# DESIGN MODIFICATIONS AND COMPARATIVE STUDY OF DIFFERENT BIOMASS COOKSTOVES

*A dissertation submitted in the partial fulfillment of the requirement for the award of the Degree of*

**Master of Technology**
**in**
**Environmental Science and Technology**

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# DECLARATION

I hereby declare that the dissertation entitled **"DESIGN MODIFICATIONS AND COMPARATIVE STUDY OF DIFFERENT BIOMASS COOKSTOVES"**, is an authentic record of my own work carried out by me as a requirement for the award of the degree of Master of Technology in Environmental Science at Thapar University, Patiala. This work was carried out by me under the joint supervision of **Dr. S. K. Tyagi** Scientist 'E', Sardar Swaran Singh National Institute of Renewable Energy, Kapurthala, Punjab and **Mr. K. S. Babu** Assistant Professor, School of Energy and Environment, Thapar University, Patiala, Punjab.

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# CERTIFICATE

This is to certify that the dissertation entitled, "**DESIGN MODIFICATIONS AND COMPARATIVE STUDY OF DIFFERENT BIOMASS COOKSTOVES**", is an authentic record of work carried out by Mr. Karmvir Singh Rana at Sardar Swaran Singh National Institute of Renewable Energy, Kapurthala, Punjab under our joint guidance in partial fulfillment for the award of the degree of Master of Technology in Environmental Science from Thapar University, Patiala, Punjab.

To the best of our knowledge, the matter embodied in this dissertation has not been submitted to any other University/Institute for the award of any degree or diploma.

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# NOMENCLATURE

| | |
|---|---|
| ICPs | Improve cookstove programs |
| RSPM | Respirable suspended particulate matter |
| TNMHC | Total non-methane hydrocarbons |
| TSP | Total suspended particulates |
| NBCI | National biomass cookstove initiative |
| PIC | Particulate inorganic carbon |
| Mmt | Million metric tons |
| IEA | International energy agency |
| PAHs | Polycyclic aromatic hydrocarbons |
| IAP | Indoor air pollution |
| IAQ | Indoor air quality |
| WBT | Water boiling test |
| KPT | Kitchen performance test |
| AQGs | Air quality guidelines |
| BIS | Bureau of Indian standards |
| SSS-NIRE | Sardar Swaran Singh National Institute of Renewable Energy |
| ASTM | American Society for Testing and Materials |
| CDM | Clean development mechanism |

| | |
|---|---|
| g | Gram |
| g/cc | Gram/cubic Centimetre |
| h | Hour |
| K | Temperature in Kelvin scale |
| Min | Minutes |
| °C | Temperature in Centigrade |
| kJ/mol | Kilo Joules per mole |
| $\eta$ | Energy Efficiency |
| $\Psi$ | Exergy Efficiency |
| kW | kilo Watt |
| P | Power |
| R | Gas Constant |
| C | Carbon |
| H | Hydrogen |
| N | Nitrogen |
| O | Oxygen |
| S | Sulfur |

# ABSTRACT


In the developing countries including India most of the population lives in rural areas depends on biomass especially wood, cow dung, charcoal, etc., for cooking purposes. Approximately half a million premature deaths and nearly 500 million cases of illness are estimated to occur annually as a result of exposure to smoke and harmful emissions coming from biomass combustion. As per World Health Organization (WHO) report, indoor air pollution is the third leading health risk affecting the people directly and indirectly especially, women and female children in the rural areas around the globe.

In order to address the above said problems associated with traditional cookstove models available to the common people, few cookstove models were designed and fabricated during this study. The designed cookstove models include, the modified traditional and improved cookstoves, besides, other models available in the market. The concept of energy and exergy analysis was applied to all the models and following conclusions are made:

- The energy, exergy efficiencies and power output of the modified traditional cookstove (NIRE-02) were found to be the highest with top spacing. However, it was found that this cookstove model exhibits the best performance when grate with top spacing is provided.
- The maximum value of energy efficiency, exergy efficiency and power output was found for the improved (NIRE-03) model with optimum insulation without wick.
- The analysis for emission exhibits that the improved cookstove model reduces 2.45 Ton of CO2/household/year while, it was found to be 2.1 Ton in the case of the modified traditional model.
- It was also found that both the models (NIRE-02 model and NIRE-03) exhibit better performance than those of the traditional cookstove models being used by the common public in the country.
- Also the improved cookstove model (NIRE-03) exhibits better combustion and higher performance than that of the modified traditional cookstove (NIRE-02).
- When the different wood samples were evaluated by proximate, ultimate and Thermo-gravimetric analysis, mixed results were obtained but sagwan (*tectona grandis*) exhibits the better results than those of the other wood samples (Shhesham, Mango, Eucalyptus, etc.) used in this study.

# CHAPTER 1

# INTRODUCTION

## 1.1 Background

The historical evidences of fire have been found as old as four lakh years i.e. during the first ice age [1]. One lakh years ago in the early part of the upper Paleolithic period the first evidence of cooking was found. However at that time the cooking took place over an open fire and was basically used to roast the meat. Mastery of fire is considered to be an important step toward human civilization which took off only about 12,000 years ago [2]. First evolution in cookstove took place when open fire cooking was replaced with three stone fire arrangement in which three stones were arranged at approximately 120 degrees from one another. Three stone fire arrangement had many drawbacks like dispersion of flames and heat during windy conditions. Exposure to heat as well as fire hazards besides the problem of low efficiency of three stone fire arrangement, As a result the requirement for a better cookstove arose which gave rise to U-shaped mud cookstove/traditional cookstove. The traditional cookstoves solved many of the technical problems such as, enhancement of thermal efficiency by many folds. However, the health, socio-economic and cultural problems were not solved completely.

Efforts were made to develop efficient cookstoves at International level in the 1940s [3]. However, in India the work on improved biomass cookstoves started during 1950s with the main objective to improve the design of biomass-fired stoves and the extensive R&D started in 1970s. Later on, improved cookstove programs (ICPs) were considered as a solution to the fuel wood crisis and to reduce deforestation and/or desertification. The improved multiport stoves were introduced by Raju (1953) which were of the high-mass and shielded-fire type, had a chimney to remove smoke and adjustable metal dampers to regulate the fire. Theodorovie (1954) conducted first controlled laboratory tests on biomass burning ICS in Egypt. Singer (1961) in Indonesia conducted cookstove efficiency tests on high mass mud stove with the main objective was to increase efficiency and save fuel, while socio-economic and cultural aspects were not undertaken [4]. However, in 1990s the focus shifted more on the issues involving the Indoor air pollution and its effect on human health [6].

In addition to above factors, the comfort of cooking, smoke free kitchens, convenience and safety of stove users were tested and considered to be the important aspects as compared to the fuel savings. Smith et al. [7] stated that the burning of biomass fuels emits high levels of smoke, containing hazardous pollutants such as respirable suspended particulate matter (RSPM), carbon dioxide ($CO_2$), carbon monoxide (CO), nitrogen oxides ($NO_x$), sulfur oxides ($SO_x$) and some cancer causing organic compounds like Benzopyrene, benzene and 1,3-Butadiene. Fullerton et.al [8] found that different types of health risks were associated with the Indoor air pollution such as, respiratory infections like e.g. pneumonia, tuberculosis, chronic obstructive pulmonary disease, birth defects, cataracts, cardiovascular events which cause serious problems in the household. Kleeman et al. [9] studied the adverse health impacts of the particle size distribution and result of deposition of those pollutants in different areas of lungs. Venkatraman et al. [10] stated that the biomass fuels had a heavy burden of time and money on the world's poorest population.

Keeping the above facts in mind, India has launched the initiated a National level program to develop next-generation cleaner cookstoves and deploy them to the households where traditional cookstoves being used for cooking and heating applications. The initiative has set itself the lofty aim of providing energy service comparable to clean sources like LPG without changing the fuels. Based on National surveys, published literature and assessments, and measurements of cookstove performance around the globe, it was found that about 570,000 premature deaths in poor women and children and over 4% of India's estimated greenhouse emissions could be avoided if such an initiative were in place. Although, the current advanced biomass stoves show substantial emissions reductions over the traditional stoves but there is a lot to be done to reach the LPG-like emission levels.

WHO has estimated that every year indoor air pollution (IAP) is responsible for the death of 1.6 million people around the globe which comes out to be one death every 20 seconds.It was further estimated that the exposure to smoke from simple act of cooking constitutes the fifth worst risk factor for disease in the developing countries and causes almost two million premature deaths per year, exceeding the deaths attributable to malaria or tuberculosis [11]. Ramanathan and Carmichael [12] recently found that the black carbon is playing a major role in global warming. In 1991 the Bureau of Indian Standards (BIS) issued a standard on solid biomass Cookstove under Annex 2 which gave the detailed scientific guideline for performing the water boiling test (WBT) to find out the thermal efficiency, $CO/CO_2$, solid particulate matter (SPM) and power output of a cookstove. Government of India launched national biomass cookstove initiative (NBCI) in 2009 to develop next generation cleaner biomass cookstoves and to deploy them to all Indian households replacing the traditional cookstoves. Using National surveys, published literature and assessments, and measurements of cookstove performance solely from India, It was found that about 570,000 premature deaths of poor women and children and over 4% of India's estimated greenhouse emissions could be avoided, if such an initiative were in place today.

Zhang et al., [13-15] reported a comprehensive database for CO emission ratios and CO emission factors respectively, for both per-fuel mass basis and per-cooking-task basis. Further, the estimation of CO concentrations and exposures were also presented in a hypothetical village kitchen resulting from the use of a range of fuels with different cookstoves, commonly used in the developing countries. The emission factors for different combinations of fuel and stove tested in China for direct and indirect GHGs as well as other airborne pollutants such as, $CO_2$, CO, $CH_4$, TNMHC, $N_2O$, $SO_x$, $NO_x$, TSP etc. for a typical set of operating parameters [15].

The Global Alliance for Clean Cookstoves (GACC), a new public–private partnership led by the UN Foundation was established to create a thriving global market for clean and efficient household cooking solutions [16]. The newly cookstoves which are known as advanced biomass cookstoves are based on better design principles; they have the better combustion efficiency and thus, reduce the fuel consumption to a greater extent. These cookstoves can deal with both the emissions and health issues resulting from cooking with open fires or traditional biomass cookstoves. These cookstoves have the ability to get carbon credits [17], not only because of their contribution to climate-change mitigation but also they can yield major co-benefits in terms of energy access for the poor people. Although, the current advanced biomass stoves show substantial emissions reductions over the traditional stoves, yet more improvements are needed to reach the LPG-like emission levels.

## 1.2 Objectives

Keeping the above aspects and concerns in mind, an extensive literature survey was carried out on different aspects of biomass cookstoves with the following objectives:

- To study the problems related to traditional cookstoves in rural India.
- To find out the problems in the existing cookstoves being used by rural population in the country.
- To modify traditional biomass cookstove to make it more efficient and less pollution producing device for end users.
- To design and develop highly efficient improved biomass cookstove based on down-draft gasifier principle having less environmental pollution.

- To perform energy and exergy analysis, emission reduction analysis of the fabricated cookstove and other cookstoves present in the market and to perform their comparative performance analysis.

## 1.3 Organization of Thesis

Thesis has been organized into five chapters and the brief information of each chapter is given below:

**Chapter 1: Introduction**

This chapter deals with the general introduction to biomass cookstoves, objectives and the chapter wise presentation of the thesis.

**Chapter 2: Literature Review**

In this chapter literature the review is performed starting from the history of cookstoves and gradually showing all the advancement in literature taking place till recent time. The design methodology for building improved biomass cookstoves, environmental, health and socio-economic impacts of biomass cookstoves are also covered.

**Chapter 3: Materials and Methods**

In this chapter, the detailed information of the materials and methods used in the study is given. All the information about the different instruments used in this study are also given in this chapter.

**Chapter 4: Result and Discussions**

In this chapter, the results are shown and explained in detail along with the comparative study of different cookstove models.

**Chapter 5: Conclusion and Recommendations**

This is the last chapter of the thesis. In this chapter several conclusions based on the results are briefly given by following the recommendations for further study.

**References**

The relevant references of the literature survey are also given in the end of the thesis.

# CHAPTER 2

# LITERATURE REVIEW

## 2.1 Introduction

The human civilization has started by making the use of refined stones and the mastery of fire and the domestication of several animals and cultivation of plants started [1]. With the developments of the shielded-fire, the three stone fire gradually changed into a U-shaped mud enclosure. However, earlier innovations have increased the cooking efficiency of various systems to an extent but the health and environmental hazards could not be considered due to lack of awareness [2]. All the cookstoves developed during early time (i.e. before 17$^{th}$ century) were called as 'traditional cookstoves' because their thermal efficiencies were very low, material of construction were poor and emitted very high level of smoke.

The developments of biomass based cookstoves started in India in the early 1940s, these cookstoves were called as improved mud cookstoves or first-generation flued (FGF) cookstoves[18]. The first improved mud cookstove named 'Magan Chulha' [3] was developed during 1947 in India. These improved multi pot mud cookstoves were introduced by Raju [19] for rural households. Theodorovic [20] conducted the laboratory tests on biomass burning improved cookstoves in Egypt in 1954. Singer [21] measured the efficiency of improved multi-pot cookstove in Indonesia during 1961 which was originally developed by Raju [19]. In these improved cookstoves, a chimney was provided to remove smoke from the kitchen; however, they were made up of high-mass and had adjustable metal dampers to regulate the air-fire control system.

The next wave of improved cookstoves appeared during the 1970s when global attention was turned to environmental and energy conservation. A number of models of improved wood-burning cookstoves (ICS) known as second generation flued cookstoves (SGF) had been developed. As these cookstove were designed and fabricated based on engineering principles and hence, were the more efficient. The aim was to increase the fuel efficiency with the reason that they would decrease the fuel consumption as it was necessary to prevent deforestation as well to lessen the drudgery and/or expense of procuring the cooking fuel with the emphasized on smoke reduction. Finally, the second generation unflued (SGU) cookstoves were developed to raise fuel utilization through improved combustion and heat transfer efficiency. Due to improved combustion the emissions per dish would be less and hence, lower emissions produced [22].

The higher thermal efficiency was achieved with the use of baffles, dampers and smoke reduction in kitchen premises with the help of a chimney; however, the dampers were not used by women resulting in consumption of more fuel due to free access of air in the fire box. The main reason behind it was that the dampers were metallic, caused burn injuries and it was difficult for women to use it properly during cooking. Keeping in mind the difficulties faced by the rural women, the damper-less cookstoves were later developed [23]. The poor people could not afford or obtain modern stoves and fuels so it was emphasized to develop more efficient, energy-saving, and inexpensive biomass stoves which could help to alleviate pressure on wood resources, shorten the walking time required to collect fuel, reduce cash outlays necessary for purchased fuel wood or charcoal, and diminish the pollution released into the open environment. The potential benefits of modern, efficient biomass stoves had been obvious since the first discussions of the "fuel wood crisis," and many Programs had been undertaken to make improved biomass stoves available to potential users and the stoves had been disseminated widely. The attempts to assess the very diverse and mixed success of the hundreds of stove Programs that had been implemented worldwide [24].

In the recent decades, various agencies including NGOs had been working towards the dissemination of the improved biomass cookstoves although the improved cookstoves disseminated were not much in numbers as compared to the numbers of households targeted in these programs. The major difficulty that encountered in the cookstove disseminated i.e. not adopting the improved cookstove by the rural households was that they used locally available material for making their traditional cookstove hence no expenditure on fuel and cookstove maintenance. Therefore, NGOs and other agencies involved in dissemination Programs had to establish reliable systems for the production, distribution and installation of improved stoves. The Kenya's Maendeleo stove program was the only one Program that had established itself as self-sustaining system. The future prospects of the dissemination programs could be better by increasing awareness of the health benefits of improved cookstoves [25].

Tukana and Lloyd [26] studied the cooking habits and wood stove cooking experience of typical rural villages of Fiji. They concluded that the current stoves were more efficient than open fire, so, they emphasized on providing more accessible fuel to the households and the kitchen environment. Smith et al. [27] examined the 'Chinese National Improved Stove' program that introduced approximately 129 million improved biomass cookstoves into rural areas during 1982-92. China's National Improved Stove program was a successful program for improved cookstoves because more than 100 million improved cookstoves are still in use; this program was implemented by the county's rural energy and other agencies. This program was focused on energy efficiency and household smoke removal with the help of chimney cookstoves. Although this program was no longer funded, but the private sector has produced stove components that lead the way to the development of more efficient and less polluting cookstove models [6].

In India, Ministry for New and Renewable Energy (MNRE), earlier known as Department of Non-conventional Energy Sources (DNES) launched a National Program on Improved Chulhas (NPIC) in 1985–1986. The program was started with the following objectives (i) reduction of deforestation through fuel wood conservation and smoke; (ii) reduction in the drudgery of tasks performed by women and children; (iii) health hazards due to exposure to smoke; and (iv) employment generation in rural areas. More than 60 fixed and portable type models, with and without chimney, single-pot and multi-pot, suitable for different fuels, cooking habits and local requirements and using different materials of construction of improved chulhas were developed and installed under this program. A total of 33.8 million improved chulhas have been installed and this program was formally declared closed in year 2004 [28].

The end users wanted more versatility in fuel usage and less time in cooking, but the improved mud cookstove were designed by the institutions on the objective of fuel economy and less smoke while the rural people were not concerned much about the cooking fuels and deforestation. The non-replacement of traditional stoves with the improved stoves also influenced by was socio-cultural factors and other benefits such as, space heating by traditional stoves. For the success of an improved cookstove program depend on the assessment surveys, proper monitoring and evaluation [4].

The greater research was undertaken through detailed studies on thermodynamic, heat transfer and aerodynamic to develop more efficient design principles along with the systematic testing and design procedures for cookstoves after 1970s [2]. Micuta [29] gave design principles, procedure and idea of placing a short chimney above fire to reduce the harmful emissions in 1985. Winiarski [30] developed various design principles to improve combustion and heat transfer efficiency in 1980 and developed famous 'Rocket stove'. Many cookstoves have been based on their design principles some of them are HELPS plancha stove in Guatemala, PROLENA EcoStove in Nicaragua, GTZ cooking stoves in Africa Justa stove in

Honduras etc. [31]. Baldwin [32] also carried out a detailed work and gave the concept of pot skirt and various design principles for designing the improved cookstoves (ICS). Reed [33] developed the concept of micro-gasification in 1985 and it has been the base for the development of gasifier and pyrolytic gasifier stoves.

Using energy efficient and clean-burning cookstoves is one of the means that can help to achieve the objective to halve the number of people without access to modern cooking fuels by 2015. The commitment of donors and the public sector therefore will play a critical role. The dissemination of cookstoves requires public sector investment it may be International and/or National. The public finances should be used for capacity development through awareness Programs for further technological development and researching appropriate dissemination strategies. Besides, a supportive political frame-work is necessary for disseminating the biomass cookstove for sustainable development.

The case of Uganda has proven that the large-scale introduction of cookstoves is possible. During the last decades many development projects have more or less successfully introduced improved stoves that burn biomass efficiently and thus reduce emissions and consumption of resources. However, scaling-up still remains the major challenge. In the 1980s, dissemination strategies mainly focused on self- help approaches or distribution of stoves for free. Experiences have shown that these approaches were not always supportive for the construction of high quality stoves thus evoking a negative image of stoves that break easily, are not worth spending money on them and in consequence are not used. Due to weak or non-existing markets, public investment from national governments, international donor organisations or NGOs is needed in the beginning to support setting up a business oriental market. The knowledge and awareness raising are important to increase the demand for improved cookstoves, thus, production and marketing of cookstoves are required [34].

Bazilian et al. [35] described the emerging public-private partnerships in the field of modern fuels and improved cookstoves to provide the modern cooking fuel to the poor people in the developing countries for their social and economic development.As mentioned earlier, some improved cookstove Programs were based on the user preferences, smoke reduction from kitchen premises only, distribute stoves of locally available material, now feels the improvement in the cookstoves. So, the new efforts have been done worldwide. The awareness about adverse health impacts due to incomplete combustion of biomass had increased with a need to take effective steps to improve indoor air quality in the rural households by providing cleaner cooking options such as improved cookstoves. Due to the increasing concerns about the climate change and outdoor air quality, it is not sufficient to remove the smoke from the kitchen only using a chimney but also there is a need for providing biomass burning cookstoves with cleaner combustion which emit low level of emissions and easily accessible to the common people at affordable price.

In view of the above, the Ministry of New and Renewable Energy, Govt. of India launched a new Program in 2009 called 'National Biomass Cookstoves Initiative (NBCI)' to facilitate the development of the next generation biomass stoves for household and community cooking and their widespread dissemination to get the benefits of health, mitigation of climate change and energy conservation [29]. There is scope for further supporting the technical development of a wide array of cookstove types and facilitating their innovation to meet performance standard benchmarks. One could encourage the development of a wide variety of low-cost or expensive cookstoves that meet certain minimum standards and expand their marketability, as already initiated by the World Bank in Africa [35] and also proposed under India's new biomass cookstove initiative [36].

## 2.2 Recent Work

Widely accepted standards and testing protocols are needed to qualify advanced biomass cookstoves as safe, durable, efficient, and clean burning. Since much of this work will involve the private sector, the International finance corporation (IFC), with its ability to provide private companies loans and technical assistance directly, could play a significant role in strengthening the emerging cookstove companies and manufacturers, as well as supporting the process of performance-based cookstove certification. The goal would be to facilitate the adoption of better stoves through promotion of businesses for designing, producing, and marketing of improved and valued cookstoves. Some of the world's major manufacturers and an increasing number of foundations including NGOs have involved in the development of improved and advanced biomass cookstoves. These include the Shell Foundation, Phillips, Appropriate Rural Technology Institute *(*ARTI), Technology Informatics and Design Endeavours (TIDE) and others [28]. To finance both the advanced cookstoves and improved cookstoves, three major funding sources could be used: (i) Global Environment Facility (GEF) grant funding support the cookstove dissemination projects in different countries; (ii) Carbon credits; and (iii) Climate Investment Funds [6].

