulha</em> with chimney</td>
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<tr>
<td></td>
<td></td>
<td>Improved <em>chulha</em></td>
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<td></td>
<td></td>
<td>Kerosene</td>
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<td></td>
<td></td>
<td>LPG</td>
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<tr>
<td></td>
<td></td>
<td>Biogas</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>2</td>
<td>Orissa</td>
<td>Traditional biomass <em>chulha</em></td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>Traditional coal <em>chulha</em></td>
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<td></td>
<td></td>
<td>Improved</td>
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<td>Kerosene</td>
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<td></td>
<td>Biogas</td>
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<tr>
<td>3</td>
<td></td>
<td>Biomass <em>bhati</em></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>4</td>
<td></td>
<td>Coal <em>bhati</em></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>5</td>
<td></td>
<td>Water boiling test during steady state cooking conditions of the stove</td>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>
Various cookstove operating conditions were tested in Orissa. Two stove operating phases were considered: start-up and steady state (Tests 2 & 3). Start-up refers to the time directly after the stove is ignited, and steady state refers to the normal operating phase, after the start-up phase has finished. These two phases of cookstove use are important to measure separately because the non-ideal combustion process at start-up (e.g. moisture in the wood) impacts emissions levels, and emissions levels may change after this phase. Examining the potential divergence between start-up and steady state conditions also provides an opportunity to exemplify the benefit of cookstove emissions indices. If raw cookstove emissions data vary considerably between these two phases, having a standardized metric of emissions levels across time of use will be useful in communicating this information more simply and effectively to decision makers. All of the household cookstoves in the Orissa sample were tested at start-up phase in L1, and in steady-state phase at L1, L2, and L3.

The impact of air-fuel ratio on cookstove efficiency and emissions levels was tested for traditional stove and measurements were taken at breathing zone using a hand-held fan to improve air-fuel mixing during fuel combustion (Test 3). In addition to the household stoves, commercial stoves, or bhatis, were also sampled for emissions (Test 4). This test includes both biomass and coal bhatis from roadside restaurants, which were sampled for PM$_{2.5}$, particulate surface area, and CO emissions at L1 and L2 in the steady-state phase for normal air-fuel ratio. The definition of L1 is consistent between the household and commercial stove tests, although L2 in the commercial stove tests is defined as 3-5 m from the stove, the location where restaurant patrons would sit and be impacted by emissions.
Finally, cookstove efficiency was tested for household cookstoves in Orissa using the water-boiling test (WBT) (Test 5).

### 2.3.4 Inverse Energy Efficiency Index

The efficiency of a stove is defined as the measure of energy transferred into the pot. Heat transfer efficiency is the fraction of energy utilized of the total energy generated by burning fuel for heating and evaporating the water in the pot (17). However, the efficiency depends on combustion of the fuel, designing of the pot, moisture content and size of the fuels (18). Thermal efficiency of the stove was calculated using the water boiling test version 3.0, prepared by the Shell foundation (19). The thermal efficiency ($\eta_e$) of the stove is be calculated by,

$$\eta_e = \frac{C_p M_w (T_f - T_i) + L M_{ev}}{F t H_f}$$

where, $\eta_e$ is the thermal efficiency (%), $C_p$ = specific heat of water (4.18 kJ kg$^{-1}$ K$^{-1}$), $M_w$ = mass of water (g), $T_i$ = Initial water temperature (K), $T_f$ = Final water temperature (K), $L$ = latent heat of evaporation (2257.2 kJ kg$^{-1}$ at 298K), $M_{ev}$ = mass of water evaporated (g), $F$ = burning rate of fuel (kg h$^{-1}$), $t$ is the burn time and $H_f$ is the net calorific value (MJ/kg) of the fuel (Solid fuel-17.3 Kerosene-43.6, LPG-47.1, Biogas-17.7, Indian coal-18.4).

To describe the stove performance and obtain a range of values from 0 to 1 (0 is described as the best efficiency and 1 represents the worst efficiency of the stove) and also to be
consistent with emissions indices defined in this study, the inverse energy efficiency indices \( (\eta) \) was defined as:

\[
\eta_l = 1 - \frac{\eta_e}{100}
\]  

\( (2) \)

2.3.5 Relationship between PM\(_{2.5}\) Mass and Surface Area Concentrations

In understanding the relationship between PM\(_{2.5}\) and surface area concentration associated with the emissions from the cookstoves both experimental measurements and theoretically calculated PM\(_{2.5}\) and surface area concentration values were used. The real time PM\(_{2.5}\) mass concentration was measured using the personal aerosol monitor (TSI SidePak AM510). As surface area characterization methods are at an early stage of development, surface area was estimated based on the number and mass concentration measurements by assuming a lognormal size distribution of the emitted aerosols with a fixed standard deviation value in previous studies (13, 14). Park et al., (2009) also measured the aerosol active surface area by using a surface area monitor and compared with the estimated surface area concentrations. They found that the estimated surface area concentrations are 2-6 times higher than the actual surface area concentration measurements (14). However, for the exposure analyses in this study, a new nanoparticle surface area monitor (TSI AEROTRAK™ 9000) was used to measure the real time surface area concentration of the emitted particles from different cookstoves. The instrument measures the surface area concentration of the particles deposited in alveolar and tracheobronchial regions of the human lungs based on the ICRP model.
The total PM$_{2.5}$ mass concentration was calculated based on aerosol particles emissions from cookstoves characterized by a lognormal size distribution. The mass concentration was calculated by integrating the initially assumed lognormal size distribution of the emitted aerosols over the particle size ranges as,

$$PM_{2.5} = \frac{1}{G_{b3}e/G_{b124}} \frac{\rho \pi}{G_{b6}e/G_{b37}} \frac{1}{G_{b52}e/G_{b72}} \frac{n_{dp}}{G_{3}b62/G_{3}b62} \frac{d(d_{dp})}{G_{b6e}/G_{b65}} \frac{\sigma}{G_{b65}/G_{b65}} \exp \left[ \frac{-(\ln d_{dp} - \ln d_{dpb})^2}{2\ln^2 \sigma_g} \right]$$

(3)

Where, $n_{dp}$ is the size distribution function and is described as,

$$n_{dp} = \frac{N_t}{\sqrt{2\pi d_{dp} \ln \sigma_g}} \exp \left[ \frac{-(\ln d_{dp} - \ln d_{dpb})^2}{2\ln^2 \sigma_g} \right]$$

(4)

Where, $\rho$ is the density of the particle, $d_{dpb}$, $\sigma_g$ are geometric mean diameter and geometric standard deviation of the distribution $N_t$ is the total emitted aerosols number concentration.

Because of the practical difficulties of carrying the presently available large sized size classification instruments for sampling in rural areas, size distribution measurements were not taken. Assuming the emitted particles are log-normally distributed, the geometric mean sizes of the emitted aerosols from the cookstoves reported in the literature were used in this analysis as the representative geometric mean sizes of the particles [20, 21, 22].

The total surface area concentration of particles deposited in different part of the lungs was calculated by integrating the size distribution of particles (equation 4) weighted with respect to the ICRP model of size dependency fraction deposited over the size range of interest.

The total surface area concentration was calculated by,
Where, $DF_{TB/A}$ is the deposited fraction of the particles corresponding to particle size deposited in tracheobronchial or alveolar region.

The following equations were used for fitting to the ICRP model for the deposition fraction of the spherical particles for the tracheobronchial and alveolar regions.

\[
DF_{TB} = \left[ \frac{0.00352}{d_p} \right] \left[ \exp (-0.234 \ln d_p + 3.40)^2 \right] + 63.9 \exp (-0.819 (\ln d_p - 1.61)^2)
\]

(6)

\[
DF_A = \left[ \frac{0.01555}{d_p} \right] \left[ \exp (-0.416 \ln d_p + 2.84)^2 \right] + 19.11 \exp (-0.482 (\ln d_p - 1.362)^2)
\]

(7)

Numerical integration was performed following the trapezoidal rule and computation was performed using MATLAB software. Using the above procedure PM$_{2.5}$ mass and surface concentrations was estimated. Furthermore, these estimated mass and surface area concentrations were used for calculating the indices.

2.3.6 Cookstove Emissions Indices

As described previously, large number of smaller sized particles has large surface area, which contributes less to PM concentrations but still may have significant health effects that are not reflected in the measurement of PM alone. CO is usually formed due to incomplete combustion of air and wood. Its fast combination with hemoglobin forms carboxyhaemoglobin and, at high concentration, is fatal to human beings. The diversity of health-relevant emissions needs to be carefully considered when analyzing the impact of
cookstoves. Emissions indices can simplify the communication of these disparate factors on health by translating raw emissions values into easily understandable scales, and they can also bring together the information communicated by different emissions measures into single, stream-lined emissions measures. The indices are calculated as,

\[
E_I = \frac{C - C_{LO}}{C_{HI} - C_{LO}}
\]  

(8)

Where, \( E_I \) is the emissions index corresponding to the dose metric selected, \( C \) is the concentration of pollutant. (Surface area concentration (in tracheobronchial or alveolar region) in \( \mu m^2/cm^3 \), PM\(_{2.5}\) mass concentration in mg/m\(^3\), CO concentration in ppm), \( C_{LO} \) is the lowest concentration and \( C_{HI} \) is taken as highest concentration.

