Efficiencies and emissions comparison and optimization of commercially available domestic LPG cooking stoves in Pakistan

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APPROVAL SHEET

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DEDICATION

This work is dedicated to my beloved Parents, Siblings, my family and relatives, their support and encouragement brought me to this stage today!!

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I am thankful to Almighty Allah for His blessings which made it possible for me to work on this novel project.

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“**Muhammad Usman**”

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LIST OF ABREVIATIONS

LPG	Liquefied petroleum gas
OGRA	Oil and gas regulatory authority
LNG	Liquefied natural gas
GLPGP	Global liquefied gas programme.
WBT	Water boiling test
US EPA	United state environmental protection agency
CCT	Controlled cooking test
UCT	Uncontrolled cooking test
KPT	Kitchen performance test
HPP	High power phase
LPP	Low power phase
CP	Heat capacity
KJ	Kilo Joule
KG	Kilo gram

Abstract

LPG is considered as one of the most convenient and clean fuels for domestic cook stoves and is a popular choice, particularly in urban areas. Considering the limited fossil fuel resources, increasing emissions with ever increasing LPG demands, it is important to improve thermal efficiency and reduce emissions of the existing LPG cooking stoves by incorporating design modifications. This study reports design modification, in the form of loading height optimization, and consequent evaluation of thermal performance and emissions of two of the most widely used LPG fuelled medium scale cooking stoves, S_a and S_b, in Pakistan. Using two standard pots P_a and P_b, Water Boiling Test (WBT) 4.3.2 is adopted to evaluate the thermal efficiencies and a specifically designed emission collection hood is used for the assessment of CO emissions. In the first part of the study, variation in the performance of stoves is evaluated with varying loading heights at fixed thermal power input. Once, the loading height was optimized, in the second part, the efficiencies of the stoves were evaluated with varying thermal inputs at fixed/optimum loading height. Averaging for both pots, thermal efficiency of stove S_a was increased by around 20% and that of stove S_b by 13% during high power phase of WBT after loading height optimization. The numbers were comparable for low power phase. Both stoves showed a decline in thermal efficiencies with increase in thermal power input. At optimum loading heights, lowest CO emissions were observed.

INTRODUCTION

1.1 Background

Air pollution generally defined as presence of contaminants (one or more) in atmosphere which bring short or long term effect on living thing or environment. It is categorized as primary and secondary pollutant which emit directly from environment and secondary derived from primary pollutants respectively (Neal Hickey, Ilan Boscarato, 2014). Globally, 4.3 M premature deaths are related with indoor air pollution which include 50 % children under five and cooking associated activities are significant contributors (WHO, 2012). Annually, around 71 thousand deaths are associated with indoor air pollution in Pakistan as 81 % population uses solid fuel for cooking purpose (Colbeck et al., 2010).

1.1.1Exhaust gases

Many pollutants in the form of exhaust gases as a result of combustion of fuel in cooking stoves are hydrocarbons (HCs), carbon monoxide and nitrogen oxides (NOx) etc. (Smith et al., 2004). Composition of exhaust gases reported in literature are CO (1300ppm), NOx (110ppm), HCs (84ppm) and CO_2 (2.9 %) during LPG stove combustion (Mishra et al., 2015; Pulkit et al., 2015).

1.1.2 Household LPG consumption:

LPG consumption in household is ranked on 50th number among the World and in values consumption is 197 thousand metric tons annually. When we combine household and other consumers then Pakistan is ranked on 41th number in the World. Consumption of LPG is 412 thousand metric tons. As for as consumption of LPG by other consumer is concerned, Pakistan is promoted to 9th number where consumption is almost half of consumption of household and other consumers (UN, 2012).