Samuha a developmental organisation in Karnataka state introduced a project activity to disseminate chulika cookstove given in the fig. 2.1 to 110 villages in Koppal district, Karnataka. With this project they are planning to save 2.31 t of $CO_2$/yr/family in the region. The project activity is expected to prevent 46,668 $tCO_2$ emissions in a year by implementing cookstove in 21,500 households.

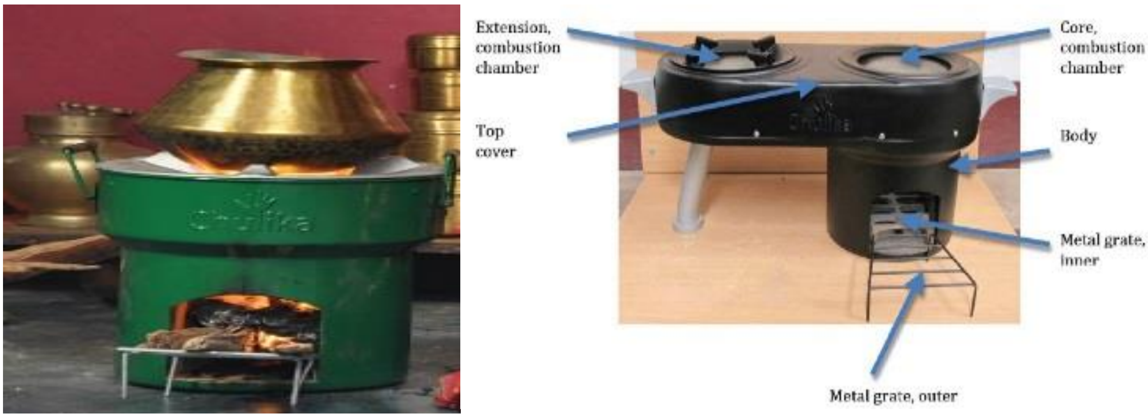



Fig. 2.1: Chulika single and double pot cookstove

Due to scientific and technical advancement through RD&D in all sectors of Science & Technology during the recent decades, the design, modelling and advancement of cookstove has taken place around the world. However, the cookstove could not be made available to the needy and poor people in both urban and rural sectors due to different constraints [6] even though the Government, NGOs and other organizations have done numerous efforts. During the recent years, few techniques such as design principle, mathematical modelling and material selection were studied by number of authors [32] and some of them are given as below:

Technological Advancements in different cookstoves components such as grate, pot skirt, dampers etc. increase the combustion and heat transfer efficiencies through different mechanisms. Therefore, these modifications increased the thermal efficiency and reduced the emissions to a greater extent. Recently, more research on emissions reductions give birth to a new stove technology called gasifier and pyrolytic stove based on micro-gasification principle. The efficiency and emission reduction achieved by generating and separating the combustible gases from the biomass through gasification and burnt it as like a gas [33].

Agun Tri Wijayanta et al. 2012 [112] studied numerical simulation for the syngas production from biomass burning and reducing the production of soot, polycyclic aromatic hydrocarbons (PAHs), and $CO_2$ emissions. Cristina Rabadan-Diehl et al. 2012[113] did extensive study on the effect of household air pollution on the Cadiovascular diseases. ILse Ruiz-Mercado et al.[114] showed the use of stove use monitors (SUMs) and implemented an algorithm to obtain counts of daily meals cooked and found that with adequate placement, standardised data collection and careful data management SUMs provided unobtrusive data of stove use with the resolution of accuracy and level which was not possible before.

Ashish Singh et al. 2012[115] studied the effectiveness of improved biomass cookstoves in reducing indoor air pollution and improvement of health in Nepal. In the study 3 different geographical positions in the country were chosen and assessment was done keeping in account $PM_{2.5}$ and CO and it was observed that reduction of indoor air pollutants after 1 year improved cookstove use was found over 60%. John A. cooper 2012[116] studied the environmental impact of residential wood combustion emissions and its implications. He found from his research that emissions from residential wood combustion appliances are a major source of winter air pollution and will affect public health, industrial growth, etc. Tyagi et al. 2013 [117] explored the advancements in the, design, developments and technological enhancements in improved cookstoves and gave a review covering all the parameters of cookstove manufacturing and recommended to introduce carbon financing to the local cookstove manufacturers to perform R&D for increasing the thermal efficiency of cookstoves.

Many international organisations like United States environmental protection agency (US-EPA), clean development mechanism from United Nations Framework Convention on Climate Change (UNFCCC). These organisations have given many guidelines and giving latest researched values of environmental pollution occurring in the world. UNFCCC was formed after Kyoto protocol was enacted and this convention lead to CDM which gives certified emission reduction credits (CERs) which is equivalent to reduction of 1 ton of $CO_2$. Any non-governmental or governmental organisation in the world can produce a project activity which will reduce carbon dioxide or equivalent units. The organisation can than sell the credits they have earned to the developed countries who cannot get the credits on their own at nominal rate. This process has speeded up the process very much and till date 7023 registered projects, 1,355,384,067 CERs issued for project activities and 58,401 CERs issued for programme of activities. CDM has proved to be a successful endeavour but India is still far behind in producing CERs than most of the other developing countries.

## 2.3 Materials of Construction

The earlier improved cookstoves generally have the chimneys and closed combustion chambers and worked mainly on the basic principle of providing excess amount of oxygen for better combustion. The number of households using these improved cookstoves roughly 166 million total, with 116 million in China, more than 13 million in the rest of East Asia, nearly

22 million in South Asia, about 7 million in Sub-Saharan Africa, and over 8 million in Latin. The process of cookstove development can be seen in the Figure 2.1 below starting from the initial models to the models developed in 1980s and the recently developed improved biomass cookstoves. America and the Caribbean. From 1980 until about 2002, thousands of artisans produce and disseminate the improved cookstove models. As one might imagine, with repeated heating and cooling, such cookstoves easily cracked and degraded. Their estimated two-year life span proved too optimistic; in practice, some failed within a year [6].

The recently developed advanced biomass cookstove are based on the higher levels of technical research and are generally more expensive. These cookstoves consists of better technological designs features such as, grates, insulation, forced air flow, and more durable materials to provide a cleaner burning. Most of these work on the principle of combustion, gasification and pyrolysis at high temperatures. They include the wood, charcoal, pellet, and gasifier cookstoves. The lower-cost improved cookstoves can also significantly lower the emissions, improves the health, and reduces the forest degradation and deforestation. So, the systematic investigation of the heat transfer and combustion efficiency of a stove design is necessary in the laboratory which, in turn, helps to ensure that the cookstoves disseminated have a significant improvement over traditional cookstoves. Nowadays cookstoves are being built with high quality cast iron body which is durable and works for at least 7-10 years further to decrease losses the insulation of high grade is provided usually refractory brick material is used which has least thermal conductivity. The new cookstoves should be based on the well-defined standards that include safety, efficiency, emissions, and durability.

## 2.4 Mode of Air Supply

The combustion efficiency should be improved to reduce smoke and harmful emissions that damage health by improved heat transfer efficiency leading to less fuel consumption. The newly developed batch feeding and fan assisted stoves increased the overall efficiency [31]. In a traditional mud stove, the gasification and combustion of fuel takes place almost simultaneously around the solid fuel which leads to higher emissions of products of incomplete combustion. If the air is entering through free convection in a cookstove this is called a natural draft stove and if the air is supplied through fans than this is called a forced draft stove. In a natural draft stove the better mixing of combustible gases could not takes place; the stove developer has to improve the combustion efficiency with the help of better stove geometry and new materials. In a forced draft stove, better mixing of combustible gases and oxygen leads to better combustion and lower emissions.

During the pyrolysis of the solid biomass fuel the volatile gas and char are produced. After releasing the volatile gases, the char gasification is initiated, leading to emission of carbon mono-oxide. The combustible gases i.e. mixture of volatile gases and carbon mono-oxide subsequently react with oxygen present in the air entering into the cookstove due to the natural draft induced by chimney effect. The newly natural draft and forced draft, combustion and gasifier stoves are designed to improve the combustion efficiency. In a gasifier stove, the generation and separation of combustible gases from fuel and its subsequent combustion to produce heat leads to greater combustion efficiency and therefore, lower emission of products of incomplete combustion [37].

### 2.5 Design Methodology

The earlier cookstoves were made by development workers on site in developing countries including India using locally available material and resources. These stoves were made according to the requirement of local households without any scientific knowledge and any quality control [45]. An improved cooking stove can be defined as a stove that needs less biomass to cook the same amount of food than a traditional one and consequently produces less smoke than a traditional stove [46]. Few researchers [29-33, 45] studied the processes inside a cookstove and gave the design principles for improved biomass cookstove and most of them have been covered in this article. As the biomass cookstove is a complex engineering device [29] involving two major phenomena named combustion and heat transfer. Stove is built keeping in mind to incorporate the principle of combustion, gasification and pyrolysis in single cookstove for better burning at high temperatures.

#### 2.5.1 Combustion of Fuel

The combustion process mechanism plays a great role in a cookstove design and performance. The solid fuel combustion is a much more complex than the liquid or gaseous fuel combustion due to the processes of pyrolysis. Generally, the solid fuel combustion such as wood takes place in two stages: flaming combustion of volatiles and glowing combustion of char. The char combustion in a cookstove depends on the surface area exposed of the fuel piece, the way a bed laid out, the rate of pyrolysis and the fluid flow through the fuel bed. The shape of the combustion chamber, cross-sectional area, height and volume are the important parameters for the design of any combustion chamber using a solid fuel. The fuel burning rate determines by the size of a grate and in the case of a stove without grate the diameter of the combustion chamber. The height of the combustion chamber should be related to the flame height [29]. The phenomenon of combustion [32] can be explained as below:

At about 100˚C, conduction of heat in the wood takes place due to which the absorbed water boiled and migrates along the wood grain to cooler areas and re-condenses. At slightly higher temperatures, the water bound to molecular groups is also evaporates. At about 200˚C, as the temperature increases, hemi-cellulose begins to decompose followed by cellulose and the decomposition becomes considerable higher at around 300˚C. Typically, about 8-15% of cellulose and hemicelluloses and roughly 50% of the lignin remain as fixed carbon and the remainder is released as volatile gases. The volatiles produced by this decomposition may escape as smoke. As the volatiles escape from the wood, they mix with oxygen and, burnt at about 550˚C, due to ignition produce a yellow flame. The radiant heat from the flame also plays a crucial role in maintaining the combustion process. The rate of combustion is controlled by the rate at which these volatiles are released. The small pieces of wood due to large surface area absorb more radiant heat, thus have more rate of release of the volatile. Thus, the fires with small pieces of wood tend to burn quickly than the larger mass.

As the volatiles rises, they react with other volatile molecules form soot and smoke and simultaneously the burning of volatiles takes place as they mix with oxygen. The temperature of the hot gas above the wood is typically around 1100˚C and is limited by radiant heat loss and by mixing with cold ambient air. The burning volatiles account for about two-thirds of the total energy released by a wood fire and if a cold object is placed close to the fire it will cool and stop the combustion of some of these volatiles and leaving a thick black smoke. The volatiles are released as long as the wood is hot and if the air supply is stopped, the combustion process also stops down. The heat output of the fire is reduced but the wood continues to be consumed as long as it is hot but releasing of unburned volatiles as smoke and leaving the charcoal behind.

As the topmost layers gradually lose all their volatiles, only a porous char is left behind. This hot char helps catalyse the breakdown of escaping volatile gases, producing lighter, more completely reacting gases to feed the flames. In some cases, the volatiles cannot easily escape through this char layer. As they expand and force their way out, they cause the burning wood to crack and produce hiss. The char layer also has a lower thermal conductivity than wood. This slows conduction of heat to the interior and thus slows down the release of volatiles to feed the flames. At the surface of the char, carbon dioxide reacts with the char's carbon to produce carbon monoxide. Slightly away from char surface, the greater concentration of oxygen completes the combustion of combustible gases by reacting with the carbon monoxide to produce carbon dioxide and heat.

The temperature near the surface of the burning charcoal is typically about 800˚C. The endothermic (heat absorbing) dissociation of carbon dioxide to carbon monoxide and oxygen, the radiant heat loss etc. limit the higher temperatures of char. When all the carbon has burned off only mineral salts remain as ash. The ash limits the flow of oxygen to the interior surface of wood and so limits the combustion rate, which is an important mechanism controls the combustion rate in the charcoal stoves. A wood fire burning at a power level of 1 kW burns 0.0556 grams of wood/second (calorific value of wood 18000 J/s) and requires about 0.278 litres of air per second. However excess air is very important to ensure the complete combustion of the wood fuel in most of the applications.

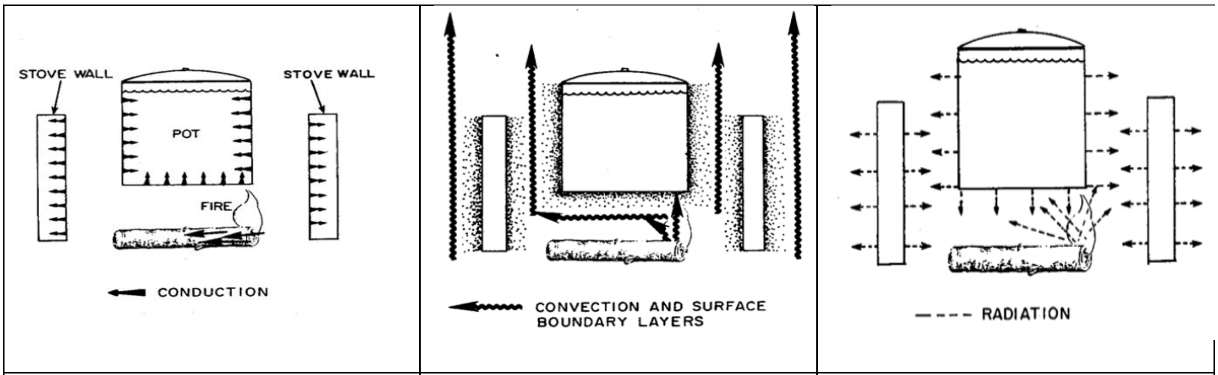
### 2.5.2 Heat Transfer

It is well known that the heat transfer is an important phenomena in a cookstove and it is helpful to transfer heat to the cooking pot by the combustion of wood. There are also different losses associated with it, and hence, thorough study of different heat transfer processes is very important and necessary to understand the mechanism of heat transfer in a cookstove. The study of different heat transfer processes in a cookstove is described by Baldwin [32] and others [2] as below:

#### (a) Conduction

In a solid material heat is conducted by vibrating atoms and they speed up the vibration rate of more slowly moving neighbours. In metals, heat is conducted by free electrons which move with a high velocity from high temperature regions into lower temperature regions where they collide with and excite atoms. For a cookstove the different areas in which the heat transfer through conduction takes place are shown in Fig. 1 (a) and written as below:

The transfer of heat from the cooking pot to the cooking material of the pot. The heat losses through the stove wall. The heat transfer storage from the flame to wood and the heat storage in the pot material and in the stove body [2]. Larger the mass and specific heat of an object, the more energy it can store for a given change in temperature. Thus, a massive object warms up slowly while a lightweight object warms up rapidly [32].




| | | |
|---|---|---|
| (a)Conduction | (b)Convection | (c)Radiation |

Fig.2.2: Different heat transfer processes in a cookstove [32].

**(b) Convection**

Convective heat transfer occurs when a gas or liquid flows naturally or forced into a region at a different temperature and exchange heat energy through conduction by the interaction of individual particles [32]. In a cookstove the areas to be taken in to consideration for convective heat transfer as shown in Fig. 2.3 given as below:

**(c) Radiation**

All materials emit greater amount of radiation energy in the form of electromagnetic radiation due to the internal molecular and atomic motion because of its higher temperature. The different areas for radiation losses to be taken into consideration while designing an improved cookstove are shown in Fig. 2.2 (c) and written as below:

The radiations emitted from the flame ;The radiation exchange between the inner walls, pot and the wood surface; and The radiation loss to the atmosphere from the wall, pot, chimney, and the opening of the combustion chamber [2]. Verhart [45] analysed the cooking processes and energy requirements that take place generally, in a household such as boiling, frying, baking, and grilling in “On designing woodstoves”. He presented a discussion on the building materials, heat transfer mechanism and energy supply options. He has discussed the role of natural draft for improving the combustion and heat transfer modes in a cookstove. He also recommended some important points to improve the combustion efficiency of the cookstove. It was suggested by him that for complete combustion of small pieces of fuel the following points should be considered.

### 2.5.3 Combustion Efficiency

The complete combustion of volatiles should be ensured before its interaction with fresh charged from new wood piece. Initially, the primary air should be regulated to ensure a char combustion rate of 13.5% of the designed power output of the cookstove. At the end of volatile combustion, the rate of air supply should be increased to get more power output from char. Baldwin [32] described few techniques related to engineering design, development, and dissemination of to improved biomass cookstove to improve the combustion quality and heat transfer rate some of the points are given as below:

The stove performance can be improved by introducing a grate because it performs several functions such as, injecting air below the fuel bed for better mixing of air which is required for proper combustion of fuel. This will increase the thermal efficiency and reduced the emissions from the cookstove. The cookstove efficiency can be increased by controlling air flow in to the combustion chamber. Also an optimum flow rate not only enhances the efficiency, combustion temperature but also reduce the emissions, which is also a very important parameter. The preheating of incoming air may also improve the quality of combustion in other words; it may achieve complete combustion and the thermal efficiency by raising the average combustion chamber temperatures. Heat and burn the tips of the sticks only. High and low heat can be created by number of sticks put into the burning fire. There should be constant cross sectional area throughout the cookstove. The wall of cookstove should be well insulated. Guzman and Jordan [47] stated that the thermal efficiency of an improved cookstove depended upon two simultaneous processes firstly, the combustion of the fuel and secondly, the heat transfer process.The combustion efficiency is the ratio of thermal/heat energy which is produced by the combustion of fuel to the total thermal/heat energy available in the fuel while heat transfer efficiency is the ratio of energy which is delivered to the cooking pot to the total heat produced by the combustion of wood.

The shape of the combustion chamber should be optimized because it affect the combustion quality and stove efficiency. Also a good insulation inside the combustion chamber raises the interior temperatures and can thus reduce the emissions. Winiarski developed the design principles to improve the combustion and heat transfer efficiency of wood burning cookstove. His design principles are given in Fig. 2 and on the base of these design principles the famous rocket stove was designed and fabricated as shown in Fig.3. Some of the designed principle described by Winiarski [31] given as below:

| | | |
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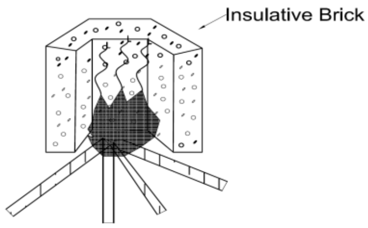
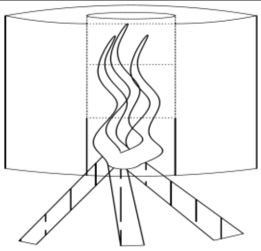
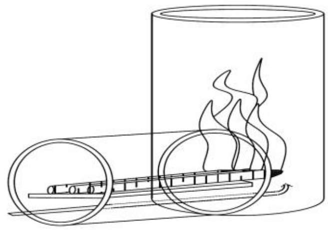
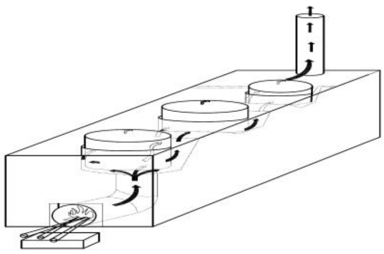
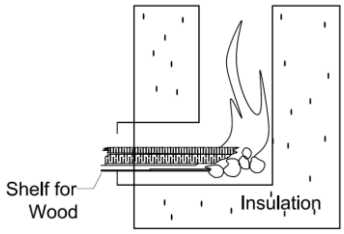
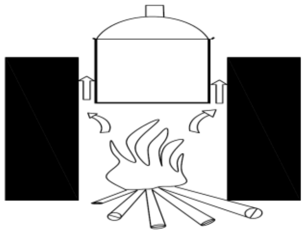
|   |  |  |
| Insulated space around the fire using lightweight, heat-resistant materials reduces the heat loss. | An insulated short chimney above the fire increased the draft. | A good fast draft should be maintained through the burning fuel. |
|  |   |  |
| A little air being pulled into the fire would result in smoke and excess charcoal. | A grate should be used under the fire. | The properly sized gaps should be made to maximize the heat transfer to the pot. |

Fig. 2.3: Winiarski's design principles [31].

The combined efficiency of both processes decides the overall efficiency of the cookstove as follows:

$$\eta_o = \eta_c \times \eta_{ht} \quad (1)$$

Where $\eta_o$ the overall efficiency of the cookstove is, $\eta_c$ is the combustion efficiency and $\eta_{ht}$ is the heat transfer efficiency. The thermal efficiency can be determined by the following equation as below:

$$\eta_f = \frac{Q_t}{Q_w} \quad (2)$$

where $Q_w$ is the total thermal energy available in the wood and $Q_t$ is the heat utilized.