The value obtained generally lies between 0 and 1. This provides a relative comparison of the effect of the stoves on human health, and also their individual and comparative efficiencies. The safety standard for CO established by the WHO during stove use is 30 ppm and therefore was used as the highest value to calculate the CO index. There are no established standards for PM\(_{2.5}\) and surface area concentrations during cookstove use. Therefore, to study the comparative values of the different stoves, the highest observed PM\(_{2.5}\) during the field sampling was considered as the highest PM\(_{2.5}\) concentration for the index calculation, where as the upper limit of the surface area monitor was used for calculating the surface area index, as the highest surface area concentration observed was close to the instrument upper detection limit.
2.3.7 Integrated Emissions Index

Studies have indicated that carbon monoxide can be used as a proxy for the suspended particulate matter (23, 24). In another study, it was found that the variability of carbon monoxide cannot be correlated to the suspended particulate matter in all scenarios (25). Also as previously discussed, ultrafine particles do not contribute much to the mass concentration even at high particle number concentration, and therefore exposure assessment using mass concentration may not reflect the potential adverse impacts of ultrafine particles. Therefore only limited information could be extracted if one parameter will be considered and it is important that all the three parameters are considered. However, due to insufficient information available on the relative adverse health impact of all the dose parameters, equal weight has been given to the individual indices in calculating the integrated emissions index. The integrated emissions index (IEI) is calculated as,

\[ \text{IEI} = \frac{\text{PM}_{2.5} \text{Index} + \text{SA Index} \left( \frac{T_B}{A} \right) + \text{CO Index}}{3} \]  

(9)

When only PM$_{2.5}$ and SA indices are considered it is defined as overall particulate index (OPI). There are number of limitations in averaging the indices. It would be more useful to extend the further research to examine accurately; the weight that should be given to each dose parameters for health studies. Issues of chemical composition and morphology of the particles need to be considered as well while examining the impacts.
2.4 Results and Discussions

2.4.1 Inverse Energy Efficiency Index

Thermal efficiency of the stoves depends on specific fuel consumption, moisture content of the fuel and net caloric values of the fuel obtained within the specific region of geographical locations sampled, as these values vary among fuels used in different places. The inverse energy efficiency index ($E_I$) was lowest for the improved stove (0.86) compared to the traditional stove (0.84). The calculated index for traditional and improved stoves studied by Zhang et al. (2000) in China was 0.87 and 0.76. The $E_I$ for traditional coal fired stove was 0.57. The $E_I$ calculated for kerosene stoves was 0.57 (26) and 0.51 (27), whereas in this study the index obtained for kerosene stove is 0.55. The discrepancies in stove efficiency obtained for stoves tested in this study compared to the values reported in other studies are due to variations in specific stove designs. Differences between stoves in design, feeding of the fuels, and fuel moisture content and control of air flow to the combustion chamber affect stove performance. This study indicates that stove performance cannot be compared directly as various designs of the stoves, fuels and variation in calorific values of the fuels and different size of the fuels used for different stoves tested across the literature. However, the present study accurately calculates performance specific to realistic stoves operation encountered in cooking practice in rural areas of Orissa, India.
2.4.2 PM$_{2.5}$ and Surface Area Concentrations as Dose Parameters

The estimated PM$_{2.5}$ and SA index assuming a lognormal size distribution of aerosol particle emissions from cookstoves is shown in Figure 2.2(A). The geometric mean diameters were varied from 0.005 µm to 0.79 µm and the particle number concentrations was varied from $10^4$ to $5 \times 10^6$#/cm$^3$, which was calculated from the measured mass concentrations from different cookstoves during emissions sampling. The range of geometric mean diameter considered in this analysis represents the geometric mean diameter of the particles reported in the literature from the cookstoves emissions using wood, kerosene and gas as the fuels (20, 21, 22). The considered geometric mean diameter for the analysis may not accurately represent the mean diameter from the cookstoves studied here, as in realistic cooking scenario different stove design and fuels are used. Different stove design, operation, and different fuels may lead to different particle sizes (19). However, this analysis might be at best qualitatively representative of the emissions from the different type of stoves emitting different sizes of particles and there are stronger contributions to SA index from kerosene and biogas stove emitting ultrafine particles compared to wood burning stoves.

Pearson’s product moment was used to calculate the correlation between these particulate emissions dose parameters for the Andhra Pradesh and Karnataka sample of household cookstoves (28). In this procedure R refers to the correlation coefficient, which gives the degree of correlation between two variables. Coefficient values range between 1 and -1, and the absolute value of the coefficient gives its strength such that 0 reflects no correlation and 1 reflects complete correlation. The p-value indicates whether there is evidence to reject the null hypothesis that the correlation is found by chance. Significant p-values (<0.05) indicate
that there is evidence to reject the null hypothesis, and that the correlation found by the procedure was not due to chance. The sample size, defined as the number of cases used in the procedure, is given by \( n \).

The correlations analysis indicates that there is moderate correlation between theoretically calculated \( \text{PM}_{2.5} \) index and the surface area index for the tracheobronchial region (TB) (\( R=0.58; p<0.01; n=66 \)) and a poor correlation in between the \( \text{PM}_{2.5} \) index and surface area index for the alveolar region (A) (\( R=0.31; p<0.01; n=66 \)).

In addition to the above theoretical analysis, the relationship between \( \text{PM}_{2.5} \) and surface area indices calculated from the field \( \text{PM}_{2.5} \) mass and surface area concentrations measured from different stoves are presented in Figure 2.2(B). Among the total sample, the correlation between the \( \text{PM}_{2.5} \) index and the surface area index for the tracheobronchial region (TB) is weak (\( R=0.38; p<0.01; n=58 \)), indicating that these variables share only 14% of their variation. The correlation between the \( \text{PM}_{2.5} \) index and surface area index for the alveolar region (A) is moderate (\( R=0.47; p<0.01; n=56 \)), indicating that these variables share 22% of their variation. From Figure 2.2(B) it is clear that the moderate correlation shown statistically is driven by cases at low concentrations. The difference in correlation between theoretically calculated indices and indices calculated from experimental values can be attributed to the assumption of different geometric mean sizes of the particles from the cookstoves.

The correlation between \( \text{PM}_{2.5} \) concentration and surface area concentration, in either the tracheobronchial or alveolar regions, is not strong enough to justify using \( \text{PM}_{2.5} \) as a proxy for surface area when selecting dose parameters for cookstove particulate emissions. The
moderate correlation between these parameters is not sufficient for information about one dose parameter to be communicated reliably by the other. Although these parameters co-vary at low concentrations, the surface area values at high smaller size particle concentrations are relevant for understanding the health impact of particulate emissions of household cookstoves, and this information is missed in the PM$_{2.5}$ measures.
Figure 2.2: Correlation of \( \text{PM}_{2.5} \) and SA emissions indices at breathing zone for the of stoves tested in Andhra Pradesh (A) Theoretically calculated (B) Experimental (TB-Index calculated for particle deposited in Tracheobronchial region, A- Index calculated for particle deposited in Alveolar region)
2.4.3 Cookstove Emissions Indices