1.1.3 Combustion cooking stoves

Cooking stoves are regularly used for cooking and heating of foods. Cooking stove can be classified in various ways such as material of construction, configuration and mode of combustion etc. (Kshirsagar & Kalamkar, 2014; Kohli & Ravi, 1996). Guidelines were presented regarding the selection of material for fabrication of cooking stoves as material properties such as strength, stiffness, impact resistance, resistance to thermal stress and shock, formability etc. (Chaplin, 1983). Numerous cooking stove fabrication materials such as cast iron, steel sheet, air dried clays, cementitious materials and fired ceramics along with their relative advantages and disadvantages were discussed. Mukunda et al. (1982) designed two commercialized cook stove called Swosthee and modified Swosthee and found their thermal efficiency about 40 %. Dixit et al. (2006) developed multi-port pulverized fuel stove along with single port using a fuel lump. Another portable single pot metal cook stove having thermal efficiency of 30% was developed by (Gusain,1990) and was commercialized as a brand name TARA. In the late 1980s, many version of single metal was available in certain parts of north India. Still and Kness (2001) described the design of a rocket cooking stove which consists of chimney constructed from tin cans, L shaped combustion chamber and cooking stove body. The chimney and combustion chamber are insulated and the pot is surrounded by an insulated metal skirt. Bhattacharya et al. (2002) tested different traditional biomass stoves including improved cooking stoves and reported their performances along with design. Boy et al. (2000) reported 12 % improvement in thermal efficiency by providing of baffles to plancha stove and overall reduction in fuel consumption about 39% as compared to open fires.

Many changes are continuously being introduced by varying cooking stoves parameters to increase their efficiencies and reduce emission. It includes air to fuel ratio, power input, loading height, moisture contents, burner material and fuel types etc.

1.1.4 Improved cooking stoves

Improved cook stoves depend on several factors i.e. type of traditional stoves, aim of design improvement and affordability issue in term of its and fuel cost. Types of traditional stoves vary from three stone open fire to extensive brick and mortar model along with chimney. Improvement in design of stoves to improve energy efficiency which resulting reduction in emission as well (World bank, 2011).

1.1.5 Liquid fuel cooking stoves

Many researchers studied the combustion of kerosene cooking stoves in porous media. They developed porous radiant burner instead of spray atomizer for kerosene burning and sprayed fuel dropwise on top of burner by supplying swirl air from bottom to analyse evaporation mechanism and combustion characteristics inside the burner (Jugjai et al, 2002; Jugjai & Polmart, 2003; Jugjai & Pongsai, 2007).

1.1.6 Liquefied Petroleum gas cooking stoves

Flow pattern of air-fuel mixture was modified in LPG cooking stoves instead of having combustion in porous media (PM), they used PM for preheating of air-fuel mixture and reported significantly improvement in thermal efficiency (Jugjai and Rungsimuntuchart, 2002).

1.2 Objectives

The objectives of the study were

- To compare thermal efficiencies of the selected domestic LPG cook stoves used in Pakistan.
- To compare emissions of the selected domestic LPG cook stoves.
- To modify the combustion process and optimize the emissions as well as thermal efficiencies of the LPG cook stoves.

1.3 Scope of the study

1.3.1 Equipment and Instrument

Following equipment and instrument were used for achieving results:

a) Extraction hood
b) Flue gas analyzer
c) Two LPG cook stoves and LPG as a fuel
d) Cooking pots
e) Digital weighing scale
f) Stop watch
g) Thermometer up to 110 ^{0}C
h) Leather gloves (pair)
i) Wood fixture
j) Lighter
k) Mask and Goggle
l) Extension with three-way switch
m) Ladder

1.3.2 Parameter monitored

- Extraction hood was used to extract flue gases for its analysis. Its specification is as per USEPA.
- Flue gas analyzers (Kane 100-1 and Crypton 295) were used to measure (analyze) flue gases composition. CO was monitored by Kane 100-1 and CO_2 & HCs were monitored by Crypton analyzer.
- LPG cooking stoves (camping valve stove and single gas stove) were used for combustion and c its performance evaluation by using LPG as a fuel.

- Standard cooking pots were used for Water boiling test(WBT).
- Digital weighing scale was used for weighing fuel consumed, pots weight and mass of water evaporated.
- Selected gases (CO, HCs and CO2) were monitored for emission test.
- Two wood fixture were used to hold thermometer in the pots according to procedure defined.
- As lid function is to holds heat within vessel and regularly utilized as a part of genuine cooking assignments, it doesn't influence the exchange of heat from the stove to the pot. Therefore, it brings variability in WBT results and making it harder for results comparison with other tests. So as per WBT 4.3.2 lid was not utilize.