Reed [33] gave the Top-Lit Up-draft (TLUD) micro gasification principle for making the gasifier and pyrolytic stove shown in Fig. 4. A gasifier stove has the potential to provide biomass as a clean cooking fuel through clean combustion of biomass where charcoal and firewood became a rare and an expensive. This simplest Top-Lit Up- draft gasifier (TLUD) had the separate entry holes for primary and secondary air. The proper mixing of the gaseous fuel (i.e. volatile matter) with oxygen takes place with the help of secondary air to ensure proper and complete combustion. A chimney above the combustion zone creates draft and further enhances the mixing of gas and oxygen. The options for providing adequate primary air depend on fuel size, for example, for thin fuel pieces natural draft is sufficient, whereas for thick fuel pieces, air needs to be forced through the fuel bed and the easiest to provide it by using a small fan or blower. Also the current research is taking place using thermo-electric generators and photovoltaic panels to produce electricity for lighting and running a small fan for forced draft cookstoves [48-50].

Yuntenwi et al. [51] studied the effects of wood-fuel moisture on heat transfer and combustion efficiencies of the three stoves named as open fire, the Chinese rocket stove and modified single walled VITA stove, respectively. These stoves were tested at a moisture content of 5%, 15% and 30% respectively, based on wet basis. The results showed that there is an optimal value of moisture content at which the efficiency attains the highest value because the combustion was found to be lover at the extremely dry and over-wet fuel conditions. They also concluded that the type of stove exhibits a stronger effect on the total emissions from the cookstove than that of the moisture content of the fuel.

## 2.6 Impact on Environment and health

The consumption of biomass is very large in developing countries due to its easy availability for cooking and heating purposes [56]. They are usually cheaper and have no monetary cost than other fuels. So, this is the primary source of energy in developing countries. But the biomass fuels are usually burn in open fire to the high levels of harmful emission products such as NOx, SOx, CO and particulate matters that causes several health problems to the user [34, 57]. With the increasing awareness about the negative health impacts due to emissions from solid biomass cooking fuels among the scientific community, the rigorous research on emissions reductions, deforestation, health and social issues etc. has started during the early 1990s [6]. The initial objective was to minimize the direct exposure to the exhaust/flue gases, decreasing the fuel consumption thereby, saving the time spent on biomass fuel collection by female child and women, besides, to make the biomass cookstove acceptable for the billions of people who were relying on it to satisfy their daily needs. Currently with the raising awareness about the cooking related issues among different countries three important issues deforestation, climate change and health and due to greenhouse gas emissions (GHG) emphasized and a number of authors have studied these issues in detail [70, 76, 84].

**(a) Deforestation**

Since use of wood as fuel has been the primary cause of deforestation. Since the fuel wood was seen as a fuel with many advantages and included cultural considerations and hence, the fuel wood could not be replaced entirely, even in households that had been using modern fuels for many years. The promotion of improved wood burning stoves was being widely sought as an essential component of the strategy for reducing the 'wood fuel crisis' which has been faced by many countries. As shown in Fig. 2.6 below a chain reaction starts as the deforestation takes place leading to water pollution, global warming, less soil moisture which further leads to decrease in agricultural productivity. Everything leads to the disturbance in the normal atmosphere leading to the problems like soil erosion, landslides, loss of biodiversity, and lesser rainfall causing desertification. In the region, improved cookstoves have been long known as a major imperative for reducing deforestation. Agarwal [59] presented the differences in approaches for diffusion of innovations in rural areas because innovations differ from one another in terms of technical, economic and social characteristics, which provides the analytical framework for improved wood burning stoves.

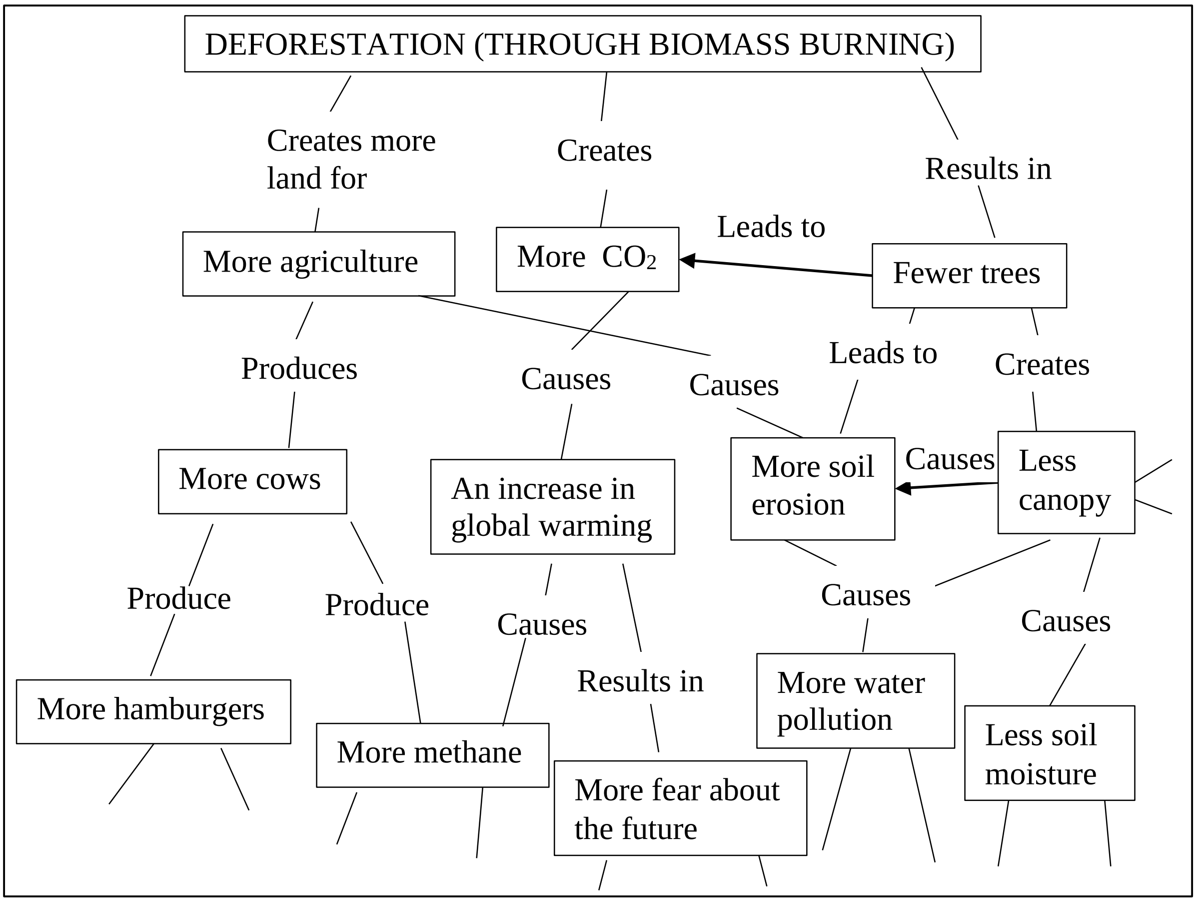



Fig. 2.4: Chain effect of biomass burning on deforestation

However, those stove diffusion program were ineffective, either in the adoption or in the required saving of wood. They suggested that the diffusion of wood-burning stoves required a different approach from the usual 'top-down' method. They noted that the process of innovation i.e. designing of a cookstove need to be linked integrally to that of the diffusion. Also whether or not the stove was adopted, or continued to be used when adopted this to be determined by the user's involvement in the design process.

Ramakrishna et al. [22] stated that in the developed countries, the transition to cooking stoves using clean fuels took place as a natural consequence of the economic development. The socio-economic and environmental consequences of wood fuel usage in the traditional cooking stove in floodplain rural areas in Bangladesh was studied by Miah et al. [61]. They conducted a study on traditional cooking stoves to determine the structural characteristics and amount of wood fuel consumed using a multistage random sampling. Alam and Chowdhury [62] evaluated the economic, ecological and socio-cultural achievements of improved earthen stoves that were provided to the beneficiaries under a project to improve decreasing biomass energy utilization. The improved earthen stove has been distributed for free of cost to the beneficiaries under a project component of Sustainable Environment Management Program of the Ministry of Environment and Forest of the Government of Bangladesh. Providing improved earthen stove to the women beneficiaries was an input among others in course of project implementation. The energy saving through improved earthen stove has brought several changes and improvements in fuel usage, economic, environment and socio-cultural aspects. The introduction of the improved stove is a safer, cost saving and proven technology that fulfils the needs of the end users. The fuel savings reduced outlays for purchasing wood, shortened collection times, alleviated local pressure of fuel resources and diminished air pollution up to a significant level.

Ayoub and Brunet [64] carried out laboratory tests to analyse the performance of traditional three stone open fire cookstove against a large-sheet metal fuel wood cookstove designed for community kitchens. The standard water boiling test was performed for both cookstoves and calculated the percentage of heat utilization, firepower and the specific fuel consumption. They found that the metal cookstove was three times more fuel efficient and took only one fifth of the energy to boiling an equivalent amount of water than open fire cookstove. They noticed an appreciable savings in fuel wood consumption, collection time, and thus, its purchase costs besides, the tangible health and social benefits using the cookstoves were also enumerated. Also, the suggestions for simplifying the stove fabrication process, improving field dissemination and creating a possible cottage industry were proposed.

Quadir et al. [65] tried to identify the barriers in dissemination of renewable energy technologies for one of the most important end uses of energy, i.e. cooking. An effort was made to provide some insight regarding the issues and factors that are likely to affect the adoption of three prominent renewable energy technologies for cooking, namely biogas plants, improved biomass cook stoves and solar cookers.Gupta et al. [66] stated that the prolonged and uninhibited use of biomass fuels for over thousands of years had resulted in massive deforestation all over the world. This in turn, caused an increased shortage of biomass fuel for cooking besides creating pressure on the households relying on the same. However, these households could not be shift towards cleaner fuels due to economic constraints and hence, continued using whatever biomass fuels they could get free and/or at a cheaper price, without thinking about the harmful health impacts while burning these fuels traditional cookstove.

Biomass smoke from combustion contained a wide range of pollutants which could prove to be extremely health damaging due to continuous exposure. They also concluded that to eliminate that indoor air pollution using improved cookstoves and cleaner fuels were too expensive for the majority of people to be adopted, due to the fact that majority of people belong to the poor section of the society. They also suggested that search for better species of non-woody biomass fuels, should be carried and to be verified by laboratory experiments, which can be introduced into the end users to lessen the extent of the indoor-air pollution problem. This may also be done through international funding agencies such as GEF, IFC, carbon finance etc.

Pokharel [68] examined the pattern of energy use for cooking in an urban area in Nepal including Energy characteristics for cooking obtained from laboratory tests, besides, the energy use cost (EUC) for various cooking alternatives. He emphasized that the actual cost of energy use depends upon the cost and the material properties of cooking utensils. For example, to cook rice, which is a fast-cooking food item, thinner utensils are better while, for slow-cooking items such as lentils and beans, thicker utensils are better mainly due to their good heat retention and uniform heat distribution (to food) capabilities. If a stove is used to cook a food item in two different utensils for the same time period, fuel-use cost (FUC) would be the same but the actual cost of energy use would be different because costs and heat absorption capabilities of different utensils are different.

This type of energy-use cost (EUC) is referred to as useful energy-use cost (UEUC) in this paper and will be considered for cost comparison of various energy alternatives. He also examined the community and household factors that affect the initial adoption of improved cookstove leading to sustainable dissemination and use of cookstove. However no detailed tracking report of stove adoption and usage patterns over has extended time period could be prepared through home visits. It was also stated that without proper understanding of the ongoing social and behavioural process of adoption and stove use. The full benefits of stove dissemination Programs cannot be realized or estimated in any region/state of any country.

Kathleen et al. [69] also identified the household and community characteristics associated with early adoption of Patsari stoves including the factors that lead to sustained use over time, by tracking of stove adoption and usage patterns over an extended time periods through repeated home visits. Further, a bi-level approach was proposed that may be used for stove dissemination Programs to target early adopter communities and households for stove dissemination. In order to increase the adoption rates within communities.

**(b) Effect on climate**

The manner in which fuel is harvested has a large influence on the climate change potential. In other words, if cooking with biomass. If biomass is harvested sustainably, the $CO_2$ released in combustion is theoretically reabsorbed by the biomass growing to replace it but if biomass is not harvested sustainably, the $CO_2$ released when the biomass is burned thereby contributing to the build-up of $CO_2$ in the atmosphere. The products of incomplete combustion such as carbon monoxide, methane, and particulate matter contribute to the changing of the climate. The large-scale use of cleaner cookstoves might reduce global warming up to certain extent. Different studies done so far number of authors are summarized here to describe the effects of biomass cookstove on the environment as below:

**(i) Greenhouse gases**

Edwards et al. [70] presented the emissions database from cooking stoves for 23 typical fuel/stove combinations tested in a simulated village house in China. They observed the pollution level enhanced due to poor combustion efficiency of biomass cookstove thereby contributing to greenhouse gases and thus global warming. Besides, a significant portion of fuel carbon goes waste as a result of poor combustion. They also concluded that due to the approximately linear decrease in combustion efficiency, there is an increase in emissions of product of incomplete combustion. On the basis of above observation they developed a linear model to the predict the emissions of greenhouse gases and health damaging pollutant which were linked to carbon dioxide $CO_2$ and PIC (particulate inorganic carbon) production and hence, predicted of the global warming contributions from residential cookstove in China.

Following table 2.1 shows the estimated greenhouse emission i.e. methane, nitrous oxide and carbon monoxide in million metric tons per year from different biomass sources, it can be observed that around 20% of methane emissions, 10% of nitrous oxide and 10 % of carbon monoxide emissions come from biomass burning. McCarty et al. [71] studied the relative emissions from five common types of biomass cookstoves. Their results showed that in sustainable harvesting situations where $CO_2$ emissions was considered neutral, some improved stoves with rocket-type combustion or fan assistance could reduce overall global warming impact from the products of incomplete combustion (PICs) by 50-95%. In non-sustainable situations where fuel and $CO_2$ savings were of greater importance, three types of improved combustion methods were shown to potentially reduce the warming by 40-60%. Although the charcoal-burning emitted less $CO_2$ than the traditional wood-burning, yet the emissions from incomplete combustion was found to be significantly greater than the traditional cookstove.

Table 2.1: Estimated greenhouse gas emission from different biomass sources

| Source | Methane (Mmt $CH_4$/yr) | Nitrous Oxide (Mmt N/yr) | Carbon monoxide (Mmt C/yr) |
|---|---|---|---|
| Biomass burning | 55-100 | 1-2 | 110 |
| Ruminants | 70-100 | | |
| Paddy fields | 70-170 | | |
| Cultivated lands | | 0.2-0.6 | |
| Fertilizer application | | 0.6-2.3 | |
| Forest clearing | | | 160 |
| Subtotal(Land use/agriculture) | 195-370 | 1.8-4.9 | 270 |
| Fossil fuels | 65-75 | 1.9 | 190 |
| Other | 40-105 | 6 | 710 |
| Total | 300-550 | 12-15 | 1170 |

Zhang et al. [72] presented systematic study of trace gases (CO, $CO_2$, NO, $NO_2$, and $NO_x$) and particulate matter from rice, wheat and corn straw etc. which were the major agricultural residues in China. They had performed their experiment by burnings the above mentioned residues in a typical cookstove and aerosol chamber of Fudan University (ACFU) in Shanghai. They also discussed the emission factors, emission inventory and emission allocation of gaseous pollutants from the burning of rice, wheat and corn straws at regional and global levels in China.

**(ii) Black carbon**

Black carbon is the most strongly light-absorbing component of particulate matter (PM), and is formed by the incomplete combustion of fossil fuels, biofuels, and biomass. It can be defined specifically as a solid form of mostly pure carbon that absorbs solar radiation (light) at all wavelengths. It is a major component of soot which is a complex light absorbing mixture that also contains organic carbon. It is the most effective form of particulate matter, by mass, at absorbing solar energy. It warms the earth by absorbing heat in the atmosphere and by reducing albedo, the ability to reflect sunlight when deposited in snow and ice. It is always emitted with other particles and gases, such as sulphur dioxide ($SO_2$), nitrogen oxides ($NO_x$), and OC. Some of these co-emitted pollutants exert a cooling effect on climate. It stays in the atmosphere for only several days to weeks, whereas carbon dioxide ($CO_2$) has an atmospheric lifetime of more than 100 years.

Table 2.2 Estimated climate forcing (w/m$^2$)

| **Component** | **IPCC (2007)** | **Hansen, *et al.* (2005)** |
|---|---|---|
| Carbon dioxide ($CO_2$) | 1.66 | 1.50 |
| Black carbon (BC) | 0.05-0.55 | 0.8 |
| Methane ($CH_4$) | 0.48 | 0.55 |
| Tropospheric Ozone($O_3$) | 0.35 | 0.40 |
| Halocarbons | 0.34 | 0.30 |
| Nitrous oxide ($N_2O$) | 0.16 | 0.15 |

Johnson et al. [73] estimated the potential reductions in emissions of gaseous and aerosol greenhouse species that would result from replacing a traditional open fire stove with an improved ‘‘Patsari’’ cookstove in rural Mexico. In addition to a reduction in overall particulate emissions from rural homes during daily activities, the ratio of organic carbon to that of the elemental carbon decreased between the open fire and improved Patsari cookstoves. However, the overall elemental carbon contribution for the Patsari cookstove reduced, the fraction of elemental carbon increased relative to that of the organic carbon.

From the above table 2.2 it can be observed that black carbon plays an important part in climate forcing. Currently, residential cookstoves contribute approximately 21% of the global BC emissions inventory, with emissions concentrated in Sub-Saharan Africa, China, India, and other developing regions of Asia. Dependence on traditional biomass fuels is highly correlated with poverty; countries with higher household income also tend to have a higher share of modern fuels for residential consumption. While the percentage of people relying on traditional biomass fuels for basic household energy needs is expected to decrease in most areas over the coming decades, the aggregate number of people relying on biomass for cooking and heating is expected to increase by 100 million people by 2030 due to population growth (International Energy Agency, 2010). IEA projects that the fastest shift toward modern fuels will occur in India, and the slowest shift will occur in Sub-Saharan Africa (International Energy Agency, 2010). The impact of these changes on emissions is still unclear, under most scenarios, residential emissions are projected to decline significantly by 2030 and further still by 2050 (Streets et al., 2004). However, a decline in emissions, and the rate of decline will depend on rates of adoption of cleaner fuels and cooking technologies described below, and some regions may experience near-term increases in emissions.

Grieshop et al. [74] analysed the impacts due to replacement of ‘traditional’ cookstove with different improved cookstove on health and climate. They observed that health and climate impacts of available household cooking options in developing countries vary sharply. They analysed and compared the health, climate impacts and the potential co-benefits from the use of fuel and stove combinations. They stated that the indoor air pollution and climate are influenced by the combustion performance, ventilation and fuel properties. They also concluded that the emission components which were not included in the current carbon trading schemes, such as black carbon particles and carbon monoxide, could contribute a large proportion of the climate change and global warming. Finally they observed that the improvements in the biomass cookstoves could improve the indoor air quality, which nonetheless remains significantly higher than as compared to those of clean fuel cookstoves like LPG.

Simon et al. [75] reviewed the possibilities of climate and local development due to improved cookstoves distribution programs that use the carbon revenues. They stated that if improved cookstoves used continuously could play an important role in local development and global climate change. They also described a number of barriers such as cultural, financial, governance and technological to achieve win-win condition. The carbon finance could make the cookstoves distribution programs scalable and enforceable by providing fund. They concluded that cookstoves distribution programs in Peru, Uganda and Cambodia, the challenge proved the importance of carbon finance to overcome the above mentioned barriers up to certain extent, however, the sustainability and popularity of such program is yet to be ascertained.

**(iii) Health Issues**

Biomass is burnt inefficiently in open three-stone fires, traditional cookstoves for cooking and heating applications and hence it causes severe health problems in women and children and also affects the environment. Sharma et al. [23] emphasized that the adoption and large-scale propagation of improved stoves could help in improving the health of rural women and in making a more efficient utilization of the available firewood resources. This will also stop the large scale denudation of forest cover in the developing countries, which is also responsible for the changes in the climate. Ballard-tremeer and Jawurek [76] compared the thermal efficiencies and the emissions of the five rural cooking devices named an open fire, an "improved" open fire built on a raised grate, a commercial one-pot metal stove, a prototype two-pot ceramic stove and a prototype two-pot metal stove following the standard VITA tests. Their study indicated that the average emission of smoke was lowest for the improved open fire, while for the two-pot ceramic stove it was found to be the highest. Both open fires emitted lowest carbon monoxide and sulphur dioxide; the other cookstoves were higher emitter of carbon monoxide and sulphur dioxide. The average efficiencies of the open fire, improved open fire, and the cookstoves were found to be 14%, 21%, 20 to 24% respectively.

From the worldwide studies done by international energy agency it was also observed that in future the number of deaths related with biomass burning will increase. When compared with other diseases and their future it was found that deaths related with biomass burning will increase at linear rate from 2008 to 2030 as compared to other common diseases like AIDS, Malaria, and Tuberculosis etc. which are causes of main problems today. As most of the medical funding is going to these diseases and as deaths from biomass burning is a silent killer it is very important for government to take steps now to save the future generations. Fig. 2.8 taken from world energy outlook provided by International energy agency shows the future trend of diseases.