Andhra Pradesh/Karnataka Site

In the Andhra Pradesh and Karnataka study site 110 households were sampled for PM$_{2.5}$ and surface area concentration. The PM$_{2.5}$ and surface area indices calculated for several types of stoves tested at breathing zone are shown in the Figure 2.3(A) (Test 1). The PM$_{2.5}$ indices value was highest for improved chulhas (0.56) followed by traditional chulhas without chimney (0.15) and traditional chulhas with chimney (0.12). The PM$_{2.5}$ indices values were very low for kerosene (0.09) and biogas stoves (0.02). The surface area indices was highest for 3-stone stoves (TBH-0.56, alveolar-0.42) followed by outdoor stoves (TBH-0.49, alveolar-0.35) and kerosene stoves (TBH-0.29), but lower surface area indices values were observed for traditional chulhas with (TBH-0.14) and without (TBH-0.21) chimneys. The high PM$_{2.5}$ indices value for improved chulhas is due to improper combustion in the combustion chamber, which leads to the emission of significant quantities of un-burnt, large-size soot particles, which contributes to higher PM$_{2.5}$ concentration. Several of the improved chulhas were broken, often due to a malfunction in the flue, or by a missing flue altogether. For traditional chulhas with chimneys, steady state particulate emissions are low, indicating that the chimney is effective in removing emitted particles. It is notable that the PM$_{2.5}$ indices values are low for 3-stone, kerosene and outdoor stoves, whereas surface area indices values are comparatively high for these stoves. The high surface area indices values for 3-stone and outdoor stoves can be attributed to emissions of large quantities of ultrafine particles, which is consistent with low PM$_{2.5}$ concentrations. Even though the PM$_{2.5}$ indices values for these
stoves are low which may be due the large number of ultrafine particles, but they can give rise to high surface area concentrations within these emissions. Emissions at 1 m (L2) from the stoves were also investigated (Test 1). The PM$_{2.5}$ indices for emissions at this distance for traditional chulhas without/with chimney were 0.11 and 0.12 respectively, compared to the PM$_{2.5}$ indices at breathing zone indices of 0.15 and 0.13. The decreasing indices values that obtain at distances further from the cookstove suggest that particulate emissions disperse through windows or to other rooms after emitted and can have less impact. The calculated overall particulate index (OPI) is shown in the Figure 2.3(B) and compared with the PM$_{2.5}$ index, as PM$_{2.5}$ is presently used as the standard measures for exposure studies.
Figure 2.3. (A) Calculated PM$_{2.5}$ and surface area emissions indices (B) Comparison of PM$_{2.5}$ and overall particulate indices at breathing zone during steady state cooking condition for different types of stoves tested in Andhra Pradesh (TB- Index calculated for particle deposited in Tracheobronchial region, A- Index calculated for particle deposited in Alveolar region)
CO could not be measured because of the malfunction of the instrument during the field sampling and is not included in the integrated index calculation for this site. The OPI value (calculated excluding the CO index) was highest for 3-stone construction *chulhas* (OPI (TB)-0.34, OPI (TB)-0.27) followed by outdoor traditional *chulhas* (OPI (TB)-0.31, OPI (A)-0.24). However, the PM$_{2.5}$ index follows a different trend than the combined index that PM$_{2.5}$ index is highest for traditional without chimney followed by outdoor traditional stove (Improve stove is excluded from this comparison as SA area index is not available for integrated index calculation). It is to be noted that the OPI (TB) for kerosene was higher than for traditional stove without chimney where as opposite in the case of OPI (A). However, the PM$_{2.5}$ index was very less for kerosene (0.09). The higher OPI is due to the dominant particle concentration of ultrafine particles from the kerosene stove. The higher OPI (TB) for kerosene compared to traditional stove without chimney is due to emissions of the smaller size particles from kerosene stoves and most these particle fraction deposits in the TB region according to the ICRP model compared to the bigger size particles that are mostly deposited in alveolar region of lungs. This clearly indicates that only considering PM$_{2.5}$ may not represents the adverse effects. Biogas is the cleanest stove both from both PM$_{2.5}$ and integrated index consideration without taking into account the CO emissions for this sampling site.

Next, the particulate emissions indices are used to quantitatively compare the particulate emissions of different types of stoves used in rural households in Andhra Pradesh and Karnataka. Ordinary Least Squares (OLS) multiple regression is employed to investigate the relative contribution each type of stove – traditional *chulhas* with and without chimneys, 3-
stone stoves, outdoor stoves, biogas stoves, improved *chulhas* - has on a household’s level of particulate emissions measured by different dose parameters, including: PM$_{2.5}$, surface area of particles in the tracheobronchial region, and surface area of particles in the alveolar region (28). By using a large, randomly selected sample, the results are generalizable to a broad, continuous region of western Andhra Pradesh and eastern Karnataka. The OLS regression procedure adds the benefit of understanding the emissions of each type of stove for an average household in this region. This is important given the wide range of variability in emissions between different individual stoves of the same type, and also between different types of cookstoves.

There are three regression models in total. The first model tests the impact of different types of stoves on household PM$_{2.5}$ emissions concentration using the PM$_{2.5}$ index as a dependent variable. The second and third model tests the impact of different types of stoves on household particulate surface area emissions concentration in the tracheobronchial and alveolar regions using the surface area (SA) index corresponding to each region as a dependent variable. Each type of household cookstove is represented as an independent variable in all three models. Households cooking with a traditional *chulha* without a chimney are used as the reference group, meaning that this variable is not included in the models and that the results for each independent variable are interpreted in terms of the type of cookstove’s average emissions compared to a traditional *chulha* without a chimney. This is an appropriate analytic approach because: 1) traditional *chulhas* without a chimney are the standard and most common form of cookstove in our study area; 2) traditional *chulhas* without a chimney are the cookstove that interventions generally intend to replace.
The $R^2$ and F statistic are both measures of an entire regression model’s explanatory power (28). The $R^2$ value gives the percent of the dependent variable’s variance that is explained by the independent variables; e.g. if the $R^2$ is 0.30, then the independent variables explain 30% of the dependent variable’s variance. The F statistic for each model represents a test of the model’s capacity to explain variance in the dependent variable at all; in other words, it is a significance test for the $R^2$. Similarly, the F test tests the null hypothesis that states: There is no linear relationship between the dependent and independent variables. The alternative hypothesis states that there is a linear relationship between the dependent and independent variables. Significant F statistics (p-value <0.05) justify rejecting the null hypothesis, and provide evidence to support the alternative hypothesis, to assert that the set of independent variables in the model explain more variance than a set of no independent variables. The $\beta$ coefficient for each independent variable gives the magnitude of effect wherein higher $\beta$ coefficients indicate stronger effect and lower $\beta$ coefficients indicate weaker effect. In the regression model, for each stove type (independent variable), the $\beta$ coefficient also indicates the direction of effect: positive coefficients represent increases in emissions in index units and negative coefficients represent decreases in emissions in index units compared to a traditional chulha without a chimney. The p-values indicate whether there is evidence to reject the null hypothesis that each type of stove’s emissions is not significantly different than a traditional chulha without chimney’s emissions; p-values lower than 0.05 indicate that a type of stove’s emissions is significantly different. According to convention for OLS regression, only the results for stove types that have significant p-values will be interpreted, and the following interpretation will be used: cooking with a cookstove type $x$ (where $x$ is
any given independent variable) compared to cooking with a traditional *chulha* without a chimney is significantly associated with a $\gamma$ emissions index unit change in emissions $y$ (where $y$ is any dependent variable) (28). The $\beta$ coefficient will give the number of units and direction of change in emissions referred to in the above interpretation; e.g., if a significant independent variable has a $\beta$ coefficient of -0.40, then it will be interpreted to be significantly associated with a 0.40 unit decrease in emissions index units compared to a traditional *chulha* without chimney. These results are summarized in Table 3.

*Table 2.3 OLS regression models for cook stove emissions comparisons across particulate dose parameters (PM2.5 and surface area in TB and A regions)*

<table>
<thead>
<tr>
<th>Cookstove Type</th>
<th>PM2.5 Index</th>
<th>SA Index (TB)</th>
<th>SA Index (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traditional <em>chulha</em>/chimney</td>
<td>-0.02</td>
<td>-0.08</td>
<td>0.03</td>
</tr>
<tr>
<td>3-stone stove</td>
<td>-0.03</td>
<td>0.35**</td>
<td>0.2</td>
</tr>
<tr>
<td>Outdoor stove</td>
<td>0.001</td>
<td>0.28***</td>
<td>0.16</td>
</tr>
<tr>
<td>Biogas stove</td>
<td>-0.12*</td>
<td>-0.18**</td>
<td>-0.18*</td>
</tr>
<tr>
<td>Improved <em>chulha</em></td>
<td>0.42***</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>N</td>
<td>106</td>
<td>59</td>
<td>57</td>
</tr>
<tr>
<td>F</td>
<td>8.22***</td>
<td>8.96***</td>
<td>3.57***</td>
</tr>
<tr>
<td>$R^2$</td>
<td>0.29</td>
<td>0.40</td>
<td>0.23</td>
</tr>
</tbody>
</table>

p-value significance level: *<.05; **<.01; ***<.001
The F-statistic for all regression models is significant, indicating that each model explains variance in the dependent variable. The $R^2$ values range between 0.23 and 0.40, indicating that the amount of variance in the dependent variable in each model is explained relatively well by the independent variables. Regarding the PM$_{2.5}$ index, there is not a statistically significant difference between the household PM$_{2.5}$ concentration when cooking with a traditional *chulha* with a chimney, a 3-stone stove, or an outdoor stove compared to cooking with a traditional *chulha* without a chimney. However, cooking with a biogas stove compared to cooking with a traditional *chulha* without a chimney is significantly associated with a 0.12 unit decrease in household PM$_{2.5}$ concentration. The PM$_{2.5}$ concentration associated with improved *chulhas* is by far the greatest of the stoves; cooking with an improved *chulha* compared to cooking with a traditional *chulha* without a chimney is significantly associated with a 0.42 unit increase in the household PM$_{2.5}$ concentration.