Literature Review

2.1 Indoor air pollution

Globally, 4.3 M premature deaths are associated with indoor air pollution which include 50 % children under five and cooking related activities are significant contributors (WHO, 2012). Annually, around 71 thousand deaths are associated with indoor air pollution in Pakistan as 81 % population uses solid fuel for cooking purpose (Colbeck et al., 2010).

2.2 Pollutants factors and types

Factors which affect the combustion process, are surrounding air and Temperature. After cooking, main components of fuel combustion are carbon oxides, oxygen-containing hydrocarbon, nitrogen oxides and polycyclic aromatic hydrocarbon which effect both human as well as environment (Chang, 2012)

2.3 Pollutants effects

NO2: Nitrogen oxide, a main source of the important pathogen of allergic rhinitis, chronic cough, chronic bronchitis and many diseases (Yi, 2001). An initial exposure to NO2 result in dry cough (Wu, 2003). This kind of gas cause chronic damage to lung tissues as it easily enters human pulmonary alveolus. When such gas inhales in large quantities, it forms denatured haemoglobin by combining with haemoglobin after entering into the blood; thus result in oxygen carrying capacity and lead to tissue hypoxia. Long-term inhalation may result in neurasthenic syndrome and chronic respiratory disease (Li, 1998).

CO: It easily combines with haemoglobin of blood than O_2 so lead to deficiency of oxygen in the blood. Longstanding breathing in its high concentration environment will cause dizziness, nauseation, and rapid heartbeat.

CO_2: It is a key constituent of greenhouse gases and affect the human health as hypoxia as it causes reduction of oxygen content in indoor air (Xu et al., 2000).

2.4 Consumer education and awareness

Due to lack of regulation and absence of implementation of safety standards in numerous countries Women's fears about using LPG are not misplaced. Consumer education and awareness about using LPG does not give idea that LPG fuel burns houses but provides tools, knowledge and enough information to women about their cooking facilities i.e. whether LPG cylinder properly installed, inspected, filled and no leakage of gas. Women of some countries should be aware from realities related to partial filling, contamination of fuel, and other deceptive practices by grey/ black market players which create uncertainty in market and restrict the continued growth of markets. Women should also know the ways to handle these worries (GLPGP, 2013).

2.5 Fuels types

Around the world almost three billion people across the developing world still depend on solid and traditional fuels such as biomass, wood, charcoal, agricultural residues, animal waste and coal for cooking on primitive stoves. They have little access to more efficient, modern forms of energy. Naturally, traditional fuels are most commonly used in rural areas, where little or no access to affordable modern energy. Fossil fuels usage is increasingly considerably but at the same time reserves are depleting at a very rapid rate. In order to meet the forthcoming fuel crisis, an extensive research is being carried out in the areas of substitute fuels and its conservation (WHO/UNDP, 2009). Poor people of developing countries have massive potential to switch to Liquefied Petroleum Gas (LPG) and other modern fuels for cooking because using that potential promises to improve living standard of peoples and provide them social, economic and environmental benefits (Morgan, 2013).

Household LPG cooking stoves are of basic significance and across the board use. In perspective of the extensive scale utilization, even little change in efficiency will lead a vast general effect on the economy of fuel use. Late study in writing likewise have highlighted the significance of this subject (Muthu Kumar and Shyamkumar, 2013). With rapid industrial growth and improvement in living standard of human beings, use of fossil fuel has been increasing day by day and is causing more environmental pollution. Environmental pollution can be minimized by improving efficiency of combustion system (Mnril, 2010). In developing countries, significant amount of energy is used for cooking out of total energy (Lucky and Hossain, 2001).

Stringent environment regulations and an energy crises demand need continual development of combustion systems with high efficiencies and low pollutants emission (Schaffel-Mancini *et al*., 2010; Chen *et al*., 2011).

2.6 Performance evaluation methods

Following methods are used to evaluate the performance of cooking stoves.

2.6.1 Water Boiling Test (WBT, 4.2.3)

The Water Boiling Test (WBT) is known to as a basic model for cooking method. It is expected to device how proficiently a stove utilizes fuel to heat measured amount of water as a part of a cooking pot and the amount of emissions created while cooking.