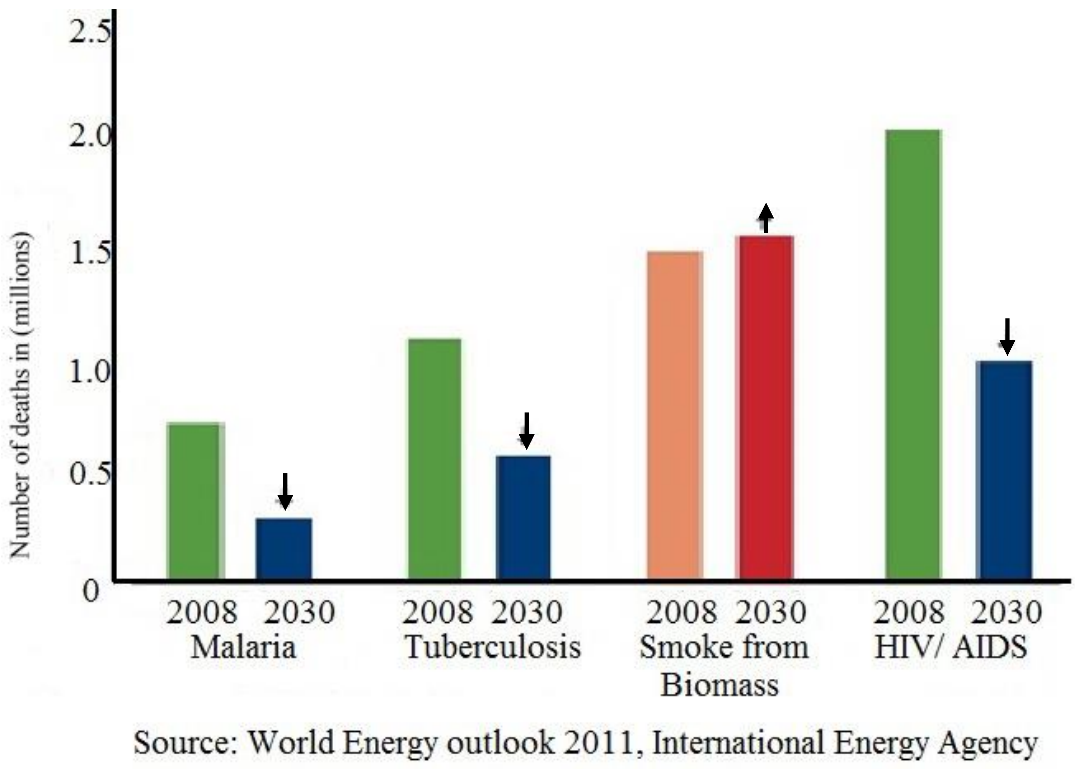



Fig.2.5: Premature annual deaths from cook stove smoke and other selected diseases.

Sexton et al. [77] described the results of an ambient air monitoring study to measure the total suspended particle in Waterbury (Vermont). The measurement of air monitoring was done during from January to early March, 1982 for a wood-burning community. This study was designed to provide data on ambient concentrations of total inhalable and respirable particles in ambient air due to wood-burning. They concluded that major source of airborne particles in residential sections of town was the wood burning. They also concluded that the variation in particulate concentration was significantly observed during the night as compared to the afternoon levels.

Raiyani et al. [78] discussed the indoor concentrations of total suspended particulates (TSP), polycyclic aromatic hydrocarbons (PAHs) and the particle size distribution due to biomass fuels in households located in eastern peripheral area of the Ahmadabad agglomeration. They measured the levels of gaseous pollutants such as carbon mono-oxide

(CO), nitrogen dioxide ($NO_2$), formaldehyde (HCHO) and Sulphur dioxide ($SO_2$) across different locations during the cooking hours using different cooking fuels such as, cattle dung, wood, coal, kerosene or liquid petroleum gas (LPG). The correlation between the pollutants for each type of fuel was presented. They found that the levels of pollutants were relatively high in the houses which were using biomass as fuel and concluded that the air quality was the worst nearby the biomass fuels users. Parikh et al. [79] carried out the statistical analysis to examine the links between pollution and the types of kitchen and fuels used for rural houses by first monitoring the indoor air quality (IAQ) followed by regression analysis of 418 households in Tamil Nadu, (India).

Exposures to the smoke from the cookstove for females, who were involved in the cooking was also measured with personal monitors. The result showed that the values of respirable particles ($PM_{10}$) varied from 500–2000 g/$m^3$ depending on the type of kitchen and fuel used. They also concluded that the individuals who stayed inside the houses during the cooking time also faced high concentrations. Two major findings from this analysis were presented [79] first the improved house designs that paid attention to kitchen location and second, the exposure was not limited to the cook alone because the rest of the family many years in the house were also exposed through a “passive cooking effect”. Wang et al. [80] analysed the emission characteristics of gaseous pollutants, including volatile organic compounds (VOCs) such as benzene, propylene, acetone, toluene, and acetaldehyde from biomass combustion in the improved cookstoves in rural areas of China, using five different types of, bio-fuels. From the emission data they showed that the gaseous pollutants were emitted at higher concentrations in the early stage and lower concentrations in the later stage of combustion.

Ryhl-Svendsen et al. [81] conducted the measurements at a Danish historical research centre using 17-19th century houses to determine how effective traditional Danish hearth systems were in removing smoke from the house, and how much exposure might have existed historically. They measured carbon monoxide (CO) and particulate matter (PM) in two reconstructed Danish farmhouses during two weeks of summer. They concluded that a woman living in such type of houses at that time would be exposed to daily averages of 1.1 ppm CO and 196 mg/ $m^3$ PM, which exceeds world health organization (WHO) guideline for particulate matter, and is comparable to what is observed in recent times for women in rural areas of developing countries.

Ding et al. [82] characterized the Polycyclic aromatic hydrocarbons present in the indoor air pollution and measured Twenty-two parent PAHs (pPAHs), 12 nitro-PAHs (nPAHs), and 4 oxy-PAHs (oPAHs) in the different locations of a household during summer and winter seasons. These compounds were measured in a typical rural household in northern China where biomass fuels have been used for heating and cooking purposes. They also investigated the differences and connections between the air pollution in the kitchen, the adjacent bedroom, indoor and outdoor air, winter and summer, and personal exposure to PAHs. They concluded that high PAH concentrations were measured in the indoor air of the household and the most severe contamination occurred in the kitchen during the winter seasons.

Table 2.3 Health effects of cook stove pollution in India and comparison with other problems.

| **HEALTH** | |
|---|---|
| Percentage of population using solid fuels for cooking | 82% |
| Number of people affected by (Household AP) | 91,38,96,934 |
| Number of households affected by (Household AP) | 16,92,40,173 |
| Number of deaths per year | 4,88,200 |
| Urban population using solid fuels (%) | 24.6% |
| Rural population using solid fuels (%) | 88.1% |
| Population using wood for cooking (%) | 57.9% |
| Population using dung for cooking (%) | 10.6% |
| Population using charcoal for cooking (%) | 0.4% |
| Population using coal for cooking (%) | 1.9% |
| Population using kerosene for cooking (%) | 3.2% |
| **COOKSTOVES BY COMPARISON** | |
| Percentage with access to improved water (%) | 86% |
| Percentage with access to improved sanitation (%) | 33% |
| Diarrhoea deaths per year | 4,54,400 |
| Deaths per year from outdoor air pollution | 119900 |
| Deaths per year from malaria | 15,900 |
| Deaths per year from tuberculosis | 3,09,000 |
| Deaths per year from HIV/AIDS | 1,26,100 |
| Population using improved biomass cookstoves (%) | 0.256 |

Saud et al. [83] presented the experimentally determined emission factors and estimates of suspended particulate matter (SPM), $SO_2$, NO and $NO_2$ emitted from biomass fuels used as energy in rural area of Indo-Gangetic Plain (IGP), India. They estimated that the average emission factor for SPM from dung cake, fuel-wood and crop residue over Delhi, Uttar Pradesh, Punjab, Haryana, Uttarakhand and Bihar were as 16.26-2.29 g $kg^{-1}$, 4.34-1.06 g $kg^{-1}$ and 7.54-4.17 g $kg^{-1}$ respectively. Similarly, they also determined the average emission factor for $SO_2$, NO and $NO_2$ from dung cake, fuel-wood and crop residue in that region, and the following results as presented here $SO_2$: 0.28-0.09 g $kg^{-1}$, 0.26-0.10 g $kg^{-1}$ and 0.27-0.11 g $kg^{-1}$, NO: 0.27-0.21 g $kg^{-1}$, 0.41-0.25 g $kg^{-1}$ and 0.54-0.50 g $kg^{-1}$ and $NO_2$: 0.31-0.23 g $kg^{-1}$, 0.35-0.28 g $kg^{-1}$ and 0.54-0.47 g $kg^{-1}$ respectively).

McCracken and Smith [84] studied the thermal efficiency and emissions of an improved biomass cookstove named 'Plancha mejorada' with respect to traditional three stone fire which was distributed and promoted in Guatemala using water boiling test (WBT) and a standardized cooking test (SCT). There was no significant difference in the efficiency of both the cookstove. However, the plancha cookstove took more time to perform both the tests but emit less total suspended particles and carbon mono-oxide (CO) per kilo-joule (KJ) of useful heat produced. They stated that the relation between improved thermal efficiencies and reduction of indoor pollutants could not establish due to the use of improved biomass cookstoves.

Kandpal et al. [85] studied the indoor air pollution, caused by a traditional and an improved mud cookstove (Sugam-II) by the combustion of four biofuels (fuel wood, dung cakes, agri-residue, and a mixture of fuelwood and dung cakes) in it. Their results showed that the concentrations of both CO and NO were higher than prescribed safe limits. The traditional cookstove released 50-40% more HCHO than that of the improved mud cookstove [86]. The results obtain indicated that the combustion of cow dung cakes had considerably higher concentrations of CO in the indoor environment and concentration of air pollutants was found to be maximum in the kitchen at the breathing level height of a standing person.

Dutta et al. [87] described the change in indoor air quality (IAQ) in the kitchens after the introduction of the ICSs for one year under field conditions in Maharashtra (India) after controlling a number of variables. The Appropriate Rural Technology Institute (ARTI), in conjunction with other non-governmental organizations, helped to establish the rural enterprises which subsequently distributed 30,000 improved cement cookstoves in Maharashtra, India between August, 2004 and December, 2005. They reported that the CO concentration on an average was reduced within the one year of installation of these cookstoves, by 39% for the Laxmi and 38% for the Bhagyalaxmi. Similarly, the $PM_{2.5}$ concentration was reduced, by 24% for the Laxmi and 49% for the Bhagyalaxmi cookstoves respectively.

Roden et al. [88] studied the field and laboratory emissions from traditional and improved biomass cookstoves in Honduras. They found that the measured particulate emissions of actual cooking in the field as around three times higher as compared to the simulated cooking in the laboratory and the emission factors are highly dependent on the skill of the cook. They measured the emissions from traditional cookstoves, new improved cookstoves, and ‘‘broken-in’’ improved cookstoves for three summers and found that the well-designed improved cookstoves significantly reduced the PM and CO emission factors as compared to the traditional cookstoves.

Mestl and Edwards [89] derived more appropriate ventilation factors for the rural population in China based on detailed measurements of indoor air pollution as a part of quantitative assessment of the Chinese national improved stove program (CNISP) in rural China. The fuel based approach used a ventilation factor to account for differences in the indoor air concentrations and exposures for different parts of the world based on regional differences in stove technology. They used these revised ventilation factors to estimate the burden of disease from household solid fuel use in Shaanxi, Hubei and Zhejiang provinces of China for cardiopulmonary and cardiovascular diseases.

Armendáriz-Arnez et al. [90] presented the differences in concentration of particulate matter in indoor air pollution as a result of biomass burning open fires cookstove and improved Patsari cookstoves in rural homes of Mexico, and stated that the adverse health impacts decreased due to installation of improved cookstoves as the concentration of particulate matter changed. Berrueta et al. [91] presented an integrated energy evaluation of an efficient wood-burning Patsari cookstove in comparison to the traditional cookstoves used in the rural communities of Michoacan (Mexico). The controlled cooking test and kitchen performance test of Patsari stoves showed that the fuelwood savings from 44% to 65% as compared to traditional open fires and 67% respectively.

Granderson et al. [92] examined the fuel use and design of an improved wood burning Plancha cookstove, comparison to the traditional cooking over an open wood fire. The study was conducted on five households over a period of four days using Kitchen Performance Test (KPT) and it was found that the KPT did not indicate any benefit with respect to fuel use.

Although there have been many studies in the literature which showed the reduction in the indoor air pollution. Johnson et al. [93] presented a simple Monte Carlo single-box model, which predicted indoor concentrations by giving a stove's emission performance and usage, as well as kitchen characteristics. They illustrated the utility of the model by presenting a simulated distribution of indoor air pollution concentrations in kitchens based on a series of stove/fuel scenarios and compared them with the air quality guidelines (AQGs) of world health organization (WHO) for particulate matter (PM) and carbon mono-oxide (CO). The overall picture of health effects and mechanism associated with each pollutant briefly were described, in Fig. 8 and in Table 2 below:

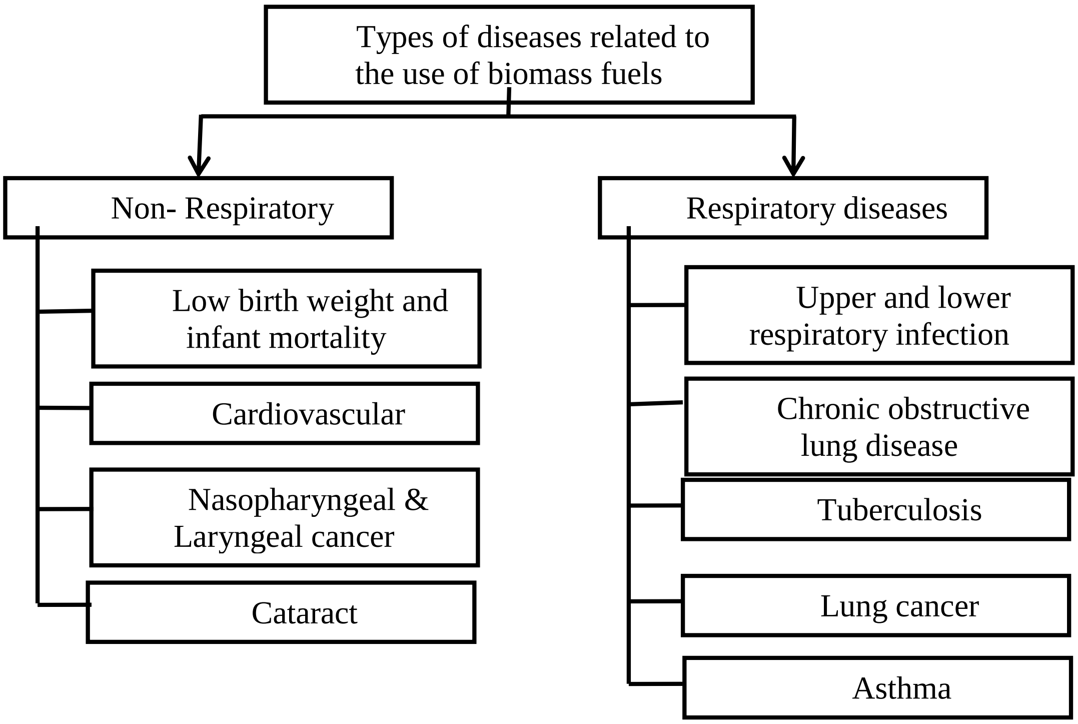



Fig.2.6: The impact of biomass fuel smoke on respiratory and other diseases [94].

Finally, the model was used to predict the stove performance characteristics that would be required for a given percentage of homes to meet the WHO AQGs. They concluded that there were several potential benefits from their modelling such as: i) estimate the potential impacts on indoor air pollution concentrations; ii) evaluate the impacts of critical stove performance parameters and environmental variables; and iii) provide a means to set stove performance standards which can be linked with air quality guidelines. Kim et al. [94] reviewed the health risks associate with cooking emissions in relation with the use of biomass and coal fuels.

### (iv) Respiratory Diseases

The fact that air pollution promotes adverse health effects is not new, studies on pollution derived from indoor sources has received considerably less attention, mostly because its effects are less evident. Saldiva and Miraglia [95] summarised the health consequences of prolonged exposure to indoor air pollution generated by biomass-burning cookstove. This kind of exposure was associated with respiratory, cardiovascular, reproductive and cancer outcomes. Considering that the use of biomass as fuel for cooking was almost entirely restricted to developing countries, some projections on the costs due to health consequences of this practice indicated that procedures must be implemented not only to avoid suffering caused to the population but also to remove the extra burden on weak economies. The firewood, cow dung and crop waste were the types of biomass used for cooking in most of the developing countries.

L´evesque et al. [96] conducted a study in Quebec City region (Canada) to compare the indoor air quality due to wood usage in heating appliances at homes. They measured the concentration of different contaminants (CO, $NO_2$, HCHO and $PM_{10}$) in houses with and without a wood-burning appliances and examined that the respiratory symptoms of the residents in the two categories of homes, as well as the relationship between the measured contaminants and the occurrence of symptoms. The residents who were exposed to fumes emitted by such an appliance, reported more respiratory illnesses and symptoms. They also concluded that the wood burning appeared to be a respiratory health risk for residents if the appliance could not be maintained and used properly.

Verma et al. [97] investigated the effect of different cooking fuels on the concentration of particulate matter and carbon monoxide (CO) in Gaborone (Botswana). Furthermore, the bad health conditions associated with particulate matter and CO could be associated with different types of fuels used for cooking. The study was conducted by monitoring the indoor air quality in 30 households, representing low, medium and high income groups by conducting interviews on the health conditions of the households' involved in cooking. They concluded that more particulate matter was found in the low income group households because these used cow dung, wood, plastic bags, paraffin, and Chibuku beer cartons as their cooking fuels. They also found that the people of low income households were the most affected as compared to those of the medium and high income groups.

Lal et al. [98] carried out a study to characterize and assess the histopathological changes observed in the lungs of rats using different period of exposure to cow-dung smoke and described the molecular mechanism of cellular toxicity caused by pollutant exposure in lung tissues of rats. They also concluded that the continuous exposure to cow-dung (kanda) smoke may lead to various respiratory disorders and increase the morbidity and mortality in the affected population.

Table 2.4: Pollutants and Mechanism emitted from biomass fuel [94].

| **Pollutant** | **Mechanism and health effects** |
|---|---|
| Particulate matter: particles less than 10µ especialy less than 2.5µ | Diseases like asthma, chronic obstructive pulmonary takes place due to the reduced mucociliary clearance; macrophage response and immunity fibrotic reaction. |
| Carbon monoxide | The carbon mono-oxide binds with haemoglobin to produce carboxy-haemoglobin, which reduces oxygen delivery to many organs of human body, causes low birth weight of small children. |
| Polycyclic aromatic hydrocarbons(PAH) | These are known as carcinogenic compounds causes premature deaths and cancer of lung, mouth, nasopharynx etc. |
| Nitrogen dioxide | The long term exposure increases the susceptibility to bacterial and viral infections in women and children which causes respiratory infections. |
| Sulphur dioxide | The serious exposure of sulphur dioxide increases bronchial reactivity which causes exacerbation of chronic obstructive pulmonary disease and cardiovascular disease. |
| Formaldehyde | It leads to upper airway irritation leading to increased sensitivity to allergens which may lead to bronchial asthma. |
| Benzopyrene | It is one of the many carcinogenic substances found in the smoke produced by biomass burning leading to lung, oral, nasopharyngeal and laryngeal cancer. |
| Biomass smoke | Toxins from the smoke are absorbed through the lens of the eye leading to oxidative damage and eventually cataract. |

### (v) Non-Respiratory diseases

Mondal et al. [99] investigated the possibility of genetic damage and repair in a group of premenopausal women in eastern India who were chronically exposed to the high level of indoor air pollution (IAP) while cooking with unprocessed solid biomass such as dung cake, wood and agricultural wastes. For assessment of genotoxicity, they have used micronucleus (MN) assay in exfoliated buccal (BEC) and airway epithelial cells (AEC) for the assessment of chromosomal damage and single cell gel electrophoresis (Comet assay) in peripheral blood lymphocytes (PBL) for the detection of DNA damage. They concluded that the chronic exposure to biomass smoke causes chromosomal and DNA damage and up-regulation of DNA repair mechanism. Li et al. [100] evaluated the effectiveness of the improved stoves in two separate Programs through air monitoring and bio-monitoring in Peru. They measured particulate matter (PM) and carbon mono-oxide (CO) in kitchen and personal air samples of participating households before and after the installation of new stoves with chimney. They concluded that improved stoves with chimney significantly reduced the human exposure to hazardous combustion products including polycyclic aromatic hydrocarbons (PAHs), particulate matter (PM) and CO. However, even after the intervention, urinary hydroxylate PAH (OH-PAH) levels in these subjects were still far exceeding than that of general population in the United States, higher than smokers, and at comparable levels to workers with known high occupational exposure to PAHs.

Northcross et al. [101] studied the levels of dioxin exist in village kitchens in Highland Guatemala using biomass fuel for cooking. They stated that the high concentration of smoke from cookstoves inside the kitchen create non-negligible exposures of households to dioxins, though the fraction of dioxins in wood smoke emissions is very less as compared to the fraction present in other sources. They explored that, in Highland Guatemala the concentration of airborne dioxin in households where wood fuel is used indoors for cooking purposes.