In the regressions testing the effect of different cookstove types on the surface area indexes, there were insufficient observations on improved *chulhas* for analysis. Therefore, this variable has been dropped from these tests. There is not a statistically significant difference in the surface area concentration of particles in the tracheobronchial region emitted when cooking with a traditional *chulha* with a chimney compared to cooking with a traditional *chulha* without a chimney. Cooking with a 3-stone stove compared to cooking with a traditional *chulha* without a chimney is significantly associated with a 0.35 unit increase in the surface area of particles deposited in the tracheobronchial region. Cooking with an outdoor stove compared to cooking with a traditional *chulha* without a chimney is significantly associated with a 0.28 unit increase in the surface area of particles deposited in the
tracheobronchial region. Cooking with a biogas stove compared to cooking with a traditional *chulha* without a chimney is significantly associated with a 0.18 unit decrease in the surface area of particles deposited in the tracheobronchial region. There is not a statistically significant difference between the surface area concentration of particles deposited in the alveolar region when cooking with a traditional *chulha* with a chimney, 3-stone stove, or an outdoor stove compared to cooking with a traditional *chulha* without a chimney. Cooking with a biogas stove compared to cooking with a traditional *chulha* without a chimney is significantly associated with a 0.18 unit decrease in the surface area concentration of particles deposited in the alveolar region.

These results corroborate the qualitative comparison of particulate emissions from different types of household cookstoves. Interestingly, improved *chulhas* represent the highest PM$_{2.5}$ concentration of any of the stoves, showing that improved devices, when not properly maintained, can actually increase health risk associated with cookstove emissions. The households in our sample that owned these stoves discussed the heavy burden associated with proper maintenance of the improved *chulhas* and were quite aware that improper maintenance led to the stoves’ malfunction. However, given other demands on time, stove users expressed inability to keep-up with the stoves’ maintenance needs. Improved biomass stoves for future dissemination should be constructed to withstand less maintenance so that decreases, instead of increases, in emissions are realized.

The increase in surface area concentration of particulate emissions associated with 3-stone and outdoor stoves indicates that the poorest households are most vulnerable to negative health impacts from cookstove emissions, as these stoves are very basic, constructed with
found materials, and are typically only used among households with no capacity to obtain newer, alternative cooking technology. More research investigating the social and economic drivers of household cooking technology use should be conducted to identify the most vulnerable populations that should be targeted for future improved stove interventions.

Biogas stoves are associated with lower concentrations of all particulate dose parameters, indicating that this is a relatively clean household cookstove. However, given the biogas stove’s high CO emissions from the Orissa field sample, it is difficult to give a full endorsement at this time. More research into the total emissions of biogas stoves should be conducted to understand the full potential of this promising technology.

An examination of regressions together has implications for the relationship between PM$_{2.5}$ concentration and surface area concentration. If these different dose parameters were good proxies of each other, one would expect similar results across the regression models. As this analysis demonstrates, the particulate emissions of each type of household stove is divergent across each of the above mentioned dose parameters. As an illustration, consider the effects of 3-stone stoves in each model. In the PM$_{2.5}$ concentration model, the β coefficient for 3-stone stove is very small and negative (-0.03), in the model for surface area concentration in the TB region, the β coefficient for 3-stone stove is moderate and positive (0.35), and in the model for surface area concentration in the alveolar region, the β coefficient for 3-stone stove is moderate but positive (0.20). There is a similar divergence for outdoor stoves across the models. These results make it clear that PM$_{2.5}$ concentration cannot be relied upon to understand surface area concentration of particulate emissions, a highly important dose
parameter on its own. The single exception in divergence across the models is found in biogas stoves, which all have negative and comparably-size $\beta$ coefficients.

**Orissa site: Various Stove Operations**

The emissions indices obtained for all the stove types at the breathing zone (L1) in the Orissa study site are shown in Figure 2.4(A) (Test 3). The calculated indices suggest that PM$_{2.5}$ emissions are highest for the improved *chulha* (0.61) followed by the traditional biomass *chulha* (0.48). For all other stoves, lower PM$_{2.5}$ emissions were observed (<0.25). The surface area index was highest for the traditional biomass *chulha* (0.59) and lowest for the biogas stove (0.03). However, CO emissions were highest (0.87) in the case of biogas stove. The CO indices values are also comparatively high for the improved *chulha* (0.44) and traditional *chulhas* (0.32). The high PM$_{2.5}$ indices value for improved *chulhas* may be attributed to incomplete combustion that resulted from continuous feeding in the improved *chulha*.

The higher CO index value for biogas is explained by improper burning of the methane gas coming from the biogas plant. However, the high level of CO also may be due to dispersed gases from the biogas plant to the household, as the biogas plants are located in the back of the household kitchens in rural India. Relatively higher CO index values and surface area indices values were observed for the kerosene stove, which could be attributed to incomplete combustion in gaseous kerosene, leading it to emit a large number of smaller particles and giving rise to high surface area concentration. The indices values obtained for measurements taken at L2 and L3 indicate lower emissions exposure than in the breathing zone (Test 3). However, for some traditional *chulbas* the emissions observed were higher.
when the sampling location was inside the same room as the stove. The increased emissions can be attributed to accumulation of the emitted particles inside the room due to the improper ventilation with the outside air. This occurs in rural one-room houses wherein a single room is used for both cooking and sleeping.

The comparison of the integrated index with PM$_{2.5}$ index for cookstoves tested in Orissa indicates that both indices are highest for improved stoves followed by traditional stove fired with wood (Figure 2.4(B)). The LPG and coal fired traditional stoves are cleanest of all the stoves tested in this site in steady state cooking conditions. Although from PM$_{2.5}$ consideration, kerosene, biogas stoves are clean, but over all indices suggest that only considering PM$_{2.5}$ will under predict the adverse impact, as the ultrafine particle emissions and incomplete combustion which produces more CO will have different level of impact. It is clearly observed from our analysis that the degree of impact of the dose parameters need to be further investigated to accurately calculate the integrated index and will help in better understanding the adverse health impacts.

The indices values for commercial scale stoves – bhatis - during steady state cooking conditions show comparatively lower emissions of particulate matter as seen in both PM$_{2.5}$ and surface area indices (Test 5), though it emits higher CO as evident from CO index (coal fired -0.52, wood fired-0.16). Bhatis are located near the roadside and are generally open from three sides, which ensure dilution with the outside environment reducing exposure. The lower PM$_{2.5}$ and surface area indices for bhatis are due to the complete mixing of the emitted particles with the outside environment, which reduces the emissions at the breathing zone.
Figure 2.4. (A) Calculated PM$_{2.5}$ and surface area emissions indices (B) Comparison of PM$_{2.5}$ and Integrated emissions indices at breathing zone during steady state cooking condition for different types of stoves tested in Orissa (TB- Index calculated for particle deposited in Trachea bronchial region, A- Index calculated for particle deposited in Alveolar region)
Figure 2.5 Comparison of PM$_{2.5}$ and surface area emissions indices for steady and start up conditions of cookstoves in Orissa. (*TB*- Index calculated for particle deposited in tracheobronchial region)

The amount of heat generated and the efficiency of the stoves depend on stoichiometric air/fuel ratio in the combustion chamber. Appropriate air/fuel ratio could result in less emissions and better stove performance. The WBT indicates that less time is required to boil the same amount of water compared to the stove without using fan. The PM$_{2.5}$ obtained was lower when using the fan (Index-0.47) compared to without fan conditions (Index- 0.79) but the SA index was higher (SA (TB) - 0.78) compared to the without fan condition (SA (TB) - 0.58). Better stove efficiency and low emissions are due to the increased supply of oxygen, which helped in proper burning of the fuel. This result provides an indication that maintaining a proper air/fuel ratio in the combustion chamber is important for better efficiency and lower emissions exposure.

The cookstove indices developed and applied in this paper will aid translating the findings of cookstove studies to a policy and cookstove dissemination intervention audience, such as
NGOs and government organizations. This paper shows that surface area concentration as a dose parameter in cookstove particulate emissions, is at least as important as the more common mass-based parameters, and that measures of PM$_{2.5}$ are not sufficient proxies for surface area concentration. Given that field-ready technology for sampling surface area concentration of cookstove particulate emissions is now available, future cookstove studies should also investigate this parameter. Further, more research is needed to directly investigate dose-response relationships between particulate surface concentration from cookstove emissions and the range of health impacts that have already been associated with particulate emissions from cookstoves. Although our study sites are both in India, the developments of this paper are applicable to any geographical setting in which the emissions and efficiency of rural cookstoves, household and commercial, are important issues.

Acknowledgements

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2.5 References


Chapter 3

3. Experimental Study of Different Fuel Properties on the Emission and Efficiency Measurements: A Parametric Study

3.1 Introduction

Present set of experiments were conducted to study the effect of varying fuel properties on the number concentration of the emitted particles, extent of combustion and also the surface area and mass concentration of these particles. These parameters help us identify the best possible form of fuel conditions that can be used in a stove to produce maximum efficiency with minimum emission factors. Laboratory analysis not always provide the exact information on the behavior of the stoves in the field conditions but they are a good tool to do parametric studies to find the best conditions in which the stove should be operated to yield maximum combustion efficiencies and minimum emissions. Previously Yuntenwi, et al (2008) [1] conducted studies to find the emission and the efficiency of the cookstoves on the basis of different moisture content in the biomass using the water boiling test. They found that combustion efficiency increased with the increase in moisture content in the fuel but decreased rapidly after a certain point. Extremely dry or wet fuel inhibits burning rate and
therefore lower the combustion efficiency. But they found that the type of stove was of primary concern rather than the moisture content of fuel. Roden et al (2009) [2] did both field and laboratory investigations to compare the emissions from both traditional and improved stoves. They found that the emissions from the field conditions were three times the emissions reported in the laboratory. The albedo factor was also very low for both the field and the laboratory conditions indicating that the particles are responsible for climate warming. The well designed improved stoves showed high combustion efficiency and reduced the emissions as compared to the traditional stoves, the single scattering albedo (SSA) was found to be unaffected by these stoves.