Benefits and limitations of the WBT

The WBT test can be performed to evaluate the performance in term of thermal efficiency all through the world with straightforward equipment but complex equipment for emission measurement. Its main advantages are

1. Provide lab evaluations of stove execution in a skillful condition
2. Compare the success of various outlines at execution comparative assignments
3. Analyze stove variations among improvement
4. Selection of encouraging items for field practices
5. Make sure that fabricated stoves encounter expected execution in view of plans

All government sanctioned tests include exchange offs. At the point of reduced variability and controlled conditions, an experiment is better ready to distinguish small variations. In case of actual cooking more controlled test is less illustrative. Controlled tests are proper to look at different specialized parts of stove configuration and pre-field assessments of execution. While lab-based tests permit separation between stoves, field-based tests give better sign of execution within genuine use.

The Water Boiling Test was created to evaluate stove execution in a controlled way, and subsequently it is apparently less like native cooking than different tests showed under. In spite of the fact that the WBT is a helpful device for the reasons given over, it's essential to remember its limits. It is an estimate of the cooking procedure and is directed in controlled conditions via prepared specialists. Laboratory test outcomes may vary from results got when cooking genuine foods with native fuels, regardless of the possibility that performance evaluating procedure remained same for both tests. Stoves must be measured under genuine states of utilization to achieve desire effects.

2.6.2 Controlled Cooking Test (CCT)

It has been created in parallel with the Water boiling test (WBT) and is used to evaluate stove performance with native food, cooking practices and still a lab test.

2.6.3 Uncontrolled Cooking Test (UCT)

The Uncontrolled Cooking Test (UCT) is used to evaluate stoves performance by using any meal with any pot and use of stove any way which is suitable to the assignments.

2.6.4 Kitchen Performance Test (KPT)

This test relates fuel utilization in domestic by using developed stove to conventional stove, must be led to assess variations in fuel utilization between stove-users. It contains two subjective reviews: the primary helps implementers (venture planners, makers, merchants, or financial specialists) to survey domestic cooking manner and practices before the presentation of another stove and alternate gives addition information but after 3-6 months of the stove has been presented in a domestic. It additionally contains a methodology to look at fuel utilization in domestic utilizing diverse sorts of stoves. Trial tests are likewise vital for indicating results for carbon credits and evaluating assistance to air pollution (Robert,2009).

2.7 Performance evaluation parameters

The thermal efficiency and emission characteristic of LPG cooking stoves are closely associated with combustion process which, in turn, depends upon factors like burner design, type and its material, loading height of stove, equivalence ratio and its mode of operation etc. (Sutar et al., 2015).

2.8 Combustion systems

Different types of combustion systems have been developed and studied for these reason (Szego *et al*., 2009 and Nymphet *et al*., 2010). Domestic LPG cooking stoves are of critical importance and widely used. As they are used on large scale, so very minute improvement in efficiency have large impact on economy of fuel usage (MuthuKumar & Shyamkumar, 2013). Many researchers have focused on combustion in porous medium due to less carbon emissions and high thermal efficiency e.g. extension in lean flammability and wide power modulation etc. (Wood & Harris, 2008; Mujeebu *et al*., 2009; Avdic *et al*., 2010).

Free-flame combustion is characterized in a conventional burner (CB) in this, the combustion entirely occurs in the gaseous environment, and convection is the main mode of heat transfer. As the gases possesses a minute emissivity and thermal conductivity so the heat transfer modes-role of conduction and radiation from the post flame to pre flame zone are negligible. due to poor heat transport, CB based procedures are less efficient and are mainly characterized by low thermal efficiency, low flammability limits and high level of pollutant emissions etc. (Howell *et al.,* 1996; Wood *et al*.,2008; Mujeebu *et al.,* 2009; Pantangi & Mishra, 2006). One of the cooking stove belonging to this category are conventional liquefied petroleum gas (LPG) cooking stoves. Byeonghun et al. (2013) conduct an experiment for making comparison among the emission characteristics and thermal efficiency of three porous-media burners having power in the range from 15 to 25 kW for condensing boiler and found higher thermal efficiency and lower CO and NOx emissions from a burner with a higher porosity. It is quite convenient for users as there is no dust after combustion. On the contrary, there are certain hidden problems. If the gas leaks from the pipe or valve, the inflammable gas will spread to rooms. Upon reaching the explosive limits of gas, result in explosion by contacting to open flame or electric spark.