Mondal et al. [102] also investigated the possibility of DNA damage in buccal epithelial cells in a group of premenopausal women from eastern India who were chronically exposed to biomass smoke during cooking of food. In contrast, it was observed the chronic inhalation of biomass smoke elicits oxidative stress and extensive DNA damage in buccal epithelial cell (BEC) from biomass based cooking fuels.

# CHAPTER – 3

# MATERIALS AND METHODS

## 3.1 Materials

Different types of wood for testing cookstoves and the materials for the construction of cookstove were available at SSS-NIRE. Four different model of cookstoves were designed and fabricated in the workshop of SSS-NIRE for the experimental study, which work on the principle of down-draft gasifier. In these models pyrolysis, gasification and combustion are taking place simultaneously. For experimental analysis, the wood samples were crushed into powder form. The water boiling test for finding the thermal efficiency of cookstove was carried out according to BIS protocol. The proximate analysis of samples was performed by following ASTM standards. The ultimate analysis of samples were performed by CHNS-O analyser. Thermo-gravimetric analyses (TGA) of all biomass samples were performed by Thermo-gravimetric analyser and the gas analysis was done by Gas chromatography (GC). Finally analysis of energy and exergy efficiency was carried out as per Tyagi et al., 2012[103]. All results related to water boiling test, TGA, GC, elemental analysis, proximate, ultimate, exergy and energy analysis are shown in next chapter.

## 3.2 Experimental Methods

### 3.2.1 Test for thermal efficiency/water boiling test according to BIS standard (IS 13152)

Thermal efficiency of a cookstove may be defined as the ratio of heat utilized to the heat produced by complete combustion of a given quantity of fuel based on the net calorific value of the fuel.

**(i) Test Room Conditions**

The room temperature shall be 25±5 ºC at the beginning. The air of the test room should be free from draughts which is likely to affect the performance of the chulha.

**(ii) Instruments and other Accessories**

a) Bomb calorimeter.

b) Mercury in glass thermometers 0-100 ºC).

c) Single pan balance 1 kg capacity (dial with least count of 10 g.).

d) Measuring jars; 1, 2 and 5 litre capacity.

e) Stop-watch or time measuring device.

f) Pairs of tong, metallic tray and sticks, etc. Piece of clean cloth.

**(iii) Fuel Preparation**

The fuel shall be Kail/Deodar/Mango/Acacia/Sheesham/Eucalyptus cut from the same log into pieces of 3x3 cm square cross-section and length of half the diameter/length of combustion chamber so as to be housed inside the combustion chamber. The fuel pieces shall be dried by the following method:

a) Weigh total quantity of wood (say 'M' kg.).

b) Pick up one piece and mark 'X' by engraving and take its mass (say 'm' g.).

c) Raise the temperature of oven up to 105 ºC.

d) Stack the wood pieces in a honey comb fashion inside the oven.

e) Maintain the oven temperature at 105 ºC.

f) After 6 hours, remove the marked 'X' piece, weigh it and note reduction in mass from 'm' g, if any. If reduction is observed put the marked piece in the oven again and repeat the weighing of 'X' marked piece after every subsequent 6 hours period till the mass is constant and no further reduction in mass is observed.

g) At this stage, weigh the total quantity of wood and note loss of mass from 'M' kg.

h) Determine the calorific value of the prepared wood with the help of bomb calorimeter.

**(iv) Determination of Burning Capacity Rate**

If the fuel burning rate per hour is not given by the manufacturer, the method described below shall be used to estimate the burning capacity of the chulha.

a) Stack the combustion chamber with test fuel in honey comb fashion up to 3/4 of the height or in a pattern recommended by the manufacturer.

b) Sprinkle 10 to 15 ml. of kerosene on the fuel from the top of chulha/fire box mouth.

c) Weigh the chulha with fuel; let the mass be M1 kg.

d) After half an hour of lighting weigh the chulha again and let the mass be M2 kg.

e) Then calculate the burning capacity of the chulha as heat input per hour as follows:

Heat input: per hour = 2 (M1 - M2) x CV kcal/h (3.1)

Where M1 = the initial mass of the chulha with test fuel in kg.

M2 = the mass of the chulha, after burning the test for half an hour in kg.

CV = calorific value of the test fuel in kcal/kg.

(Note: this weighing applies only to portable metal stoves)

**(v) Vessels**

The size of the vessel and the quantity of water to be taken for the thermal efficiency test shall be selected from the table 3.1 as given below, depending upon the burning capacity rating of the chulha.

Table 3.1: Mass of Water in the Pot according to Heat Input Rate

| S. No. | Heat Input Rate kcal/h | Vessel Diameter (Ext) mm (±5%) | Vessel Height (Ext) mm (±5%) | Total Mass with Lid g (±20 %) | Mass of Water in Vessel kg. |
|---|---|---|---|---|---|
| 1 | Up to 2,000 | 180 | 100 | 356 | 2.0 |
| 2 | 2001 – 2800 | 205 | 11 0 | 451 | 2.8 |
| 3 | 2801 – 3200 | 220 | 120 | 519 | 3.7 |
| 4 | 3201 – 3800 | 245 | 130 | 632 | 4.8 |
| 5 | 3801 – 4200 | 260 | 140 | 750 | 6.1 |
| 6 | 4201 – 4800 | 285 | 155 | 853 | 7.7 |
| 7 | 4801 – 5400 | 295 | 165 | 920 | 9.4 |
| 8 | 5401 – 6000 | 320 | 175 | 1100 | 11.4 |
| 9 | 6001 – 6600 | 340 | 185 | 1200 | 12.5 |
| 10 | 6601 – 7200 | 350 | 195 | 1310 | 14.0 |
| 11 | 7201 – 7800 | 370 | 200 | 1420 | 16.0 |
| 12 | 7801 – 8400 | 380 | 210 | 1530 | 18.0 |

**(vi) Procedure**

a) Take the test fuel according to burning capacity rating for one hour. Let the mass be 'X' kg.
b) Stack the first lot of test fuel in the combustion chamber in honey comb fashion or as indicated by the manufacturer.
c) Select and weigh the vessel with the lid in accordance with the table above. A minimum of two such vessels in a set will be required. Put the recommended quantity of water at 23 ± 2 ºC ($T_1$).
d) Sprinkle measured quantity 'X' ml. (say 10 - 15 ml.) of kerosene for easy lighting on the test fuel and light. Simultaneously start the stop watch.
e) Feeding of fresh test fuel lot shall be done after every 15 minutes.

f) The water in the vessel shall be allowed to warm steadily till it reaches a temperature of about 93 ºC, then stirring is commenced and continued until the temperature of water reaches 5 ºC below boiling point at a place. Note down time taken to heat the water up to final temperature (less than 5 ºC below the boiling point) $T_2$ ºC.

g) Remove the vessel of from the cookstove and put the second vessel immediately on the cookstove. Prepare first vessel for subsequent heating.

h) Repeat the experiment by alternatively putting the two vessels taken till there is no visible flame in the combustion chamber of the cookstove. Note down the temperature of the water in the last vessel.

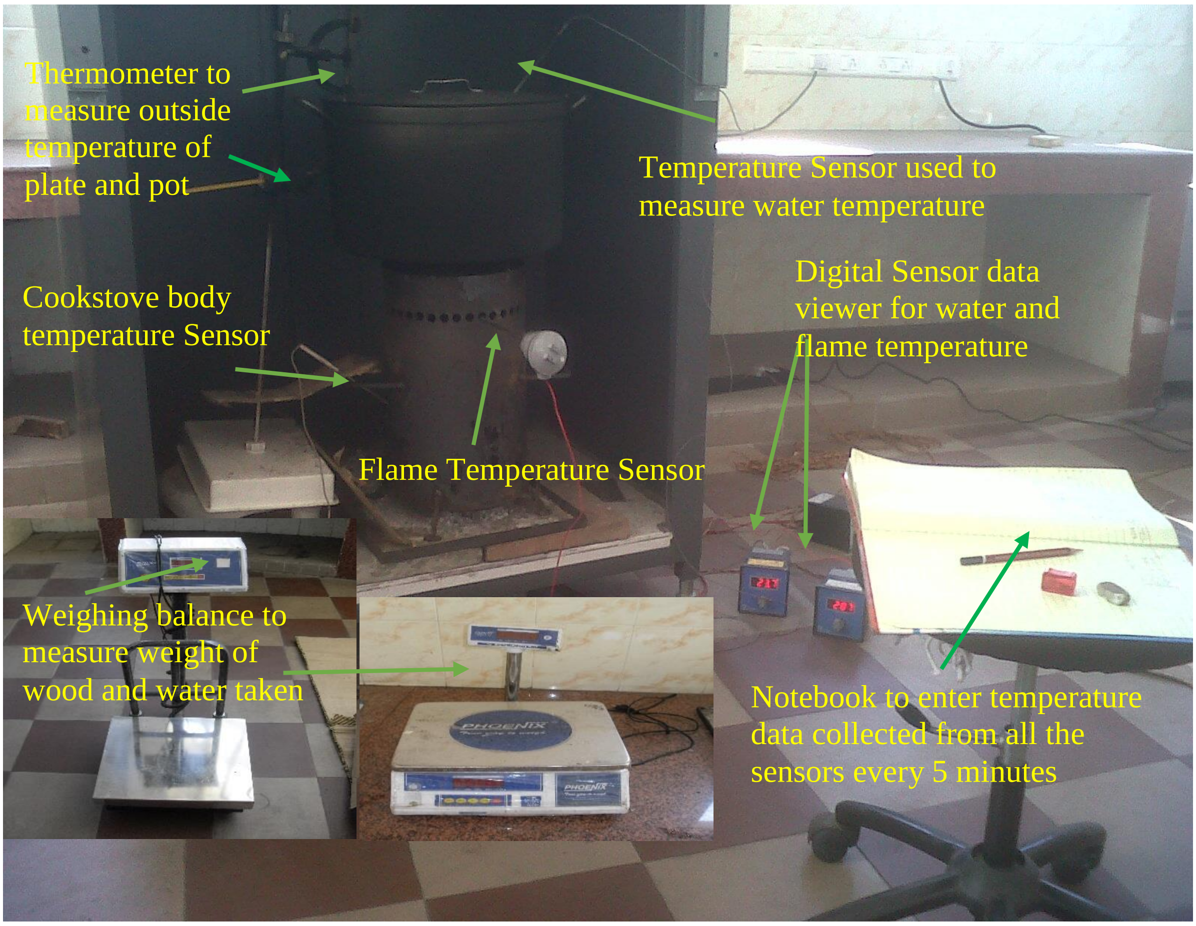



Fig. 3.1: Photographic picture depicting the basic lab settlement

**Formulas used**

Heat utilized= $\{(n-1)(W \times 0.896 + w \times 4.1868)(T_2 - T_1)(W \times 0.896 + w \times 4.1868)(T_3 - T_1)\}$ kJ

Heat produced= $4.1868\{(X \times c_1) + (x \times d \times c_2/1000)\}$ kJ

$$\text{Thermal efficiency } \eta = \frac{\text{Heat Utilized}}{\text{Heat Produced}} \times 100 \qquad (3.2)$$

$$\eta = \frac{\{(n-1)(W\times 0.896 + w\times 4.1868)(T_2 - T_1)(W\times 0.896 + w\times 4.1868)(T_3 - T_1)\}}{4.1868\{(X\times c_1) + (xd\,c_2/1000)\}}\times 100$$

where w = mass of water in vessel, in kg;

w = mass of vessel complete with lid and stirrer, in kg;

X = mass of fuel consumed, in kg;

$c_1$= calorific value of wood, in kcal/kg;

x = volume of kerosene consumed, in ml;

$c_2$ = calorific value of kerosene, kcal/kg;

d = density of kerosene, g/cc;

$T_1$= initial temperature of water in °C;

$T_2$ = final temperature of water, in °C;

$T_3$ = final temperature of water in last vessel at the completion of test, in °C; and

n = total number of vessels used. (Specific heat of aluminium = 0.896 kJ/kgºC).

(1 kcal = 4.186 8 kJ)

**(i) Power Output Rating**

The power output rating of a cookstove is a measure of total useful energy produced during one hour burning of fuel wood. It shall be calculated as follows:

$$\text{Power output rating} = \frac{F\times CV\times \eta}{3600\times 100}, \text{kW} \tag{3.3}$$

where F = quantity of fuel wood burnt, kg/h;

CV = calorific value of fuel wood, kcal/kg; and

H = thermal efficiency of the cookstove, as calculated above.

**(ii) Energy and Exergy analysis of cookstove**

The performance evaluation of different types of cookstoves has been done using energy and exergy analysis following earlier authors (Tyagi et al., 2012)[103] as below:

- **Energy Analysis**

An energy balance for the overall process:

Energy input – (Energy recovered+ Energy loss) = Energy accumulation (3.4)

Energy input is given by: $E_{in} = m_{wd}c_1 + x\times d\times c_2$ (3.5)

where $M_{wd}$ = mass of wood

$c_1$ = calorific value of wood

$c_2$ = calorific value of kerosene

x = volume of kerosene and

d = density of kerosene.

Energy output is given by: $E_o = m_w C_p (T_{fw} - T_{iw}) + m_{pot} C_{pA1} (T_{fp} - T_{ip})$ (3.6)

where $C_p$ = specific heat of water

$T_{fw}$ = final temperature of water

$T_{iw}$= initial temperature of water

$C_{pA1}$= specific heat of Aluminium

$M_{pot}$= mass of pot

$T_{fp}$ = final temperature of pot

$T_{ip}$ = initial temperature of pot

- **Exergy Analysis**

An overall exergy balance can be written as:

Exergy input–(Exergy recovered +Exergy loss)–Exergy consumption =Exergy accumulation

Exergy input is given by:

$$Ex_{in} = m_{wd} c_1 (1 - \frac{T_a}{T_{fuel}}) \times \eta + x \times d \times c_2 \quad (3.7)$$

Where:

$T_a$ = ambient temperature

$T_{fuel}$ = temperature of burning fuel

The exergy output is given by:

$$Ex_o = m_w C_p (T_{fw} - T_{iw})(1 - \frac{T_a}{T_{fw}}) + m_{pot} C_{pA1} (T_{fp} - T_{ip})(1 - \frac{T_a}{T_{fp}}) \quad (3.8)$$

In general, energy efficiency is defined as the ratio of output energy to input energy and can be written as:

$$\eta = \frac{\text{Energy output}}{\text{Energy input}} = \frac{E_o}{E_{in}} \quad (3.9)$$

And in general, exergy efficiency is defined as the ratio of output energy to the input exergy and given by:

$$\psi = \frac{\text{Exergy output}}{\text{Exergy input}} = \frac{E_o}{E_{in}} \tag{3.10}$$

### 3.2.2 Proximate Analysis

Composition of wood samples were analysed by grinding them in powder form. The proximate analysis consisted of moisture, ash, volatile matter and fixed carbon measurement on dry basis was performed and ultimate analysis by CHNS-O analyser was used to find out percent carbon, hydrogen, nitrogen, sulphur and oxygen present in the biomass.

**(a) Determination of Moisture content**

**(i) Apparatus**

An ordinary drying oven with openings for natural air circulation and capable of temperature regulation of 105 ± 1°C shall be used, ceramic crucible, desiccators.

**(ii) Procedure**

- Place the samples in an airtight container immediately after collection. Maintain the samples in the airtight container whenever possible to prevent gains or losses in moisture from the atmosphere.
- Place the crucible for 30 min at 105 °C for removal of moisture in the Oven. Then cool in desiccators to room temperature. Weigh to the nearest 0.02 g and record as crucible weight $W_c$.
- Place a minimum of 1 g of sample in the crucible, weigh the sample and crucible to the nearest 0.01 g, and record as initial weight, $W_i$.
- Place the crucible with sample in the oven for 1.5 h at 105 ± 1°C.
- Remove the sample and the crucible from the oven and cool in the desiccators to room temperature and weigh immediately to the nearest 0.01 g, and record the weight $W_f$.
- Return the sample and crucible to the oven at 105 ± 1°C for 1 h. Repeat.
- Continue until the total weight change between weighing varies less than 0.2 % and record as the final weight.

**(iii) Formula used**

$$\text{Moisture}\% = \frac{w_i - w_f}{w_c - w_c} \times 100 \tag{3.11}$$

where $w_i$ = initial wt. of sample plus crucible

$w_c$ = wt. of empty crucible

$w_f$ = wt. of sample plus crucible after oven dry

**(b) Determination of Ash content**

**(i) Apparatus**

Muffle furnace for igniting the sample, Silica or porcelain crucible, Analytical balance, Drying oven, Desiccators.

**(ii) Procedure**

- Ignite the empty crucible in muffle furnace at 600 °C and cool in desiccators and weigh.
- Place 1g of sample in crucible and dry it in an oven at 100 to 105 °C. After 1 hr. replaces the crucible, cool in desiccators and weigh it. Repeat the drying and weighing until the weight is constant to within 0.1mg.
- Place the crucible with sample in a muffle furnace at 550 °C for 2 hr. and remember that all the carbon is eliminated from the sample. Avoid heating above this maximum temperature.
- Now remove the crucible from furnace and place it in desiccators to cool down and weigh accurately. Repeat the heating for 30-min periods until the weight after cooling is constant to within 0.2 mg.

**(iv) Formula used**

$$\%\,Ash = \frac{w_1}{w_2} \times 100 \qquad (3.12)$$

Where $w_1$ = weight of Ash

$w_2$ = weight of oven dry sample.

**(c) Determination of Volatile Matter**

Volatile matter was determined by establishing the loss in weight resulting from heating biomass under rigidly controlled conditions.

**(i) Apparatus**

Muffle furnace for igniting the sample, Silica or porcelain crucible, Analytical balance, Desiccators.

**(ii) Procedure**

- Weigh the empty crucible and record as crucible weight $w_c$. Place approximately 1 g of sample in the crucible and weigh the whole, record as initial weight $w_i$.
- Place the crucible with sample into the furnace chamber, which shall be maintained at a temperature of 950 ± 20°C for 7 minutes.
- Remove the crucible from the furnace; allow it to cool in desiccators.
- Weigh the crucible with sample as soon as cold to the nearest 0.1 mg and record as final weight, $W_f$.

**(iii) Formula used**

$$A = \text{Weight loss}\% = \frac{w_i - w_f}{w_i - w_c} \times 100 \quad (3.13)$$

Volatile matter% = A - % moisture (3.14)

**(d) Determination of Fixed carbon**

The fixed carbon is a calculated value. It is the resultant of the summation of percentage moisture, ash, and volatile matter subtracted from 100.

**(i) Formula used**

Fixed carbon% = 100 – (% Ash + % Volatile matter) (3.15)

### 3.2.3 Determination of Calorific Value

Estimation of gross and net calorific value/heating value of wood was calculated with the help of bomb calorimeter of Toshniwal make as shown in the figure 3.2. The waste wood was burnt in a stainless steel sealed chamber (Bomb) under high oxygen pressure. It provides a simple, inexpensive and accurate method for determination of heat of combustion, calorific values, and sulfur contents of solid & liquid fuel. Before using bomb calorimeter it was calibrated by the combustion of known calorific value fuel (benzoic acid). The gross (HHV) and net (LHV) calorific values for all biomass are shown in Chapter 4.

**Equation Use for Calculating the Calorific Value (Dulong Formula)**

$$HHV = 33.86 \times C + 144.4 \times \left( H - \frac{O}{8} \right) + 9.428 \times S \tag{3.16}$$

$$LHV = HHV - 0.09 \times H \times 587 \tag{3.17}$$

Fig. 3.2: Bomb Calorimeter

### 3.2.4 Elemental Analysis of Biomass

This study was performed by Elementar make CHNS-O analyser, the analyser worked on the principle of "Dumas method" which involves the complete and instantaneous oxidation of the sample by "flash combustion". The combustion products were separated by a chromatographic column and C, H, N, S and O organic compounds were detected by the thermal conductivity detector (TCD), which gave an output signal proportional to the concentration of the individual Components of the mixture.


Fig. 3.3: CHNS (O) analyser

Analyser shown is in Fig.3.3. This instrument works with two modes first is for identification and determination of Carbon, Hydrogen, Nitrogen, and Sulfur using combustion tube at 1150°C temperature with helium as the carrier gas and second with oxygen supply for the better combustion, at around 850 °C temperature.

### 3.2.5 Thermo Gravimetric Analysis (TGA)

Experimental tests were carried out in both inert and air atmospheres to investigate different steps of thermal degradation of each wood sample and to determine activation energy parameters. In general, TGA Measurement are used primarily to determine the decomposition of material and to predict their thermal stability at temperature up to 1000 $^0$C, Photographic view of TGA is shown in Fig. 3.4. In kinetic studies Low heating rates generally up to 40°C/min are preferred. To explore the kinetics of thermal decomposition of waste biomass TGA was performed on Perkin Elmer instrument model 2000 at 30°C to 950°C temperature with a constant heating rate at 20°C and gas flow rates like 20 ml/min in air atmosphere and a constant nitrogen flow rate at 20 ml/min for pyrolysis. The balance was calibrated with the given standards according to TGA instruction. In this study biomass particles are distributed in cylindrical shaped holders or crucibles. Gases (air and nitrogen) are used for determined the combustion or pyrolysis characteristic of biomass.