3.2 Experimental Analysis

3.2.1 Experimental Setup

![Experimental setup](image)

*Fig 3.1- Experimental set up- to do a parametric study on improved and traditional 3-stone stove*
The experiments were conducted inside a fume hood (fig 3.1) and the personal aerosol monitor, Nanoparticle aerosol monitor, SMPS and CO analyzer were used to study PM\(_{2.5}\), surface area, size distribution and CO concentration of the particles emitted from the cookstoves in the fume hood. Water boiling test was employed to study the combustion efficiency of the cookstove under different conditions.

![Fig 3.2- [A] Traditional/3 stone stove [B] Improved stove](image)

3.2.2 Types of Stove Used

3-stone construction and an improved stove (obtained from Orissa) were used to conduct the parametric study on these stoves (Fig 3.2). The three stone stove was constructed using three stones kept at 120° to each other. This provides free flow of air from all the sides in the stove leading to a big and uncontrollable fire. This is the most traditional form of cooking and requires no technology and involves very less or no cost at all. The main reasons for its popularity across the world includes its versatility, easy assembly, could be used for multiple purposes including cooking and heating, choice of any solid combustible material as a fuel and also any size of cooking pot can be used for cooking purposes, and
also acts as a focal point in social gatherings. The disadvantages of using this type of stove includes low efficiency, wastage of heat and the release of heavy smoke which may cause eye ailments and respiratory problems, and also the inefficient use of the already scarce fuelwood. Improved stoves were introduced in these communities in order to make efficient use of the fuel which will decrease the pressure on the local forests, reduce the emission of smoke and particulate matter, reduce the time and money spent to collect the fuel, and also create employment in these communities. Although, there have been multiple efforts to study and design the new improved stoves, they have not been success in the large part of the world. High cost and inefficient designs have resulted in the low acceptance rate in these parts of the world. The efficiencies obtained in the laboratory cannot be converted in the field conditions. Lack of maintenance and easy to breakdown have driven people to resort to their old traditional cooking practices. The traditional food items that are cooked on their traditional stoves cannot be cooked on the new improved stoves which discourage people from using clean cooking practices. It is often seen that the use of traditional stove along with the improved stove often negates the use of improved cookstove in a particular household.

3.2.3 Types/Size of Fuelwood Used

Hardwood oak was used to carry out the experiments with both the types of wood. Large sticks (30 x 2 x 2 cm) and small briquettes (2 x 2 x 2 cm) (Fig. 3.3) were used to study the effect of size on the combustion efficiency and also on the emissions from the improved
stove (Fig. 3.4). Emissions and efficiency were also measured as a function of the moisture content in the briquettes.

In many parts of the world, wood is the predominant source of fuel which is used for varied purposes. It is often seen that people collect large pieces of wood from the forest or buy it at a local market. The process is quite exhaustive, and it takes more than 2.5 hours daily after travelling for 4.8 km each day. To save time, women in the households do not prefer to cut wood into small pieces for maximum combustion efficiency. It is therefore essential to design the improved stove to use the large pieces of wood, which will not only save the time but also the money they spend to buy the small expensive wood.

*Fig 3.3 Large wood sticks and small briquettes of wood*

*Fig 3.4 Schematic representation of an improved stove for (a) long pieces of wood (b) small briquettes of wood*
3.2.4 Instruments Used

Different Instruments were used to study the emissions from the cookstoves at the breathing zone. Assuming that the women sit, when they cook and are at the same level as the top of the stove, emissions were collected at the breathing zone (where women usually sit while cooking). A Personal Aerosol Monitor (TSI SidePak AM510, TSI, Inc., St. Paul, Minnesota, USA) was used to collect the air samples coming from the combustion of the biofuels and fossil fuels from the cookstoves. This monitor works on the principle of scattering of light from the particles which in turn is converted into voltage by a photodetector which is proportional to the mass concentration of the particles. The monitor is potable and is operated by battery which makes it easy to operate. The surface area concentration of the particles was measured by Nanoparticle aerosol monitor (AEROTRAKTM 9000) which indicates the surface area of the nanoparticle aerosols that deposit in the lung in accordance with the curves published by international commission for Radiological protection (ICRP) for the tracheobronchial and alveolar regions of the respiratory tract. The particles are charged by counter flow diffusion charging and are measured by the electrometer. A microprocessor controls the instrument flows and measures various operational parameters and converts the electrometer measurement into surface area concentration in units of square micrometers per cubic centimeter ($\mu m^2/cc$).

Water boiling test (WBT) was used to measure the efficiency of different stoves. This standard test was performed in Orissa for the fixed amount of water and the time to boil was noted down. The different time required for the water to boil is shown in the table 2. High power test was conducted for the traditional stoves in Andhra Pradesh. The constant

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variables used for the study were Gross calorific value (HHV); Net calorific value (LHV); wood moisture content (m); Effective calorific value (ceff); dry weight of empty pot (P); weight of empty container for char (k) (grams); local boiling point of water (Tb) (deg C). These variables were measured before beginning the test. Assuming that the high power test reflects the efficiency of the particular stove, it was started using a given mass of the biomass (the stoves were started using a match stick for the LPG and Biogas stoves). Other variables included the measurement of the weight of the fuel before test (g) (fci), weight of pot with water before test (g) (Pci), water temperature before test (deg C) (Tci), time at the start of the test (min) (Tci), weight of the wood after the test (g) (Fcf), weight of the charcoal and container after the test (g) (cc), weight of pot with water after the test (g) (Pcf), water temperature after test (deg C) (Tcf) and time at the end of the test (min) (Tcf). The other variables that can be calculated are wood consumed (fcm), Net change in char (∆cc), and equivalent dry wood consumed (fcd). This is calculated using,

\[ Fcd = fcm \ast (1-(1.12\ast m))^{-1.5} \ast ∆cc \] (1)

The factor 1-(1.12*m) is required to adjust the amount of wood used to evaporate water from the moist wood, water vaporized (Wcv), time difference (∆tc) which is the time required to boil a certain amount of water. This was used to calculate the thermal efficiency of the stove [2].

Thermal efficiency is defined as the ratio of energy used to heat and evaporate the water in the pot to the energy released by the fuel. It is very often the misleading indicator of the efficiency of the stove because it may produce steam in order to achieve high efficiencies.
Thermal efficiency of the stove was calculated using the water boiling test [WBT] version 3.0, prepared by the Shell foundation [3].

The thermal efficiency (TE) of the stove is given by

$$TE = \frac{\frac{4.186(P_{ci}-P)(T_{cf}-T_{ci})+2260(w_{cv})}{f_{ed}\cdot LHV}}{G_{bci}/G_{bci}}$$

where,

TE is the thermal efficiency, $P_{ci}$ = mass of water, $T_{cf}$-$T_{ci}$= change in water temperature

### 3.2.5 Experimental Plan

The experiment was conducted to study the various parameters associated with fuel in the cookstoves. These are the type of the stove, type of the fuel, size of the fuel, moisture content of the fuel, sampling location, air-fuel ratio and the combustion efficiency. These parameters were studied for the traditional (3-stone) and improved stove. In Test #1, small briquettes of wood were burnt to study the effect of the type of stove on combustion and the emissions. PM$_{2.5}$, surface area concentration and CO were measured along with the size distribution of the particle. Water boiling test was conducted for each set of experiment to study the combustion efficiency under the given condition. In Test #2, the experiments were carried out for large sticks and small briquettes of wood. Emissions for this were also sampled at the breathing zone. In Test #3, small briquettes of wood of 15% and 35% moisture content were used to study the size distribution of the particles. In Test #4, small dry briquettes (15% moisture content was used to sample at the different heights from the ground level). The breathing zone was presumed to be at the same level as the top of the stove which was approximately 13 inches above the ground level. Subsequently, the
sampling location was changed to 20, 24 and 31 inches above the ground level. In Test #5, a fan was used to study the effect of change in the air fuel ratio on the size distribution of the particles. Small briquettes of wood were used in the improved stove to study the effect of increasing the air fuel ratio. Since, many new improved modifications of the stoves have introduced a small battery operated fan to improve their combustion efficiency; it would help us understand the effect of forcing air through the combustion chamber on the emissions.