Moreover, there are struggles due to better contact with hot gasses. A large portion of the heat loss throughout cooking happens because of heat diverted by the vent gasses (Kakati, 2006). There have been studies in the writing to minimize such troubles by partly enclosing the fire (Hou *et al.,* 2007). Some struggles have been made toward expanding the home time of flue gasses by presenting swirl (Hou *et al.,* 2007). There have recommendations of reorienting vective heat exchange. There have suggestions of reorienting vective heat transfer. In a depth measurements of velocities and OH chemiluminescence, it is found that the burner design causing the residence time of hot gases influences the output of the burners (Makmool *et al.,* 2011). For recycling the hot gasses and achieving radiant heat exchange, the utilization of permeable media which decreases the heat loss through the flue gases has been recommended (Pantangi and Kumar, 2007). Yung et al. (2003) studied the effect of loading height on thermal efficiency and CO emission and with increasing loading height, the thermal efficiency and CO emission found to be decreased but CO emissions in all cases of experiments remained within the upper limit of the Chinese National Standard.

Stubington et al. (1994) studied the efficiencies and emissions from natural gas manufacture cooktop burners and found that loading height and thermal input to flame length ratio significantly affected the thermal efficiencies and emissions of natural gas cook stoves. With increase in loading height and thermal input to flame length ratio affected the emission rate of each of the types differently, and generally reduced thermal efficiency of cooking stoves. With increase in thermal input and loading height to flame length ratio both NOx and NO usually increases with either.

2.9 LPG stoves performance

Ashman et al. (1994) determine the effects of loading height and thermal input of cook stove burner and thermal efficiency of the burner found to be decreased with increase of loading height. At low loading height and thermal inputs, the thermal efficiency and CO emission were higher but lower NOx emission.

Liu and Hsieh (2004) studied the combustion characteristics in term of flame speed, temperature profile and emissions such as CO and NOx in porous heating burner with LPG. They observed that increase in porous bed length, flame speed was found to decrease and having 200 ^{0}C less flame temperature i.e. (1050-1250 ^{0}C) than adiabatic flame temperature. As reaction zone increased causing high preheating temperature and less emissions of CO and NOx.

Pantangi et al. (2007) developed porous material burner to achieve objective to increase thermal efficiency and decrease emissions such as CO and NOx of LPG cooking stoves. In their study reported in Ref. (Pantangi *et al*., 2007), they performed different experiment with metal chips and ensured work to bring improvement in the cooking stove performance by using two layer porous radiant burners. Combustion was permitted to occur in the PM, and preheating of air/fuel ratio was accomplished in a preheating zone made of graduated class balls in Ref. (Pantangi *et al*., 2007), and alumina frame work in Ref. (Muthu Kumar and Shyamkumar, 2013) They found significance affects in term of increase in thermal efficiency and decrease in emissions.

Pankaj and Salim (2011) performed Emission and Water boiling test according to IS 4246:2002 to evaluate the performance of conventional LPG cooking stove in term of thermal efficiency and found 66.27% thermal efficiency of LPG cooking stove.

Yunus and Saxena (2013) investigated the performance of LPG cooking stove with burner made of different material and observed that variation in thermal efficiency of cooking stove using burner made of cast iron and brass. They found thermal efficiency 48 % with Cast iron burner and 52% with brass burner.

Prasad et al. (2014) investigated thermal efficiency of LPG cooking stove burners experimentally and found thermally efficiency of conventional cooking stove increased up to 24 mm loading height then decreased gradually with increase of loading height at maximum flow rate. It has 10 % more thermal efficiency at optimum loading height 24 mm than base line.

Mishra et al. (2015) used two-layer porous radiant burner and observed higher heat transfer rate to water through pot at optimum loading height and concluded that this particular loading height facilitated optimum equivalence ratio for combustion and provided maximum residence time for combustion gases to come into contact with the pot, resulting in higher efficiencies. It was further reported that thermal efficiency of the stove decreased and CO and NOx emissions increased with increase of thermal load. Higher concentrations of CO and NOx were associated with fuel rich environment and high temperature reaction zone respectively.