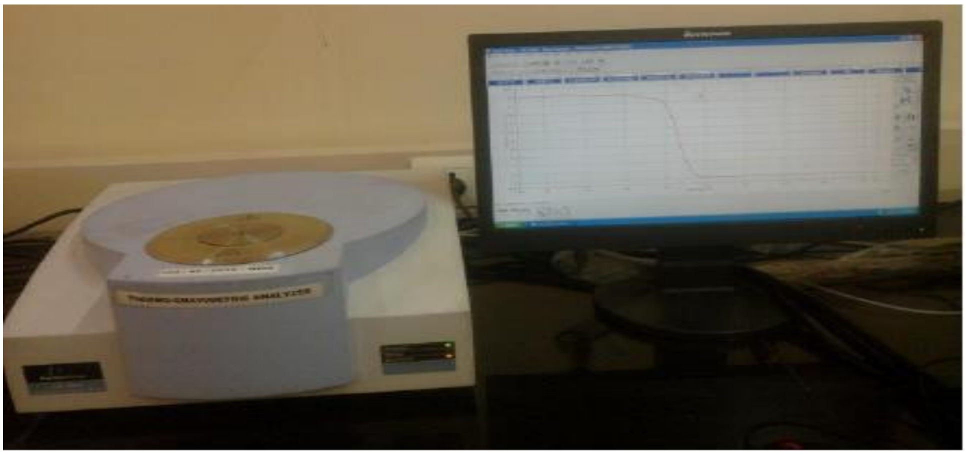


Fig. 3.4: Thermo gravimetric analyser

**(a) Method Used for Evaluation of Activation Energy from TGA Data**

Two methods were used for evaluation of kinetic parameters:

- Friedman method
- Differential method (direct Arrhenius method)

### (i) Activation energy $E_a$

It is defined as the minimum energy required for starting a chemical reaction i.e. the minimum energy that possessed by the reacting molecules before the reaction Activation energy is denoted by $E_a$ with a unit of kJ/mol. From the kinetic theory of gases the factor $\exp\left(-\frac{E_a}{RT}\right)$ gives the fraction of collision between molecules that together have this minimum energy.

**Evaluation by Friedman method**

General kinetic equation is given by

$$\ln\frac{dx}{dt} = \frac{A}{\beta}\exp\left(-\frac{E}{RT}\right)f(x) \tag{3.18}$$

$$\ln\left(\frac{\beta dx}{dT}\right) = \ln f(x) + \ln A - \frac{E}{RT} \tag{3.19}$$

Substitute dT/dt for β in the above equation (3.17), we get equation (3.18) as follows:

$$\ln\left(\frac{dx}{dt}\right) = \ln f(x) + \ln A - \frac{E}{RT} \tag{3.20}$$

Where f(x) = A (1-x) so, Friedman method can also be expressed mathematically as

$$\ln\left(\frac{dx}{dt}\right) = \ln[A(1-x)] + \ln A - \frac{E}{RT} \tag{3.21}$$

Equation (3.21) is known as the Friedman equation, which can be used to calculate the kinetic parameters without the need for a mathematical model. By, plotting $\ln\left(\frac{dx}{dt}\right)$ and $\frac{1}{T}$ curves can get a straight line which gives the activation energy (E), (Changbo et al., 2009). The results are reported in chapter 4.

### (ii) Evaluation by Differential method

Thermo gravimetric data can be used to characterize the materials (solid or liquid samples) to determine the thermodynamics and kinetics of the reactions (Chand et al., 2009). The kinetic analysis used for the thermal conversation of the biomass is discussed below. The rate of conversion, dx/dt for the biomass conversion is expressed by

$$\frac{dx}{dt} = kf(x) = k(1-x)^n \tag{3.22}$$

Where n is the order of reaction, k is the reaction rate constant and x is the extent of conversion x is given by

$$x = \frac{w_o - w_t}{w_o - w_f} \tag{3.23}$$

Where, $W_0$, $W_t$ and $W_f$ are the initial weight, weight at time t and final weight of the sample respectively. It is based on the TGA thermo - gram, reaction (1) was found to be of first order, thus n =1 and equation (1) becomes

$$\frac{dx}{dt} = k(1-x) \tag{3.24}$$

For the non-isothermal case, the above equation can be further modified to

$$\frac{dx}{dt} \cdot \frac{dT}{dx} = k(1-x) \tag{3.25}$$

Where dT/dt is the heating rate = β

According to the Arrhenius relationship, the reaction rate constant k is given by equation and can be expressed as

$$k = A\exp(-\frac{E}{RT}) \tag{3.26}$$

Where Ea is the activation energy, R gas constant and T is the temperature. For the direct Arrhenius plot method for the non-isothermal kinetic parameters with constant heating rate (β=dT/dt), equation (4) was rearranged to

$$\ln\left[\frac{1}{1-x}\frac{dx}{dt}\right] = \ln\left(\frac{A}{B}\right) - \left(\frac{E}{RT}\right) \tag{3.27}$$

The plot of $\ln\left[\frac{1}{1-x}\frac{dx}{dt}\right]$ versus $\frac{1}{T}$ should give a straight line with slope (-E/RT) from which the activation energy, E can be calculated.

### 3.2.6 Gas Chromatography

With the help of gas chromatography with Porapack column, the percentage of various gases emitted from the cookstoves were determined. The photographic view of the NUCON make gas chromatograph used in the experimental study is shown in the Fig. 3.5. This instrument operates in two different modes one is the TCD and other one is FID. For gas analysis TCD was used with oven temperature 70°C. Argon (Ar) gas was used as the carrier gas with flow rate of 10 ml/min. Results with percentage composition of $CO_2$, CO, $NO_x$ and $CH_4$ were obtained with the graphical representation.

Fig. 3.5: Photographic view of Gas chromatograph

### 3.2.7 Method used for calculating Emission reduction [UNFCCC, 2013]

**The formula for emission reductions is given as below:**

$$ER_y = B_{y,savings} \times f_{NRB,y} \times NCV_{biomass} \times EF_{projected\_fossilfuel} \quad (3.28)$$

where

$ER_y$ Emission reductions during the year y in $tCO_{2e}$

$B_{y,savings}$ Quantity of woody biomass that is saved in tonnes

$f_{NRB,y}$ Fraction of woody biomass saved by the project activity in year y that can be established as non-renewable biomass

$NCV_{biomass}$ Net calorific value of the non-renewable woody biomass that is substituted (IPCC default for wood fuel, 0.015 Tj/tonne)

$EF_{projected\_fossilfuel}$ Emission factor for the substitution of non-renewable woody biomass by similar consumers. Use of value of 81.6 $tCO_2$/TJ

$$B_{y,savings} = B_{old} \cdot \left(1 - \frac{\eta_{old}}{\eta_{new}}\right) \quad (3.29)$$

where

$B_{old}$ Quantity of woody biomass used in the absence of the project activity in tonnes

$\eta_{old}$ Efficiency of the baseline system being replaced, measured using representative Sampling methods or based on referenced literature values (fraction), use weighted Average values if more than one type of system is being replaced; a default value of

0.10 may be optionally used if the replaced system is the three stone fire or a Conventional system with no improved combustion air supply or flue gas Ventilation system i.e., without a grate or a chimney; for other types of systems a Default value of 0.2 may be optionally used.

$\eta_{new}$ Efficiency of the system being deployed as part of the project activity (fraction), as Determined using the water boiling test (WBT) protocol. Use weighted average Values if more than one type of system is being introduced by the project activity.

# CHAPTER-4

# RESULTS AND DISCUSSION

### 4.1 Designed of Developed Cookstove Models

Different types of cookstove models were designed, fabricated and tested for the experimental study, besides, the traditional cookstove was modified by using grate and by providing top space. Further, on the basis of results obtained from experimental study of the NIRE 3 cookstove other three models were designed and fabricated but due to time constraint they were not tested. Cast iron was used as material of construction for improved biomass cookstove and for the insulation purpose simply the mixture of mud and wheat straw was used. Besides this, one cookstove (traditional cookstove) was modified using same material as for traditional one except the iron grate was used in this model. Other than the modified traditional and fabricated biomass cookstoves, experimental study was also carried out on already developed models of different makes. The photographic view and schematic diagram of modified traditional cookstove is shown as below:

Fig. 4.1: Photographic views of the modified traditional cookstove (NIRE 02)

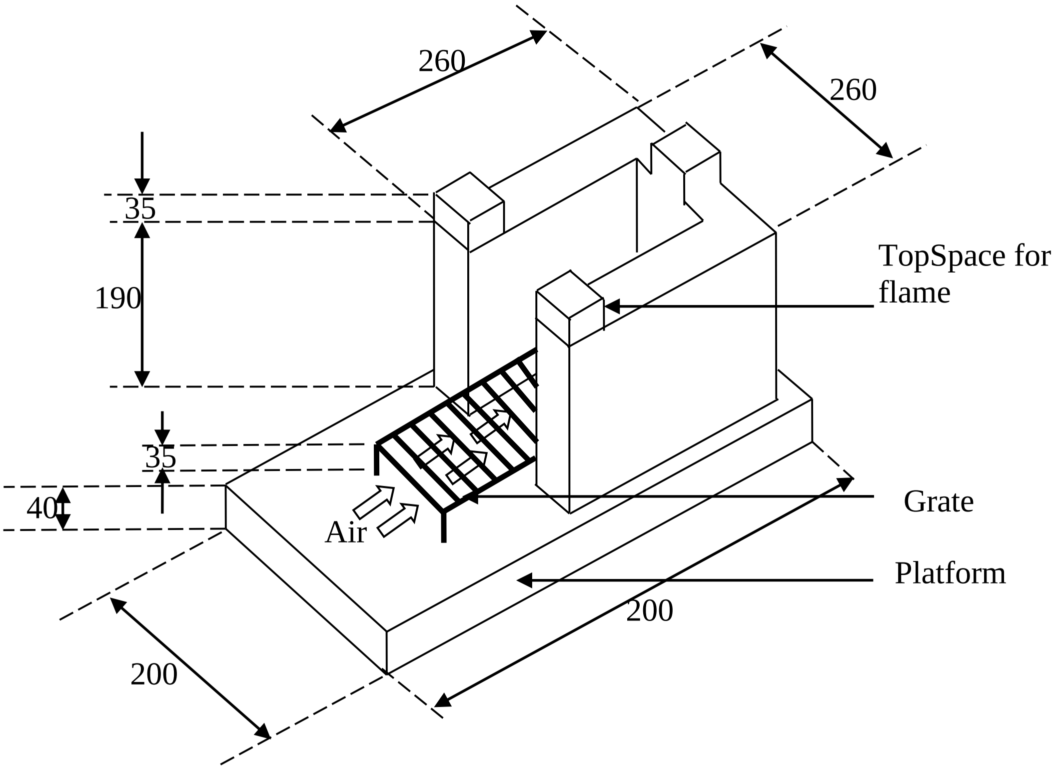



Fig. 4.2: Schematic diagram of modified traditional Cookstove (NIRE-02)

NIRE-03 NIRE-04 NIRE-05 NIRE-06

Fig. 4.3: Photographic views of fabricated cookstove model**s**.

NIRE-03 was the first model which was designed and fabricated, during this study using locally available material for insulation. It was tested thoroughly and from the results obtained further three models named, NIRE-04, NIRE-05 and NIRE-06 with model air gap which decreased the thermal conductivity and allowed to decrease the insulation size and transportation costs of cookstove.

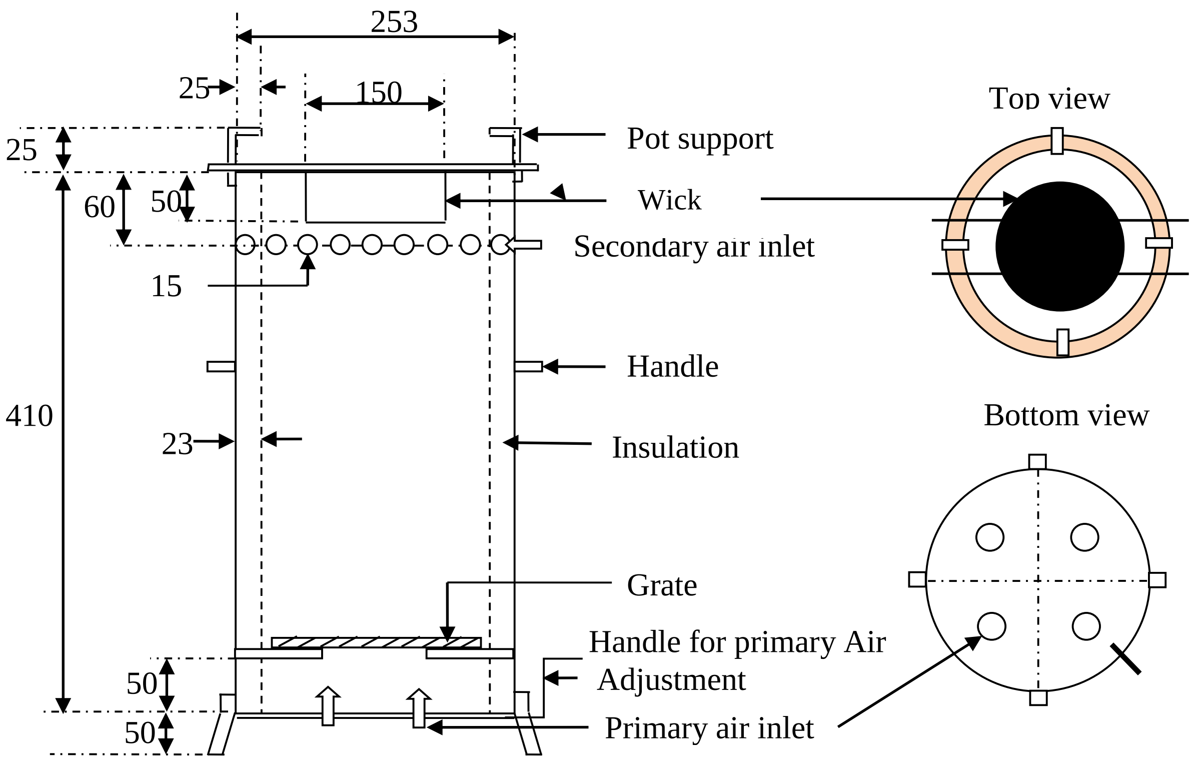



Fig. 4.4: Schematic diagram of (NIRE-03)

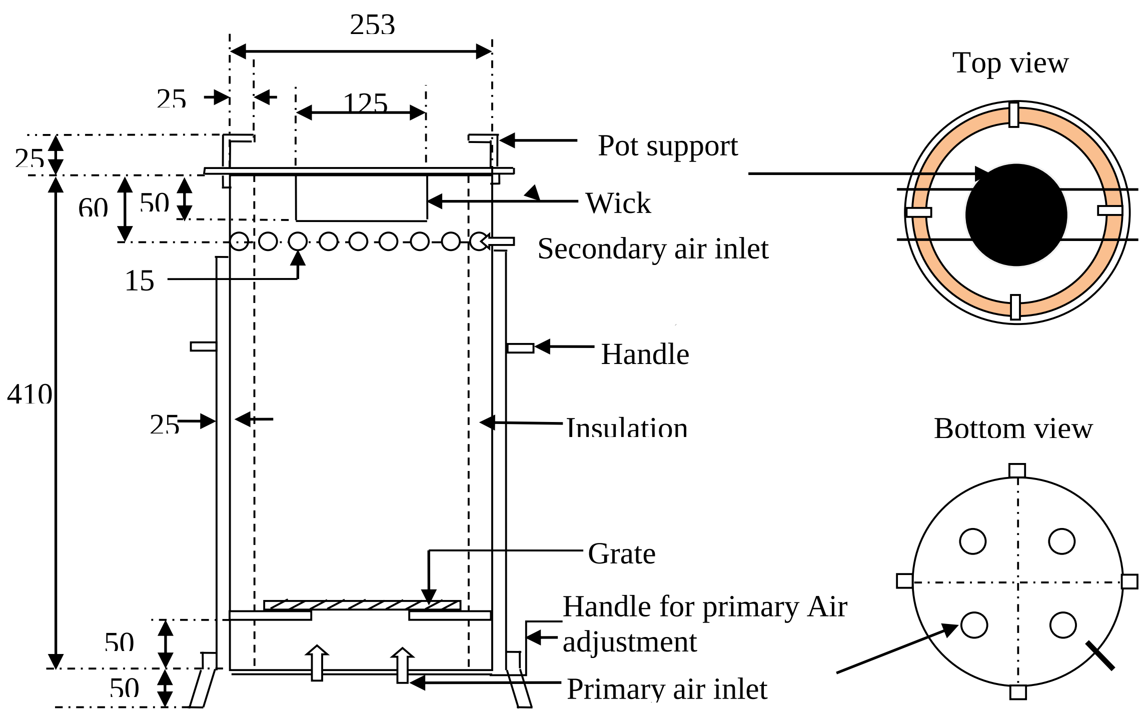



Fig. 4.5: Schematic diagram of (NIRE-04)

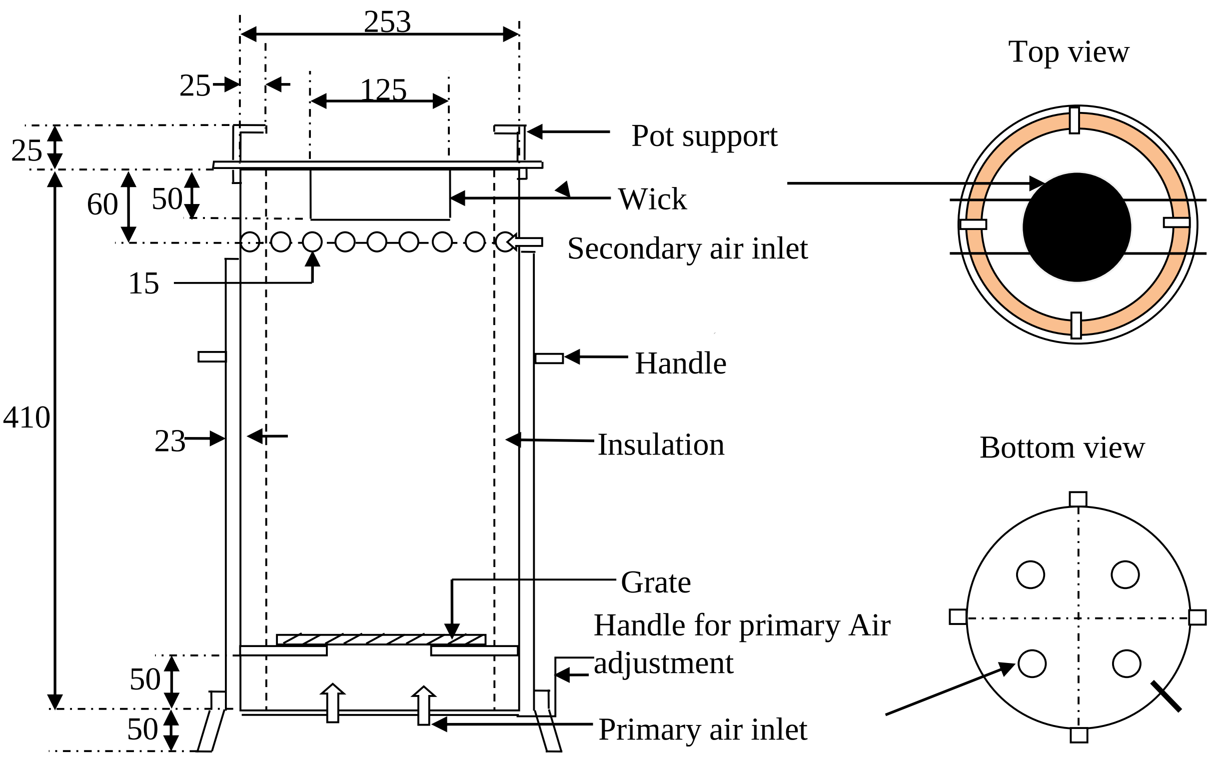



Fig. 4.6: Schematic diagram of (NIRE-05)

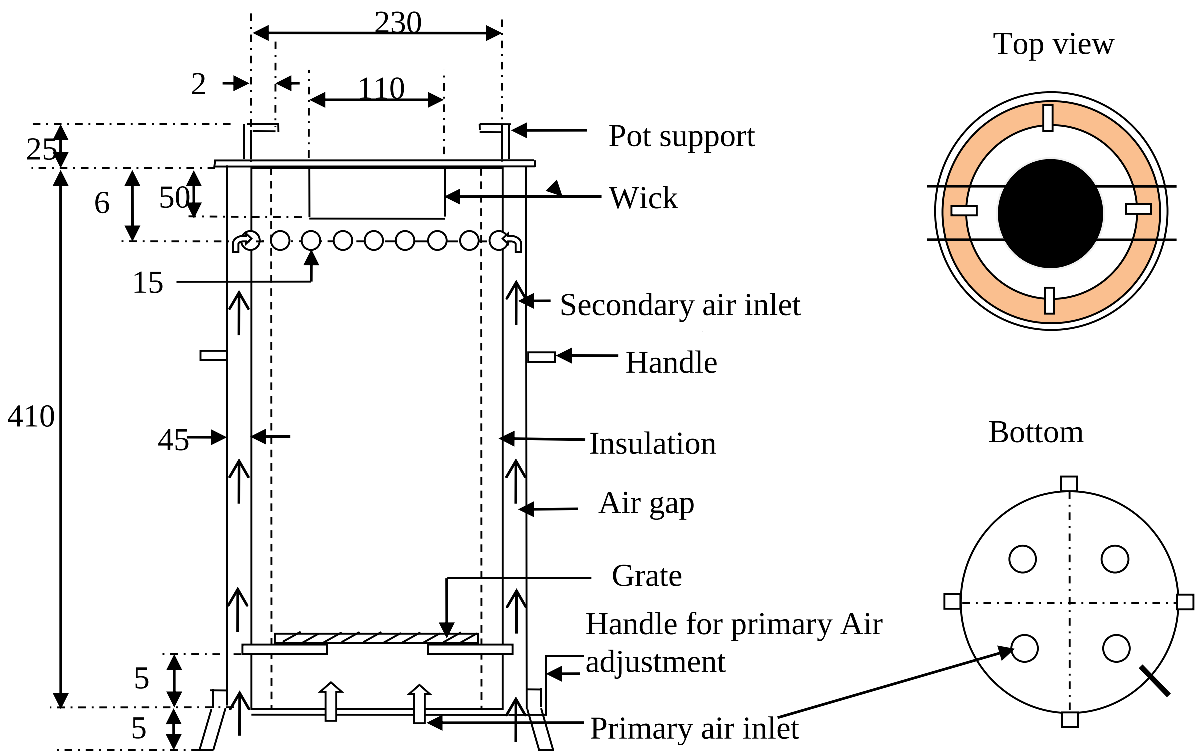



Fig. 4.7: Schematic diagram of (NIRE-06)

## 4.2 Wood Sample analysis

Fabricated cookstove were tested for different wood samples available at SSS-NIRE. However as per the availability, sheesham wood was preferred for carrying out the experimental study. Muffle furnace, drying oven, desiccators and weighing balance were used for determination of moisture, ash, volatile matter and fixed carbon content. Elemental analyser was used for determination of chemical composition of C, H, N, S, and O in different wood samples. Bomb calorimeter was used to find out the calorific value of different wood samples. Gas chromatography (GC) was used to determine the percentage of different gases in the smoke emitted from the cookstove. Thermo-gravimetric analysis (TGA) was used to determine the degradation of wood with respect to temperature and the details of different analysis is given as below:

### 4.2.1 Proximate Analysis

The experiments had been carried out using the above mentioned methodology and the proximate analysis of the collected data was done as shown in Fig. 4.9. As can be observed from Fig. 4.9 the percentage of moisture, ash and fixed carbon was found to be highest in the sheesham wood as compared to other wood samples. The percentage of ash content was found to be the lowest in Eucalyptus wood. However, the volatile matter percentage was found to be the highest in the Sagwan wood whereas, it was found to be the lowest in the sheesham wood. As far as fixed carbon is concerned, it was found that mango wood is having the lowest fixed carbon as compared to other wood samples mentioned above.