### 3.3 Results and Discussion

#### 3.3.1 Change in Dose Parameters on the Basis of Stove Type and Size of the Fuel

Low PM$_{2.5}$ was observed for the improved stove in the presence of high moisture in the fuel. Contrary to this, high surface area concentrations were obtained for the particles emitted from the improved stoves. (Fig 3.5) This could have been due to the presence of high concentration of the ultrafine particles whose low mass are not reflected in the total mass concentration of the emissions. This indicates the importance of surface area as the dose parameter as was seen previously in the field studies. Fig 3.6 also indicates the high concentration of the particles in between 10-100 nm which remain unnoticed in the mass concentration studies suggestive of new dose parameter that should be used to analyze dose exposure studies. High CO was observed for the traditional stove as compared to the improved one which could have been due to poor air fuel ratio which led to the production of charcoal predominantly due to inefficient combustion and high rates of CO emissions [1].
Fig 3.5 Change in dose parameters for different types of stove and size and the moisture content of the fuel

Large wood also produced high PM$_{2.5}$, but there was no notable difference that was observed in the surface area concentrations. This could have been due to the poor supply of air within the chamber which resulted in inefficient combustion and therefore high rate of large sized particulate matter and CO concentrations. It was often observed that high PM$_{2.5}$ was often accompanied by high concentrations of CO indicating it being used as a proxy for the former [4], no such trend was observed for the surface area concentrations for both the tracheobronchial and the alveolar regions.
Fig 3.6- Change in number concentration of the particles for improved and the traditional stove

Large wood also showed high number concentration (Fig 3.7) for the particles in the nanometer range (10-100 nm) confirming the presence of ultrafine particles responsible for adverse health effects when compared to the small briquettes of stoves. It was also observed that the fire kept reaching the farther ends of the wood when in steady state and led to wastage of heat as compared to small briquettes where the fire was concentrated only in the combustion chamber without wasting heat to the surroundings.
Fig 3.7 Change in number concentration over a size range on the basis of the size of the wood

3.3.2 Change in Size Distribution of the Particles on Increasing/Decreasing the Moisture Content in the Wood

Previously, it was reported [1] that increase in the moisture content in the wood lead to an increase in the PM and CO concentrations. It was suggested that it could be due to the fire that is cooler in the presence of water and burns more slowly. Similar results were obtained in our study but the effect was pronounced in the case of the improved stove. Although PM concentrations were low in the improved stove in the presence of moist briquettes, high surface area concentration especially in the alveolar region was observed in the case of improved stove. It was also observed that increase in the moisture from 15% to 35% led to
an increase in the number of ultrafine particles (Fig 3.8) where high concentration of nanometer sized particles were released.

![Graph of size distribution and number concentration of particles with moisture content](image)

**Fig 3.8 Change in the size distribution of the particles with increase in the moisture content**

### 3.3.3 Change in Different Dose Parameters and Number Concentration of the Particles with the Height from the Stove

The top of the stove was about 13 inches above the ground level. To study the dispersion of the plume above the stove and its concentration at various levels above the ground, various measures were conducted at 13, 20, 24 and 31 inches above the ground level. It was observed that (Fig 3.9) low concentrations of mass and surface area concentrations were present at the same level as the stove. This could be because that the particulate matter and carbon monoxide are lighter than air and therefore rise up in the air. Higher concentrations
of the large and fine sized particles were observed at 20 inches. This could be attributed to
the rising emissions from the stove. It was indeed observed that after a while the particles
start getting dispersed and therefore lesser particles and low CO concentration was observed
at 24 inches above the ground level. It was surprising to see higher concentrations at 31
inches above the ground level. This could be due to the accumulation of large sized particles
which are not removed quickly or as fast as the fine and ultrafine particles and results in
higher mass concentration of the particles and surface area concentrations in the
tracheobronchial regions.

Fig 3.9- Change in the concentration of the dose parameters for different heights
above the stove
3.3.4 Change in Different Dose Parameters and Size Distribution of the Particles on the Basis of Air Fuel Ratio.

It is observed that increasing the air fuel ratio assists in combustion, which uses lesser fuel and results in cleaner combustion. People in rural areas use a hollow pipe to blow air inside the fire which results in accidental burns and other health related problems. In many versions of the improved cookstoves, a fan is used to improve the combustion efficiencies.

Fig 3.10- Effect of increasing air fuel ratio by forcing air in the combustion chamber

It was observed that forcing air inside the combustion chamber to improve the combustion efficiency of the cookstoves can lead to adverse health effects. The major factors of the biomass stoves which are responsible for poor health are the particulate matter, ash produced and the gases released due to the poor combustion. Fig 3.10 suggests that forcing the air inside the cookstoves increased the concentration of ultrafine particles five folds.
Another set of experiments were conducted to find if the ash particles were also responsible for high concentration observed in the previous experiment. It was observed that ash particles were a significant contributor to an increase in the particulate emissions. It is therefore essential to curb the ash particles within the combustion zone while designing new improved stoves for better efficiencies.

3.3.5 Combination of the Indices to Design an Integrated Index for Stoves

![Graph showing comparison of PM$_{2.5}$, emission Index, and Efficiency Index for different types of briquettes.](image)

**Fig 3.11- Comparison of PM$_{2.5}$, emission Index and Efficiency Index**
It was observed that low combustion efficiencies were observed for all the stoves except for the open fire where the combustion efficiency was found to be higher than the other stoves. The PM$_{2.5}$ for all the stoves except improved stove with dry wood briquettes showed high emission index. The moisture in the wood would have helped localize the fire which would have decreased the release of volatiles out of the combustion zone before burning. The emission indices were found to be the high for the improved stove using dry biomass due to high mass concentration and in the traditional stoves using moist wood. This shows that no one factor is responsible for high emissions. It is therefore important to study all the factors together in order to analyze the true effects of the emissions from the cookstoves. It was also observed that the integrated index for all the conditions was almost the same which suggest that the high combustion efficiency in the cookstoves was obtained at the expense of high emissions.

3.4 Summary and Conclusions

The experiments suggested that no single factor can determine the efficiency of the improved stove. It is important that all the factors are considered while designing new improved stove. High combustion does not necessarily indicate improvement in the stoves. The new improved stoves should also be designed keeping in mind the climate of the area which decides the moisture content in the fuel. Improved stoves when used for the moist fuel can result in increase in the emissions as compared to the traditional stove. The dispersion of the smoke above the stove can also be a factor that needs to be considered when designing new stoves. Change in the height of the stove above the ground can also
result in decrease of the emissions and lesser respiratory problems. It is therefore suggested that surface area can be used as a very important dose parameter while conducting new studies which would also assist in better understanding of the exposure dose relationships.

3.5 References


Appendix I – Instruments Used

SIDEPAK™ AM510 Personal Aerosol Monitor

Theory of Operation

Aerosol Monitor uses light scattering technology to determine mass concentration in real-time. An aerosol sample is drawn into the sensing chamber in a continuous stream. One section of the aerosol stream is illuminated with a small beam of laser light. Particles in the aerosol stream scatter light in all directions. A lens at 90° to both the aerosol stream and laser beam collects some of the scattered light and focuses it onto a photodetector. The detection circuitry converts the light into a voltage. This voltage is proportional to the amount of light scattered which is, in-turn, proportional to the mass concentration of the aerosol. The voltage is read by the processor and multiplied by and internal calibration constant to yield mass concentration. The internal calibration constant is determined from
the ratio of the voltage response of the SIDEPAK AM510 to the known mass concentration of the test aerosol.

Light scattering-type aerosol monitors respond linearly to the aerosol mass concentration. That is, for a monodisperse aerosol, one particle scatters a fixed amount of light; two particles scatter twice as much light; and 10 particles scatter 10 times as much light. The scattered light is dependent upon

**AEROTRAK™ 9000 Nanoparticle Aerosol Monitor**

**Theory of Operation**

The AEROTRAK 9000 Nanoparticle Aerosol Monitor is based on diffusion charging of sampled particles, followed by detection of the charged aerosol using an electrometer. An aerosol sample is drawn into the instrument continuously at a rate of 2.5 L/min. The flow is split with 1 L/min passing through two filters (a carbon and a HEPA) and an ionizer and 1.5 L/min of aerosol sample flow.

The flow streams are merged in a mixing chamber where particles in the aerosol flow mix with the ions carried by the filtered clean air. This patented *counter-flow diffusion charging* brings the aerosol particles into a defined, charged state. The separation of particles from direct interaction with the corona needle and/or the strong field near it reduces particle loss and makes the charging process more efficient and reproducible. The charged aerosol then passes through an ion trap to remove excess ions and charged aerosol. The aerosol then
moves onto an electrometer for charge measurement. In the electrometer, current is passed from the particles to a conductive filter and measured by a very sensitive amplifier. A microprocessor controls the instrument flows and measures various operational parameters and converts the electrometer measurement into surface area concentration in units of square micrometers per cubic centimeter ($\mu m^2/cc$)

**Thermo Electron Corporation**  
**Model 49i CO Analyzer**

This instrument was used to measure the real time concentration of Carbon monoxide emitted from the stoves. The instrument is based on the principle that CO absorbs infrared at the wavelength of 4.6 microns. Since it is a non linear measurement technique, it is essential that the basic analyzer signal is converted to a linear output. The instrument uses a calibration curve to convert the analyzer signal to the linear output upto 10,000 ppm.