Panigarhy et al. (2016) analysed the performance of domestic LPG cooking stove numerically and experimentally with porous radiant burner and with increased in thermal load, thermal efficiency of cooking stove found to be decreased and CO emission increased.

Materials and Methods

3.1 Materials

Two commercially available domestic LPG cook stoves S_a and S_b domestically available in Pakistan were used to check its performance in term of thermal efficiencies and emissions. LPG cylinder Stove S_a outer diameter, height, weight and capacity 290 mm, 310±3mm, 6.82 kg and 8kg respectively was used. Two standard aluminium pots P_a and P_b were selected as medium sized cook stove is generally used for both sizes. P_a was of 5 litre capacity having internal diameter and height of 235 and115 mm respectively and P_b was of 7 litre capacity having internal diameter and height of 260 and 132 mm respectively. The maximum burning rate of cook stoves was 1 kg/hr and during experiment average burning rate was 0.30 kg/hr for HPP and 0.28 kg/hr for LPP which is within range of single family domestic cooking of 0.5-6 kg/hr. The burning of fuel was conducted with free air supply through an opening or a width of gap of the hood as shown in (Figure 3.4). With an opening width adjusted to around 15 cm, the flame was above the opening. During burning both the door were remained close.

A hood was constructed to capture the flue gases from cooking stoves (Fig. 3.4). Sampling was done through a port in the hood flue pipe. To ensure uniform flow of the flue gases, the port was located at a distance 8 times that of the diameter downstream and 2 times that of diameter of upstream from disturbances respectively as shown in Fig. 3.4. The small stack diameter could accommodate only one cross point with the position determined by the US EPA method 1. The sampling probe nozzle was thus fixed and the sampling port was closed using insulated material such as rubber cork to minimize disturbances of gas flow.

3.2 Methods

WBT 4.2.3 is used to evaluate the performance of cooking stoves.

3.3 Experimental procedure

3.3.1 WBT 4.2.3 conducted for Thermal Efficiency calculation:

Thermal efficiencies of commercially available domestic LPG cooking stoves in Pakistan were measured by following guidelines prescribed in WBT 4.2.3.

The complete WBT comprises of three phases i.e. **cold, hot** and **simmer** phase that instantly follow each other. These phases are discussed below and graphically represented in Figure 1. The complete WBT was conducted three times for each pots and stove, which is called WBT set.

1) The **cold-start high-power stage**, tester starts stage with the stove at room temperature and use LPG fuel to heat up a deliberate amount of water in a standard pot. The tester then replaces the bubbled water with a new pot of surrounding temperature water to perform the second stage.

2) The **hot-start high-power stage** is run after the first stage while stove is still hot. Once more, the deliberated amount of water in pot is heated up to its boiling point. This stage distinguishes difference in stove execution at cold and hot phase. This is especially vital for stoves with high warm form, subsequent to these stoves may be kept warm by and by.

3) The **simmer low power stage** gives the measure the amount of LPG fuel required to heat the deliberate amount of water 6 °C below the boiling point for 45 minutes. This step reproduces the extended cooking of vegetables basic all through a significant part of the world.