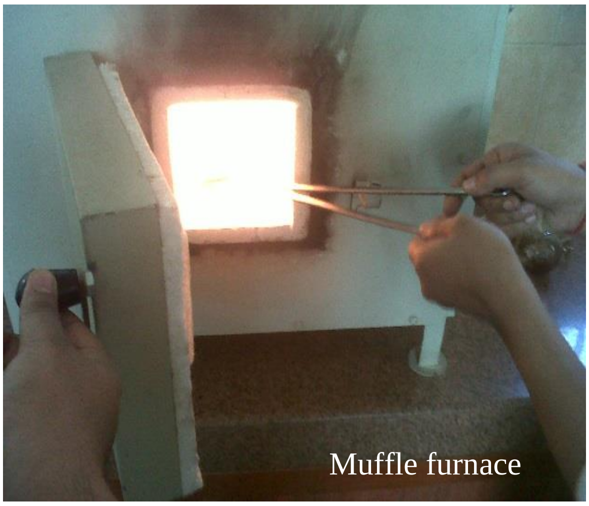




Fig. 4.8: Muffle furnace used for proximate analysis and Hot air oven for moisture reduction.

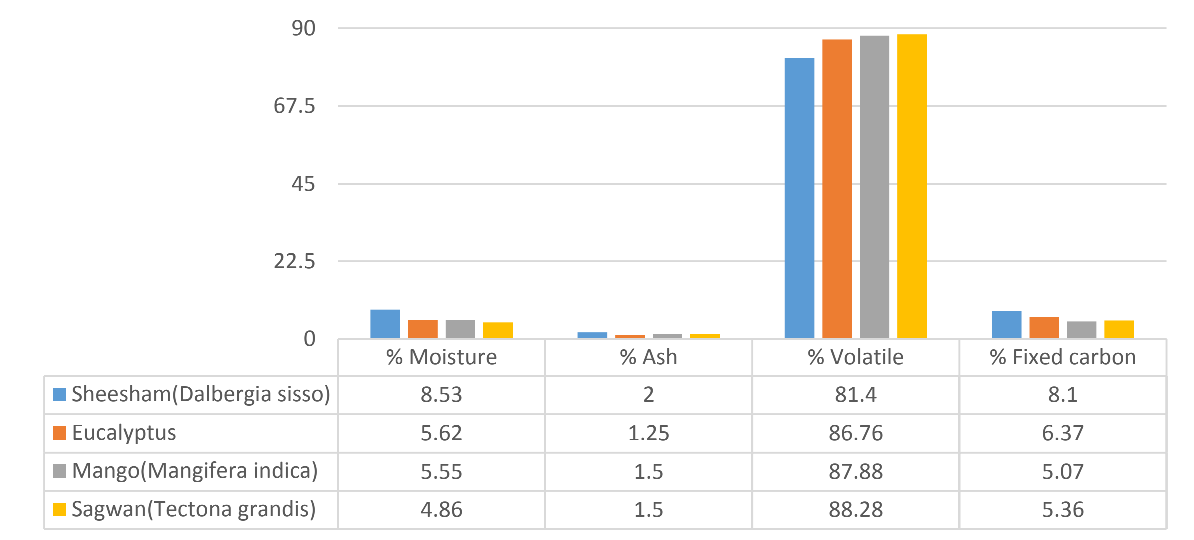



Fig. 4.9: Proximate analysis

### 4.2.2 Ultimate Analysis

And the results of ultimate analysis are shown in the Table 4.10. In this experiment the percentage of different components viz. C, H, N, S and O was calculated via elemental analyser instrument. As can be seen from Table 4.1 the percentage of carbon and nitrogen was found to be highest in sheesham and the percentage of hydrogen was found to be the maximum in sagwan, while percentage of sulphur was found to be high in Sheesham whereas the percentage of oxygen was found to be highest in the mango wood. Based on the results the calorific value of wood was calculated using theoretical/analytical formulation [eq. 3.16 and 3.17].

Table 4.1: Ultimate analysis of different wood sample

| **Feed stock (wood)** | **%C** | **%H** | **%N** | **%S** | **%O** | **Empirical formula** |
|---|---|---|---|---|---|---|
| Sheesham*(Dalbergia sisso)* | 48.515 | 6.242 | 1.160 | 0.0 | 44.082 | $C_{49}H_{75}O_{33}N$ |
| Eucalyptus | 48.050 | 6.510 | 1.160 | 0.0 | 44.280 | $C_{48}H_{78}O_{33}N$ |
| Mango(Mangifera indica) | 44.955 | 6.375 | 1.670 | 0.0 | 47.001 | $C_{31}H_{53}O_{25}N$ |
| Sagwan*(Tectona grandis)* | 47.825 | 6.648 | 0.990 | 0.0 | 44.538 | $C_{56}H_{93}O_{39}N$ |

### 4.2.3 Determination of Calorific Values

Calorific values of wood samples was determined by ultimate analysis data and the results are shown in Fig. 4.10, It can be observed that the high heating value (HHV) for Sagwan wood found to be the highest followed by Eucalyptus and Sheesham while it is found to be the lowest for the Mango wood. However, the low heating value (LHV) was found to be the lowest for Mango while it is found to be the highest for Sagwan wood.

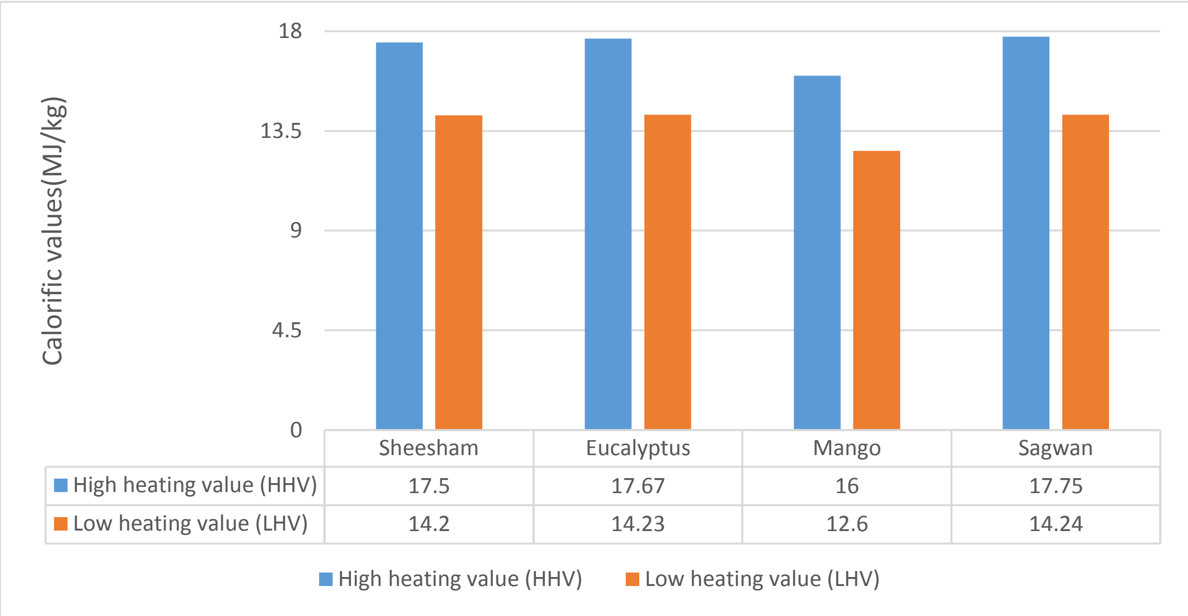



Fig. 4.10: Calorific values of different wood samples.

### 4.2.4 Determination of Activation Energy

The activation energy of different types of wood was determined by thermo gravimetric analysis at heating rate of 20°C/min first with air at flow rate 20 ml/min and then with nitrogen gas at the same flaw rate. Figs. 4.11 & 4.12 shows the percentage weight loss against temperature in air and nitrogen. From Fig. 4.11, it was found that all the wood samples have the initial weight loss of 3.5% in the temperature range of 30 to 100°C which is due to presence of moisture in wood samples. However, the weight loss percentage was found to be constant in the temperature range 100-210°C. The degradation behaviour of all types of wood was almost similar in this case. In the temperature range 210 to 400°C the degradation in weight percentage was sharp which is due to the combustion in this temperature range. After 400°C the weight loss became constant and ash started to form.

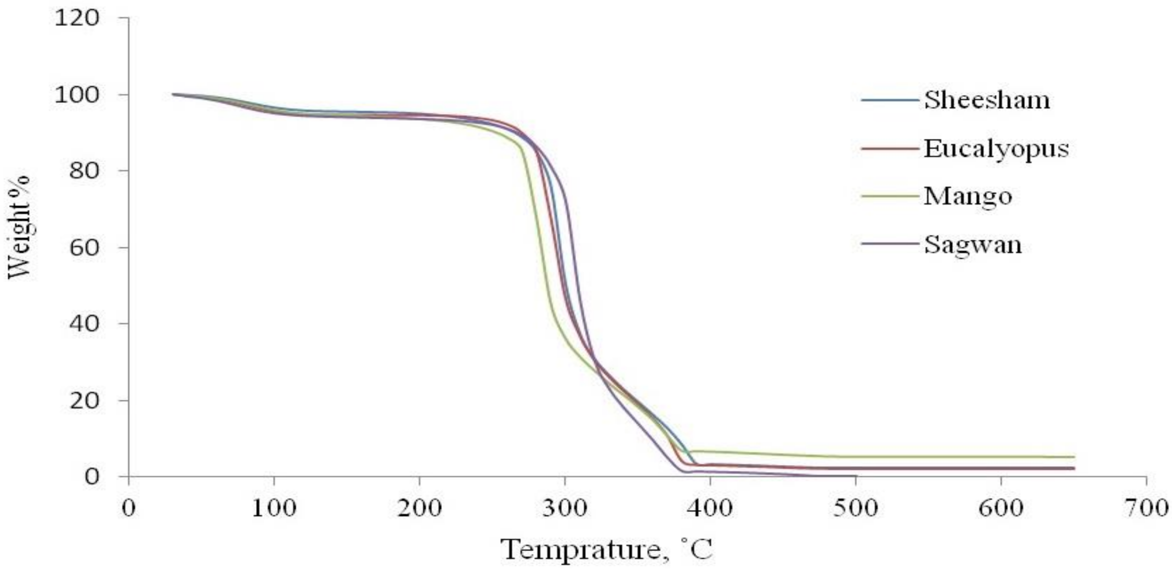



Fig. 4.11: TGA of wood in air atmosphere

Figure 4.12 shows the percentage weight loss with respect to temperature in the presence of nitrogen. All type of wood have the initial weight loss up to 3.7% due to the presence of moisture. In the range from 110 to 220$^{o}$C the weight loss was constant. In the nitrogen atmosphere Mango wood shows the abnormal behaviour and it is clear from the graph the degradation temperature is very low as compared to any other type of wood. The degradation of Sagwan wood was very sharp in the temperature range 220-380$^{o}$C and after that the weight loss was constant and ash was formed after 400 $^{o}$C. However, the degradation in the wood other than the Sagwan wood was found to be in the temperature range from 220-570$^{o}$C as can be seen from the Fig. 4.12. After the temperature 570$^{o}$C the percentage weight loss was found to be constant.

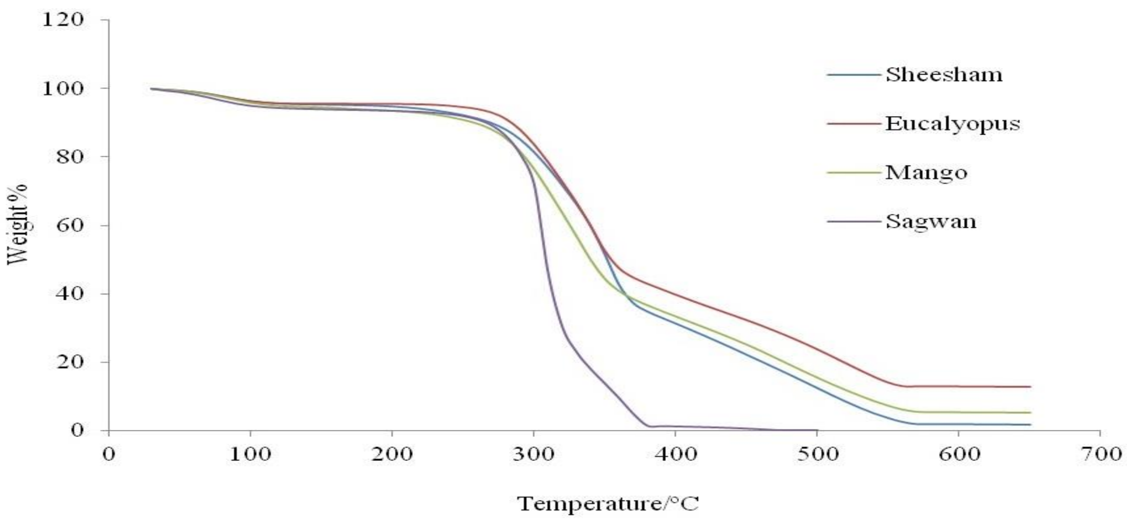



Fig. 4.12: TGA of wood in nitrogen atmosphere

The activation energy of all woods was calculated by two different methods first with Friedman method and then with Differential method (Direct Arrhenius plot) and the results are shown in Table 4.3. The activation energy of Sheesham wood was found to be 157.41 (kJ/mol) and 140.33 kJ/mol with two different methods viz. Friedman method and Differential method respectively and was highest as compared to the other woods tested. Therefore, it can be said that energy required for changing the Sheesham wood into gaseous product is high. However the activation energy of mango wood was found to be lowest as compared to the other woods which means that the energy required for mango wood is minimum to change it into gaseous products.

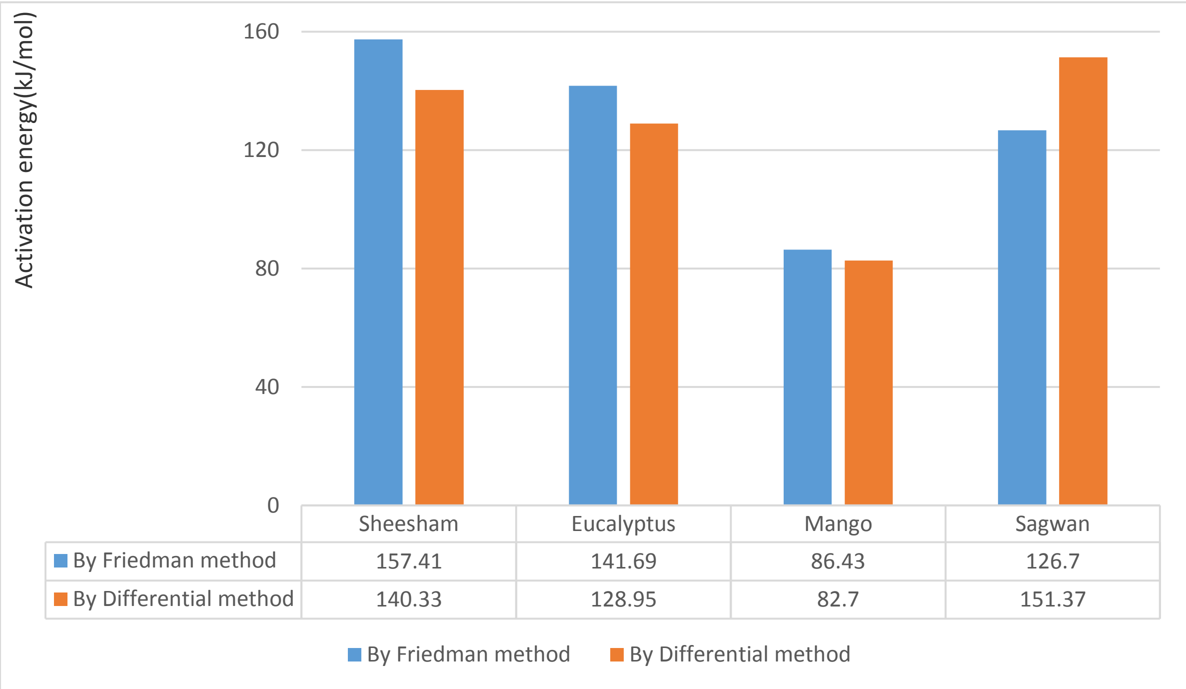



Fig. 4.13 Activation energy

### 4.2.5 Gas chromatography

The gas analysis of pollutants emitted from NIRE-03 cookstove model was done with the help of gas chromatography and results are shown in the Fig. 4.14 and Table 4.3 shows the different components detected in the smoke emitted from the cookstove with concentration amount and percentage amount of these gases. According to BIS protocol the ratio of $CO/CO_2$ should be less than 0.04 for a good improved biomass cookstove. From Table 4.5 it was found that this ratio comes out to be 0.035 which is in the range set by BIS. So this criterion was fulfilled by the new fabricated cookstove model NIRE-03.