**Model 3936 SMPS (Scanning Mobility Particle Sizer)**

It is essentially composed of three main units. These include the Electrostatic Classifier, Differential mobility analyzer (DMA) and the Condensation particle counter (CPC). This instrument measures the number size distribution of the particles using an electrical mobility detection technique. A bipolar charger in the classifier is used to the particles to a known charge the particles to a known size distribution. The particles are classified according to a known charge distribution using a differential mobility analyzer. These particles are the counted using a condensation particle counter (CPC)
Appendix II - NSAM Calibration Using SMPS

Objective: Calibration of NSAM (Nanoparticle Surface Area Monitor) using SMPS (scanning mobility particle sizer) for polydisperse combustion particles

Explanation: NSAM is used to measure the surface area of the particles in the tracheobronchial and the alveolar regions. The instrument is calibrated using a sodium chloride (NaCl) solution. The aerosols are then generated using a 0.01% sodium chloride solution with the size distribution centered at 60 nm. Long DMA is then used to generate monodispersed 80 nm particles which are then used to calibrate the instrument. The Model 3550 calibration constant is determined by running the monodispersed aerosol simultaneously between the SMPS and the Model 3550. The total surface area of the 80 nm particles determined by the SMPS is then multiplied by the lung deposition efficiency of 80 nm particles as determined by the ICRP lung deposition curve for a reference worker. A ratio of the Model 3550’s response to SMPS determined lung deposited surface area is the calibration factor. Verification of the calibration factor was determined using polydispersed sodium chloride aerosols. For each size the calibration factor is then determined (Fissan, 2007) using the ICRP deposition curves. The resulting calibration factor is then programmed into the NSAM to obtain the total surface area concentration.

This study was done in order to study the effect of polydispersed combustion particles on the calibration factor. Since, the calibration factor for the monodispersed sodium chloride particles is already programmed into the system, it is not possible to compare the values obtained for combustion particles and the standard aerosol particles. Instead the calibration
factor for the combustion aerosols was determined by comparing the NSAM and the SMPS data and calculated by finding the ratio of SMPS to NSAM data.

**Procedure:**

1) Using the surface area obtained for the polydispersed combustion particles, the total surface area was calculated for all the 64 channels. The total concentration is obtained by multiplying the obtained concentration with the deposition fraction for the tracheobronchial and the alveolar regions. Since, the concentration obtained are normalized with respect to the individual bins, the total concentration was obtained by adding the total surface area concentration for all the bins and then dividing the total by 64.

2) The surface area values obtained by NSAM were then compared with the surface area values for different fuel size, stove type and different moisture conditions.
### Results:

<table>
<thead>
<tr>
<th>Condition</th>
<th>Stove Type</th>
<th>Fuel Size</th>
<th>Moisture Content</th>
<th>SMPS</th>
<th>NSAM</th>
<th>SMPS/NSAM</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Improved</td>
<td>Large pieces of wood</td>
<td>Low moisture</td>
<td>1.53E+03</td>
<td>1.32E+04</td>
<td>6.75E+02</td>
<td>5.14E+03</td>
</tr>
<tr>
<td></td>
<td>Traditional</td>
<td>Small briquettes of wood</td>
<td>Low moisture</td>
<td>1.47E+03</td>
<td>1.21E+04</td>
<td>7.02E+02</td>
<td>2.66E+03</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
<td>High moisture</td>
<td>1.78E+03</td>
<td>1.60E+04</td>
<td>7.07E+02</td>
<td>4.80E+03</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Low moisture</td>
<td>1.53E+03</td>
<td>1.32E+04</td>
<td>6.75E+02</td>
<td>5.14E+03</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
<td>High moisture</td>
<td>3.60E+03</td>
<td>1.91E+04</td>
<td>9.63E+02</td>
<td>6.80E+03</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>SA(TB)</th>
<th>SA(A)</th>
<th>SA(TB)</th>
<th>SA(A)</th>
<th>SA(TB)</th>
<th>SA(A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Improved</td>
<td>1.53E+03</td>
<td>1.32E+04</td>
<td>6.75E+02</td>
<td>5.14E+03</td>
<td>2.27E+00</td>
<td>2.57E+00</td>
</tr>
<tr>
<td>Traditional</td>
<td>1.47E+03</td>
<td>1.21E+04</td>
<td>7.02E+02</td>
<td>2.66E+03</td>
<td>2.09E+00</td>
<td>4.55E+00</td>
</tr>
<tr>
<td>Large pieces of wood</td>
<td>1.78E+03</td>
<td>1.60E+04</td>
<td>7.07E+02</td>
<td>4.80E+03</td>
<td>2.52E+00</td>
<td>3.33E+00</td>
</tr>
<tr>
<td>Small briquettes of wood</td>
<td>1.53E+03</td>
<td>1.32E+04</td>
<td>6.75E+02</td>
<td>5.14E+03</td>
<td>2.27E+00</td>
<td>2.57E+00</td>
</tr>
<tr>
<td>High moisture</td>
<td>3.60E+03</td>
<td>1.91E+04</td>
<td>9.63E+02</td>
<td>6.80E+03</td>
<td>3.74E+00</td>
<td>2.81E+00</td>
</tr>
</tbody>
</table>
**Discussion:**

Asbach et al. (2009) studied the limitations and the extensions of lung deposited nanoparticles in the nanoparticle surface area and concluded that neither the particle concentration nor the particle material seem to affect the total surface area concentration. Both the deposition curves in the considered size range and the unipolar diffusion charging showed no distinct material dependency, so it was suggested that it could be safely assumed to predict the exact surface area concentration irrespective of the material of the particle. But the instrument is calibrated for the spherical particles and does not hold true for the particle aggregates. The discrepancies in the results suggest that the combustion particles may contain particle aggregates and therefore the calibration factor can change for different fuel properties (moisture content in this study). The surface area concentration was found to increase by approximately two times when measured using SMPS. This was found to be true for all the cases except where high moisture wood was used in an improved stove.
Appendix III - Field data

Linear Regression Report for PM$_{2.5}$ vs Surface area (A) [Field Data]

<table>
<thead>
<tr>
<th>Linear Regression</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data source: Data 2 in PM and SA</td>
</tr>
<tr>
<td>SA(A) = 0.141 + (0.783 * PM)</td>
</tr>
<tr>
<td>N = 56</td>
</tr>
<tr>
<td>Missing Observations = 70</td>
</tr>
<tr>
<td>R = 0.468</td>
</tr>
<tr>
<td>Rsqr = 0.219</td>
</tr>
<tr>
<td>Adj Rsqr = 0.205</td>
</tr>
<tr>
<td>Standard Error of Estimate = 0.199</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>Std. Error</th>
<th>t</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>0.141</td>
<td>0.0324</td>
<td>4.35</td>
</tr>
<tr>
<td>PM</td>
<td>0.783</td>
<td>0.201</td>
<td>3.894</td>
</tr>
</tbody>
</table>

Analysis of Variance:

<table>
<thead>
<tr>
<th>DF</th>
<th>SS</th>
<th>MS</th>
<th>F</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regression</td>
<td>1</td>
<td>0.601</td>
<td>0.601</td>
<td>15.16</td>
</tr>
<tr>
<td>Residual</td>
<td>54</td>
<td>2.141</td>
<td>0.0396</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>55</td>
<td>2.742</td>
<td>0.0498</td>
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</table>

Normality Test (Shapiro-Wilk) Failed (P = <0.001)

Constant Variance Test: Passed (P = 0.328)

Power of performed test with alpha = 0.050; 0.959
## Linear Regression Report for PM$_{2.5}$ vs Surface area (TB) [Field Data]

<table>
<thead>
<tr>
<th>Linear Regression</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Data source: Data 2 in PM and SA correlation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SA(TB) = 0.134 + (0.635 * PM)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>N = 58</td>
<td>Missing Observations = 68</td>
<td></td>
<td></td>
</tr>
<tr>
<td>R = 0.381</td>
<td>Rsqr = 0.145</td>
<td>Adj Rsqr = 0.130</td>
<td></td>
</tr>
<tr>
<td>Standard Error of Estimate = 0.217</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>Std. Error</th>
<th>t</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>0.134</td>
<td>0.0348</td>
<td>3.845</td>
</tr>
<tr>
<td>PM</td>
<td>0.635</td>
<td>0.206</td>
<td>3.082</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Analysis of Variance:</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>DF</td>
<td>SS</td>
<td>MS</td>
<td>F</td>
</tr>
<tr>
<td>Regression</td>
<td>1</td>
<td>0.446</td>
<td>0.446</td>
</tr>
<tr>
<td>Residual</td>
<td>56</td>
<td>2.627</td>
<td>0.0469</td>
</tr>
<tr>
<td>Total</td>
<td>57</td>
<td>3.073</td>
<td>0.0539</td>
</tr>
</tbody>
</table>

| Normality Test (Shapiro-Wilk) | Failed | (P < 0.001) |
| Constant Variance Test: | Passed | (P = 0.131) |

| Power of performed test with alpha = 0.050: 0.845 | | | |
### Linear Regression Report for PM_{2.5} vs Surface area (A)