Table 4.2: Analysis of Gas by Gas Chromatography

| S. No. | Compound name | Retention time, min | Concentration amount | Percentage amount |
|---|---|---|---|---|
| 1 | $CO_2$ | 2.03 | 30.57 | 39.57 |
| 2 | $N_2$ | 3.21 | 42.64 | 55.21 |
| 3 | $CH_4$ | 4.38 | 2.97 | 3.84 |
| 4 | CO | 5.56 | 1.07 | 1.38 |
| | | Total | 77.25 | 100.00 |

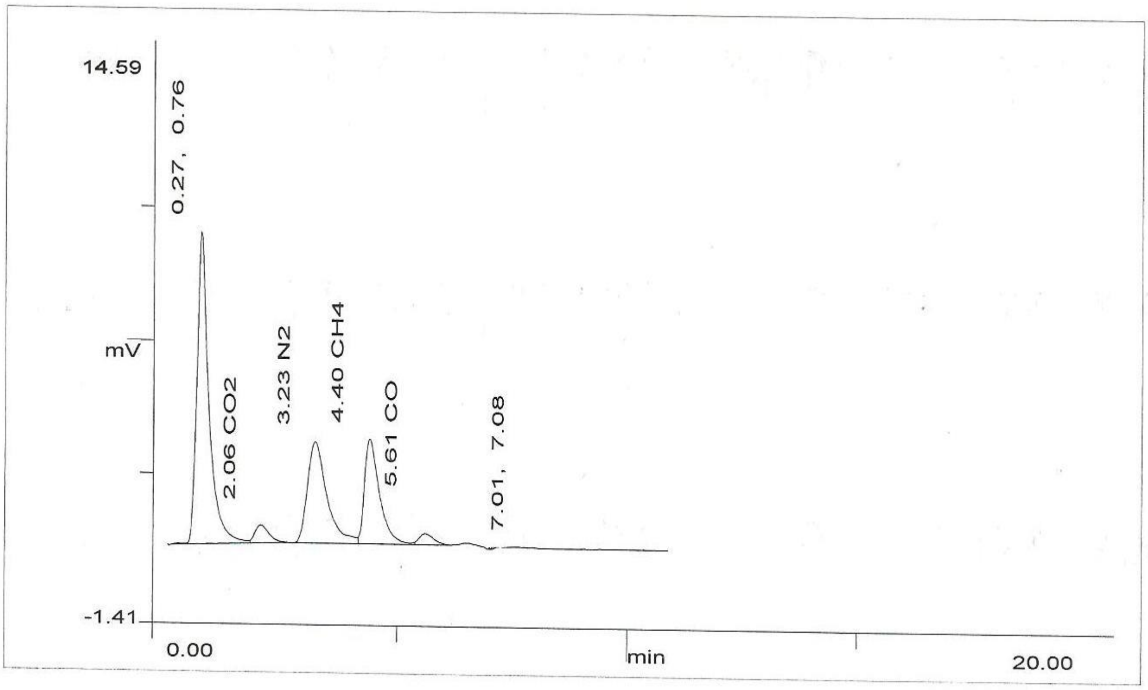
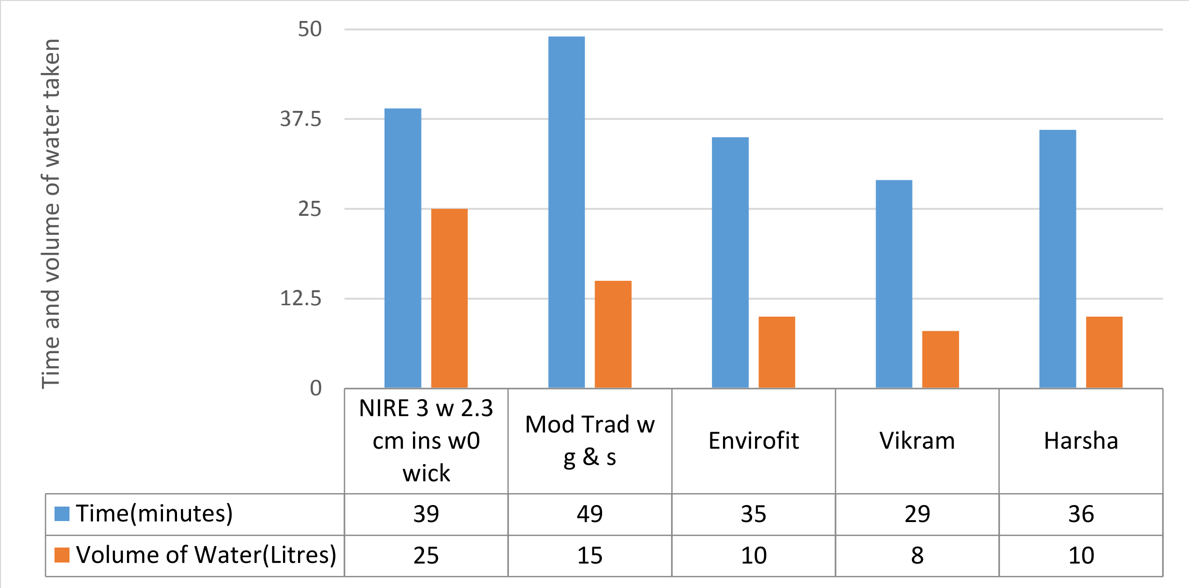



Fig. 4.14: Gas analysis of gases emitted from the NIRE-03 with Gas chromatography

Fig. 4.15 shows the variation in time taken to boil varying amount of water in different cookstove models. It was observed that the 25kg of water took only 39 minutes to boil in NIRE 3 model as compared to 49 minutes in traditional cookstove to boil 15 litres of water, 35 minutes for 10 litres of water in Envirofit model, 29 minutes for 8 litres of water in Vikram and 38 minutes for 10 litres of water in Harsha model. Therefore it can be inferred from the above that NIRE 3 has saved a lot of time from cooking which can help the family cooking food from devoting that time in doing some other work.




| | NIRE 3 w 2.3 cm ins w0 wick | Mod Trad w g & s | Envirofit | Vikram | Harsha |
|---|---|---|---|---|---|
| Time(minutes) | 39 | 49 | 35 | 29 | 36 |
| Volume of Water(Litres) | 25 | 15 | 10 | 8 | 10 |

Fig. 4.15: Variation of time taken to boil water in different models.

### 4.2.7 Thermal Efficiency of Cookstove Using Water Boiling Test (WBT)

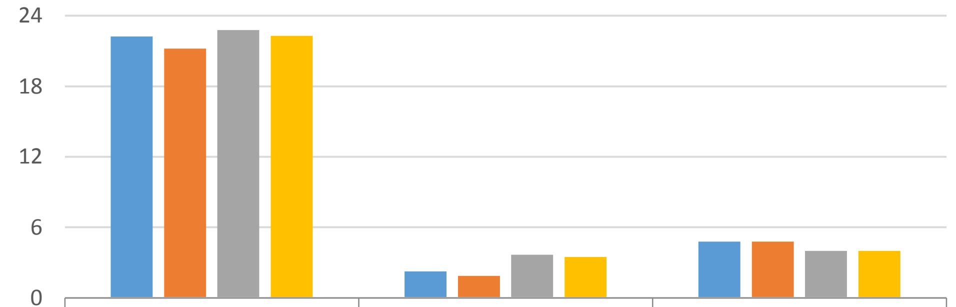
#### (a) Modified traditional Cookstove (NIRE-2)

The traditional cookstove was tested with certain modification such as:

- Tested without grate and without top spacing (gap between pot and top surface of the cookstove)
- Tested with grate.
- Tested with grate and top spacing
- Tested only with top space.

On the basis of modification done in the traditional cookstove various results were obtained by water boiling test following BIS protocol. All these modifications in the traditional cookstove model were evaluated by water boiling test with specific quantity of water in the aluminium container using the same type of fuel wood prepared as per the BIS standard. The quantity of water in the container was calculated using heating capacity rate of the cookstove. All the modification in traditional cookstove was tested with 3kg of wood. 15 kg of water as per BIS protocol. As the quantity of wood remained the same therefore the comparison between different modifications were done. The experimental data for each pot was collected manually. The temperature of water, pot, lid, ambient, flame and outer surface temperature of cookstove were measured at an interval of 5 minutes. The energy efficiency, exergy efficiency and the power output were evaluated for each experiment and plotted against the different modifications in the cookstove.

Fig. 4.16 shows the variation of energy efficiency, exergy efficiency and power output of traditional and modified traditional cookstove. From fig. 4.16 it is found that power output decreased with modifications in traditional cookstove. However mixed responses were found in case of energy and exergy efficiencies. Both the efficiencies were found to be highest for modified cookstove with top space and without grate i.e. energy efficiency of 22.79% and exergy efficiency of 3.68%. Least efficiency was observed in modified traditional with grate i.e. energy efficiency of 21.21% and exergy efficiency of 1.87. For modified traditional cookstove with grate and top space it was observed that grate introduction does increase the heat losses but it on contrary increases the quality of combustion, as in this model very few (only 5-7%) ash was left in comparison to traditional cookstove which shows that better combustion took place in this case .




| Model Type | Energy η | Exergy Ψ | Power Output |
|---|---|---|---|
| Traditional | 22.25 | 2.25 | 4.770814589 |
| Traditional with Grate | 21.21435014 | 1.868023408 | 4.797771324 |
| Traditional with S n g | 22.79148276 | 3.675940095 | 3.99904828 |
| Mod Trad w g & s | 22.29186719 | 3.464628379 | 3.996210672 |

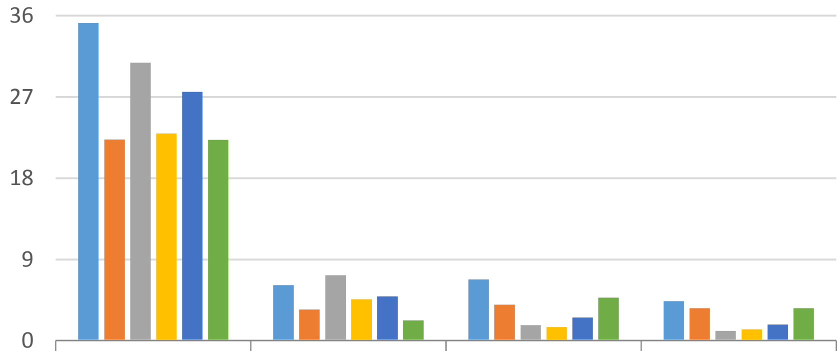
Traditional   Traditional with Grate   Traditional with S n g   Mod Trad w g & s

Fig. 4.16: Comparative study of NIRE-02 with different modifications.

**(b) Comparison of NIRE-03 with other available models:**

The schematic diagram of newly fabricated model is shown in Fig.4.1, and given the name as NIRE-03. Cast iron was used as a material of construction for biomass cookstove NIRE-03 and for insulation purpose simply mixture of mud and wheat husk was used. This model was tested with varying thickness of mud insulation, without insulation and also with or without wick. By following BIS protocol testing was carried out with 3kg of wood being used in all the experiments and the experimental data for each pot was collected manually. The temperature of water, pot, lid, ambient, dry, flame and outer surface temperature of cookstove were measured at an interval of 5 minutes. The energy efficiency, exergy efficiency, power output and the burning rate were evaluated for cookstove models.

Fig.4.17 shows the variation of energy efficiency, exergy efficiency, power output and burning output of NIRE 3 and modified traditional with grate and top space with other available models. It was observed that NIRE 3 had the highest energy efficiency which is almost 13% more than the traditional cookstove and 4.4% more than the most advanced cookstove present in the market i.e. Envirofit. From this, inference is made that approximately 236 Kg of wood/year can be saved per family i.e. approximately 47 days of fuel consumption saved. Which will further decrease the harmful gases that will be released by the burning of the saved wood.




| Model name | Energy η | Exergy Ψ | Power Output | Burning Rate |
|---|---|---|---|---|
| NIRE 3 w 2.3 cm ins w0 wick | 35.19352152 | 6.167541157 | 6.802832104 | 4.384 |
| Mod Trad w g & s | 22.29186719 | 3.464628379 | 3.996210672 | 3.6 |
| Envirofit | 30.79248573 | 7.247537571 | 1.71642191 | 1.078 |
| Vikram | 22.98 | 4.578681309 | 1.494827935 | 1.258 |
| Harsha | 27.58313211 | 4.918643432 | 2.571578854 | 1.803 |
| Traditional | 22.25 | 2.25 | 4.770814589 | 3.6 |

Fig. 4.17: Variation of energy efficiency, exergy efficiency, power output and burning rate

It was further observed from the calculations that NIRE 3 model came second in exergy efficiency which was observed due to the heat loss from the cookstove body which can be further amended by using refractory brick material as insulation or giving an air gap as we gave in the further models to reduce the thermal conductivity occurring from the cookstove body. As in NIRE 3 model we have used mud as insulation due to its availability and low cost therefore slight decrease in the exergy efficiency is justified as compared to the high quality insulated material used in the Envirofit model. Further NIRE 3 gave maximum power output as compared with the other models which tells us basically how fast the wood will burn and how fast the energy from wood can be transferred to the pot. With highest burning rate of 4.38 kg/hr it proves the fact that cooking time will be reduced.

### 4.2.8 Emission reduction calculations(UNFCCC protocol)[111]

#### (a) For (NIRE 3) model:

Approximate cost of cookstove=₹500

Efficiency of cookstove according to WBT testing=35%

$$ER_y = B_{y,savings} \times f_{NRB,y} \times NCV_{biomass} \times EF_{projected\_fossilfuel}$$

$$B_{y,savings} = B_{old} \cdot \left(1 - \frac{\eta_{old}}{\eta_{new}}\right)$$

Here fuelwood use $B_{old}$ is take 2.94 from [109]

$$B_{y,savings} = 2.94 \cdot \left(1 - \frac{0.10}{0.35}\right) = 2.10 \text{t/household/year}$$

$$f_{NRB,y} = \frac{NRB}{NRB + DRB}$$

Here (NRB=2.80, DRB=0.14) from [110]

$$f_{NRB,y} = 0.953$$

$$NCV_{biomass} = 0.015 \text{TJ/tonne}$$

$$EF_{projected\_fossilfuel} = 81.6 \text{tCO2/TJ}$$

$$ER_y = 2.1 \times 0.953 \times 0.015 \times 81.6 = 2.45 tCO_2 / household / year$$

If estimated 10,000 stoves are manufactured and supplied than 24.5kt$CO_2$ will be checked from entering into atmosphere producing similar amount of CER's i.e. certified emission reductions.

#### (b) For Modified Traditional cookstove/NIRE 2:

Approximate cost of chulha=₹50

Efficiency of chulha according to WBT testing=26%

$$ER_y = B_{y,savings} \times f_{NRB,y} \times NCV_{biomass} \times EF_{projected\_fossilfuel}$$

$$B_{y,savings} = B_{old} \cdot \left(1 - \frac{\eta_{old}}{\eta_{new}}\right)$$

Here fuelwood use $B_{old}$ is take 2.94 from [109]

$$B_{y,savings} = 2.94 \cdot \left(1 - \frac{0.10}{0.26}\right) = 1.81 \text{t/household/year}$$

$$f_{NRB,y} = \frac{NRB}{NRB + DRB}$$

Here (NRB=2.80, DRB=0.14) from [110]

$f_{NRB,y} = 0.953$

$NCV_{biomass} = 0.015$TJ/tonne

$EF_{projected_fossilfuel} = 81.6$tCO2/TJ

$ER_y = 1.81 \times 0.953 \times 0.015 \times 81.6 = 2.1\ tCO_2 / household / year$

If estimated 10,000 stoves are manufactured and supplied than 21kt$CO_2$ will be checked from entering into atmosphere producing similar amount of CER's i.e. certified emission reductions.

**(c) For Envirofit model:**

**Approximate cost of chulha=₹500**

**Efficiency of chulha according to WBT testing=31%**

$$ER_y = B_{y,savings} \times f_{NRB,y} \times NCV_{biomass} \times EF_{projected\_fossilfuel}$$

$$B_{y,savings} = B_{old} \cdot \left(1 - \frac{\eta_{old}}{\eta_{new}}\right)$$

Here fuelwood use $B_{old}$ is take 2.94 from [109]

$B_{y,savings} = 2.94 . \left(1 - \frac{0.10}{0.31}\right)$=1.99t/household/year

$$f_{NRB,y} = \frac{NRB}{NRB + DRB}$$

Here (NRB=2.80, DRB=0.14) from [110]

$f_{NRB,y} = 0.953$

$NCV_{biomass} = 0.015$TJ/tonne

$EF_{projected_fossilfuel} = 81.6$tCO2/TJ

$ER_y = 1.99 \times 0.953 \times 0.015 \times 81.6 = 2.32\ tCO_2 / household / year$

If estimated 10,000 stoves are manufactured and supplied than 23.2kt$CO_2$ will be checked from entering into atmosphere producing similar amount of CER's i.e. certified emission reductions.

**(d) For Vikram model:**

Approximate cost of chulha=₹250

Efficiency of chulha according to WBT testing=22.98%

$$ER_y = B_{y,savings} \times f_{NRB,y} \times NCV_{biomass} \times EF_{projected\_fossilfuel}$$

$$B_{y,savings} = B_{old} \cdot \left(1 - \frac{\eta_{old}}{\eta_{new}}\right)$$

Here fuelwood use $B_{old}$ is take 2.94 [109]

$$B_{y,savings} = 2.94 \cdot \left(1 - \frac{0.10}{0.23}\right) = 1.66 \text{ t/household/year}$$

$$f_{NRB,y} = \frac{NRB}{NRB + DRB}$$

$f_{NRB,y} = 0.953$ Here (NRB=2.80, DRB=0.14) from [110]

$NCV_{biomass} = 0.015$TJ/tonne

$EF_{projected_fossilfuel} = 81.6$tCO2/TJ

$$ER_y = 1.66 \times 0.953 \times 0.015 \times 81.6 = 1.93\ tCO_2 / household / year$$

If estimated 10,000 stoves are manufactured and supplied than 19.3kt$CO_2$ will be checked from entering into atmosphere producing similar amount of CER's i.e. certified emission reductions.

**(e) For Harsha model:**

Approximate cost of chulha=₹250

Efficiency of chulha according to WBT testing=27.58%

$$ER_y = B_{y,savings} \times f_{NRB,y} \times NCV_{biomass} \times EF_{projected\_fossilfuel}$$

$$B_{y,savings} = B_{old} \cdot \left(1 - \frac{\eta_{old}}{\eta_{new}}\right)$$

Here fuel wood use $B_{old}$ is take 2.94 from [109]

$$B_{y,savings} = 2.94 \cdot \left(1 - \frac{0.10}{0.28}\right) = 1.89 \text{t/household/year}$$

$$f_{NRB,y} = \frac{NRB}{NRB + DRB}$$

$f_{NRB,y} = 0.953$ Here (NRB=2.80, DRB=0.14) from [110]

$NCV_{biomass} = 0.015$TJ/tonne

$EF_{projected_fossilfuel} = 81.6$tCO2/TJ

$$ER_y = 1.89 \times 0.953 \times 0.015 \times 81.6 = 2.3\ tCO_2 / household / year$$

If estimated 10,000 stoves are manufactured and supplied than 23kt$CO_2$ will be checked from entering into atmosphere producing similar amount of CER's i.e. certified emission reductions.

Fig. 4.18 shows the variation of $CO_2$ Emission reduction values of different models. It is clearly understood that NIRE 3 model performs best and gives a large amount of emission reduction value i.e. 2.45 tonnes of $CO_2$ reduced per household per year which means if approximately 10,000 NIRE-3 cookstove are provided to the consumers it will save approximately 24,500 tonnes of $CO_2$ in one year. From the above figure it can also be observed that modified traditional cookstove perform better than the vikram model by reducing 0.17 tonnes of $CO_2$ more than vikram.

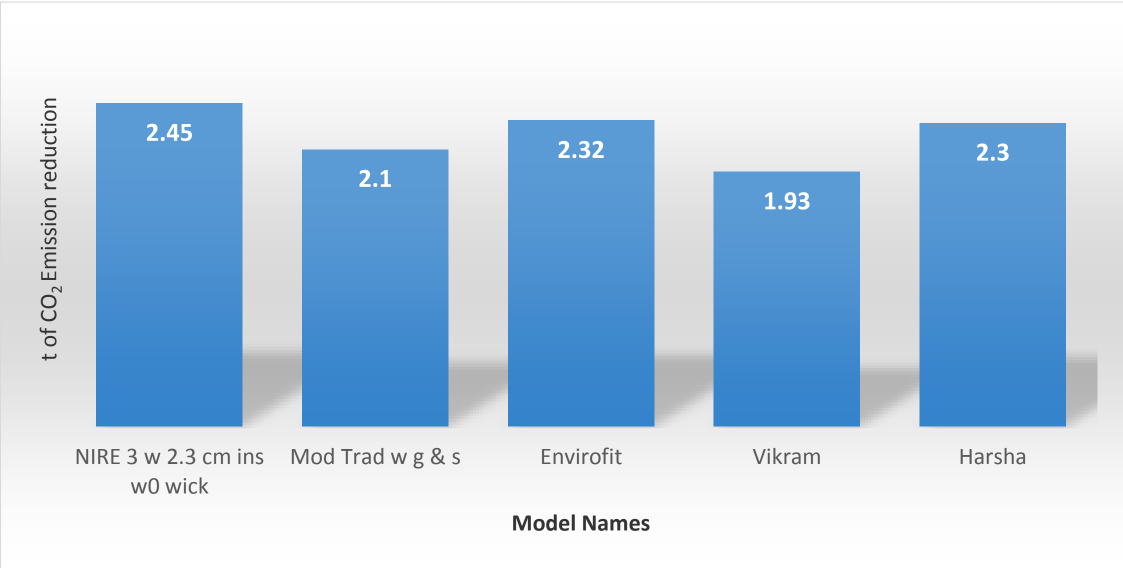



Fig 4.18: $CO_2$ Emission reduction values of different models

# CHAPTER-5

# CONCLUSIONS AND RECOMMENDATIONS

From the above discussion it is concluded that there is a need to replace the traditional and inefficient cooking devices with efficient cooking devices such as the improved and advanced biomass cookstove. From the present study, the following conclusions are drawn:

- Proximate analysis of wood samples showed that sagwan (*tectona grandis*) and mango (*mangifera indica*) have high volatile matter and produce lesser ash.
- Ultimate analysis of wood samples showed that sheesham and eulayptus have high carbon content therefore producing more energy and sagwan (*tectona grandis*) has least percent nitrogen from all other samples leading to lesser pollution.
- Calorific values of wood samples showed that mango (*mangifera indica*) has least calorific value and sagwan (*tectona grandis*) has highest calorific value.
- Thermo-gravimetric analysis showed that mango (*mangifera indica*) has least activation energy and therefore burns easily whereas sheesham (*dalbergia sisso*) has highest activation energy and requires time and high temperature to catch fire.
- From all the wood samples mixed results were obtained but sagwan (*tectona grandis*) showed the best results overall and is therefore recommended to be used.
- From the analysis of different modifications of modified traditional cookstove it was observed that model with grate and top space gives good results with energy and exergy efficiency and produce less smoke leaving lesser ash.
- Further from the analysis it was observed that NIRE 3 model showed highest efficiency as compared to other models it also showed high exergy content which can further be improved by providing air gap which will decrease the thermal conductivity occurring from cookstove body and hence increasing efficiency and exergy efficiencies.
- It was found from time analysis that NIRE 3 model took least amount of time to boil large amount of water as compared to other cookstoves which will save a large amount of time.
- Modified traditional cookstove showed high efficiency and exergy content as compared with the cost and repair amount of other cookstoves and can serve in the poor rural market by just providing some basic training.

- From the literature survey it was observed that currently not much is being done in India related to biomass cookstove development as compared internationally. There is a need for the major funding to cookstove dissemination programs which is available through carbon revenue which can help in the development of cookstove markets.
- Further it was observed that NIRE-03 model showed highest amount of emission reduction i.e.2.45 $tCO_2$/household/year. Whereas modified traditional cookstove showed reduction of 2.1 $tCO_2$/household/year.

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