#### [Theoretical Data]

<table>
<thead>
<tr>
<th>Linear Regression</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Data source: Data 3 in PM and SA correlation</td>
<td></td>
</tr>
<tr>
<td>( SA(A) = 0.215 + (0.220 \times PM) )</td>
<td></td>
</tr>
<tr>
<td>( N = 66 )</td>
<td></td>
</tr>
<tr>
<td>( R = 0.304 )</td>
<td>( \text{Rsqr} = 0.0925 ) ( \text{Adj Rsqr} = 0.0784 )</td>
</tr>
<tr>
<td>Standard Error of Estimate = 0.254</td>
<td></td>
</tr>
<tr>
<td>Coefficient</td>
<td>Std. Error</td>
</tr>
<tr>
<td>Constant</td>
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</tr>
<tr>
<td>PM</td>
<td>0.22</td>
</tr>
<tr>
<td>Analysis of Variance:</td>
<td></td>
</tr>
<tr>
<td>DF</td>
<td>SS</td>
</tr>
<tr>
<td>Regression</td>
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</tr>
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<td>Residual</td>
<td>64</td>
</tr>
<tr>
<td>Total</td>
<td>65</td>
</tr>
<tr>
<td>Normality Test (Shapiro-Wilk)</td>
<td>Failed</td>
</tr>
<tr>
<td>Constant Variance Test:</td>
<td>Passed</td>
</tr>
<tr>
<td>Power of performed test with alpha = 0.050: 0.703</td>
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</tr>
</tbody>
</table>
# Linear Regression Report for PM\textsubscript{2.5} vs Surface area (TB)

[Theoretical Data]

<table>
<thead>
<tr>
<th>Linear Regression</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Data source: Data 2 in PM and SA correlation</td>
<td></td>
</tr>
</tbody>
</table>

\[
\text{SA(TB)} = 0.134 + (0.635 \times \text{PM})
\]

<table>
<thead>
<tr>
<th>(N = 58)</th>
<th>Missing Observations = 68</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>(R = 0.381)</th>
<th>Rsqr = 0.145</th>
<th>(\text{Adj R}sqr = 0.130)</th>
</tr>
</thead>
</table>

Standard Error of Estimate = 0.217

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>Std. Error</th>
<th>(t)</th>
<th>(P)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>0.134</td>
<td>0.0348</td>
<td>3.845</td>
</tr>
<tr>
<td>PM</td>
<td>0.635</td>
<td>0.206</td>
<td>3.082</td>
</tr>
</tbody>
</table>

Analysis of Variance:

<table>
<thead>
<tr>
<th></th>
<th>DF</th>
<th>SS</th>
<th>MS</th>
<th>(F)</th>
<th>(P)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regression</td>
<td>1</td>
<td>0.446</td>
<td>0.446</td>
<td>9.501</td>
<td>0.003</td>
</tr>
<tr>
<td>Residual</td>
<td>56</td>
<td>2.627</td>
<td>0.0469</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>57</td>
<td>3.073</td>
<td>0.0539</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Normality Test (Shapiro-Wilk) Failed \(P = 0.001\)

Constant Variance Test: Passed \(P = 0.131\)

Power of performed test with alpha = 0.050: 0.845
## Indices for Andhra Pradesh

<table>
<thead>
<tr>
<th>Method</th>
<th>PM2.5</th>
<th>PM2.5 Standard Deviation</th>
<th>SA (TB)</th>
<th>SA (TB) standard deviation</th>
<th>SA (A)</th>
<th>SA (A) standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-Stone</td>
<td>0.1109</td>
<td>0.1703</td>
<td>0.5591</td>
<td>0.32</td>
<td>0.4196</td>
<td>0.0541</td>
</tr>
<tr>
<td>traditional (no chimney)</td>
<td>0.1503</td>
<td>0.1564</td>
<td>0.2147</td>
<td>0.2008</td>
<td>0.2409</td>
<td>0.1552</td>
</tr>
<tr>
<td>traditional (with chimney)</td>
<td>0.1185</td>
<td>0.1564</td>
<td>0.1432</td>
<td>0.1584</td>
<td>0.235</td>
<td>0.2526</td>
</tr>
<tr>
<td>traditional (outdoors)</td>
<td>0.1286</td>
<td>0.1269</td>
<td>0.4904</td>
<td>0.2619</td>
<td>0.3541</td>
<td>0.298</td>
</tr>
<tr>
<td>Improved</td>
<td>0.5616</td>
<td>0.3574</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kerosene</td>
<td>0.0922</td>
<td>0.1347</td>
<td>0.2905</td>
<td>0.0432</td>
<td>0.0315</td>
<td>0.0255</td>
</tr>
<tr>
<td>Biogas</td>
<td>0.0205</td>
<td>0.0512</td>
<td>0.0358</td>
<td>0.0442</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

## Indices for Orissa

<table>
<thead>
<tr>
<th>Method</th>
<th>PM2.5 Index</th>
<th>Surface area Index (TB)</th>
<th>Surface area Index (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traditional (wood)</td>
<td>0.4787</td>
<td>0.5902</td>
<td>0.3207</td>
</tr>
<tr>
<td>Traditional (coal)</td>
<td>0.0143</td>
<td>9.89E-03</td>
<td>0</td>
</tr>
<tr>
<td>Improved</td>
<td>0.6088</td>
<td></td>
<td>0.4406</td>
</tr>
<tr>
<td>Kerosene</td>
<td>0.0207</td>
<td>0.195</td>
<td>0.1967</td>
</tr>
<tr>
<td>Biogas</td>
<td>0.0377</td>
<td>0.0339</td>
<td>0.8767</td>
</tr>
<tr>
<td>Commercial (wood)</td>
<td>0.1496</td>
<td>0.231</td>
<td>0.154</td>
</tr>
<tr>
<td>Commercial (coal)</td>
<td>0.0348</td>
<td>8.85E-03</td>
<td>0.5183</td>
</tr>
<tr>
<td>LPG</td>
<td>0.0109</td>
<td>0.0113</td>
<td>0.0442</td>
</tr>
</tbody>
</table>
## Indices for Start Up and Steady State in Orissa

<table>
<thead>
<tr>
<th></th>
<th>PM index (start up)</th>
<th>PM index (steady state)</th>
<th>Surface area index (TB) (start up)</th>
<th>Surface area Index (TB) (steady state)</th>
</tr>
</thead>
<tbody>
<tr>
<td>traditional (wood)</td>
<td>0.2417</td>
<td>0.4787</td>
<td>0.3806</td>
<td>0.5902</td>
</tr>
<tr>
<td>traditional (coal)</td>
<td>0.0403</td>
<td>0.0143</td>
<td>0.4647</td>
<td>9.89E-03</td>
</tr>
<tr>
<td>Improved commercial (wood)</td>
<td>0.3145</td>
<td>0.6088</td>
<td>0.0886</td>
<td></td>
</tr>
<tr>
<td>Commercial (coal)</td>
<td>0.3232</td>
<td>0.1496</td>
<td>0.3568</td>
<td>0.231</td>
</tr>
<tr>
<td>Commercial (coal)</td>
<td>0.832</td>
<td>0.0348</td>
<td>0.5225</td>
<td>8.85E-03</td>
</tr>
</tbody>
</table>
# Appendix IV - Experimental Data

<table>
<thead>
<tr>
<th>Test #</th>
<th>Stove types</th>
<th>Fuel type</th>
<th>Sampling Location</th>
<th>Condition</th>
<th>PM$_{2.5}$</th>
<th>SA (TB)</th>
<th>SA(A)</th>
<th>CO</th>
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<tbody>
<tr>
<td>1</td>
<td>Improved stove</td>
<td>Large sticks of wood</td>
<td>Breathing zone</td>
<td>Start up</td>
<td>0.86</td>
<td>0.19</td>
<td>0.14</td>
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<td></td>
<td>steady state</td>
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<td>0.20</td>
<td>0.18</td>
<td>0.21</td>
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<tr>
<td>2</td>
<td>Improved stove</td>
<td>small dry briquettes of wood</td>
<td>Breathing zone</td>
<td>start up</td>
<td>0.54</td>
<td>0.18</td>
<td>0.19</td>
<td>0.12</td>
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<td>steady state</td>
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<td>0.26</td>
<td>0.37</td>
<td>0.19</td>
</tr>
<tr>
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<td>Breathing zone</td>
<td>start up</td>
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<td>0.18</td>
<td>0.09</td>
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<td>Improved stove</td>
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<td>Breathing zone</td>
<td>start up</td>
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<td>0.18</td>
<td>0.19</td>
<td>0.27</td>
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</table>
Vita

Vidhi Singhal

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Place of Birth  New Delhi, India

Degrees  B.S. in Chemistry(H), May 2006
          M.Sc. in Environmental Sciences, May 2008
          M.S. in Energy, Environmental and Chemical Engineering, August 2010


            Manoranjan Sahu, John Peipert, V.Singhal, Pratim Biswas, and Gautam Yadama. Establish the energy efficiency index and respiratory air quality Index for different kinds of stoves, Environment Science and Technology (to be submitted)


August 2010