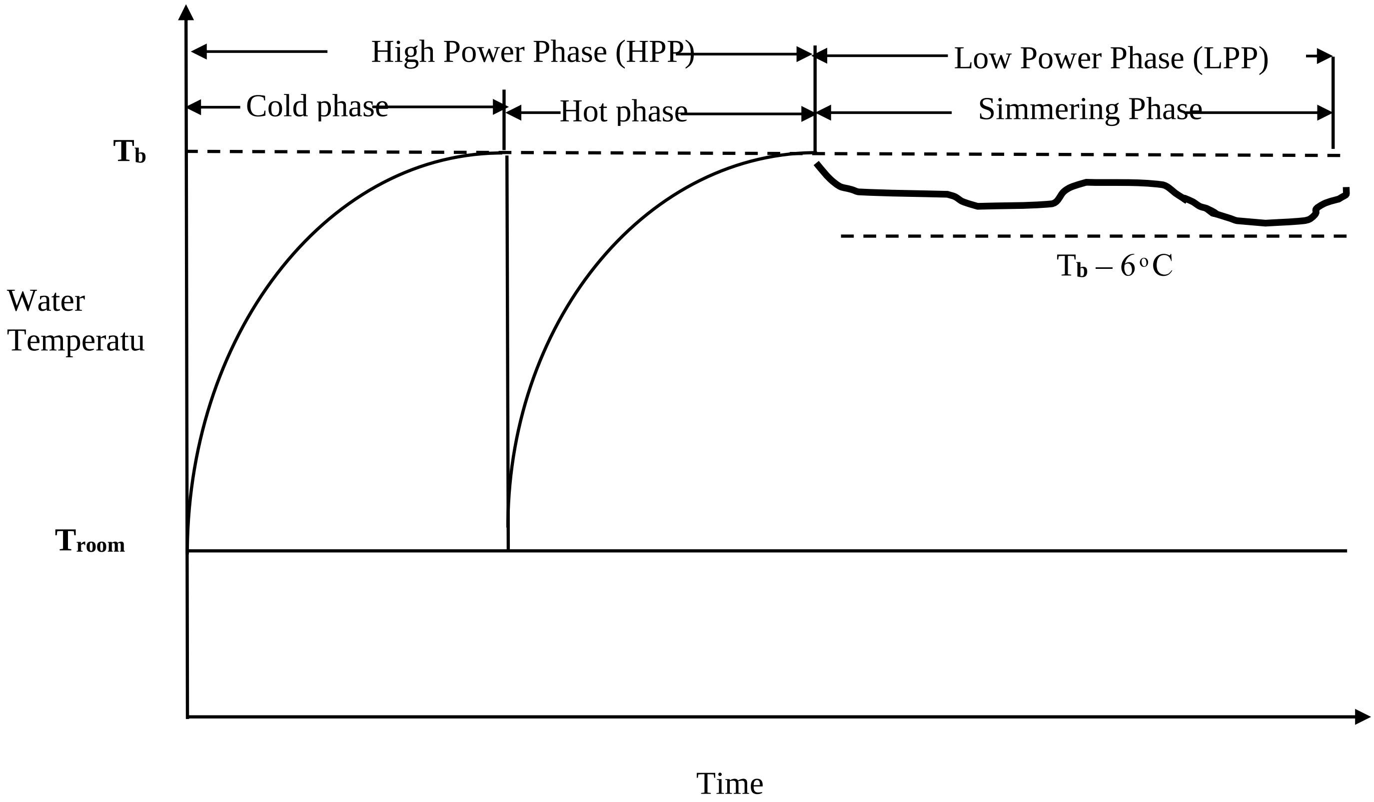

Fig. 3.1. Temperature stages of Water Boiling Test (WBT 4.2.3)

The thermal efficiency of the LPG cook stove is calculated based on WBT 4.3.2 prescribed formulas:

Thermal Efficiency (Cold & Hot) = {(M* Cp* (Tb-Ti) +M_{evap}*2260) /X*C}*100…………(1)

Thermal Efficiency (Simmering) = {(M_{avg}*Cp*(Tf-Ti) + M_{evap}*2260)/ X*C}*100………...(2)

M_{avg} = (Mass at start of simmering phase + Mass at end of it)/2

Where M is the mass of water, M_{evap} mass of water evaporated Cp is the specific heat of water, Tb is boiling temperature, Ti initial water temperature, X is the mass of the LPG consumed and C is the calorific value (45,800 kJ/kg) of LPG (Smith et al.,2001).

However thermal efficiency calculation for simmering phase is different from cold and hot stage. In simmering phase average mass (M_{avg}) is used instead of M which is average of mass at start of simmering phase and mass at the end of completion of simmer test and T_f is final temperature instead of boiling temperature. However, stove performance in low power phase cannot evaluated in term of thermal efficiency so calculation difference should not be important. Because sensible heat and evaporation losses are important in thermal efficiency.

Cooking time cannot be reduced by providing excess steam in most of cooking cases because temperature is fixed at boiling point in pot. Production of extra steam is not good indicator of stove performance but energy is supplied to cooking pot (Robert, 2009).

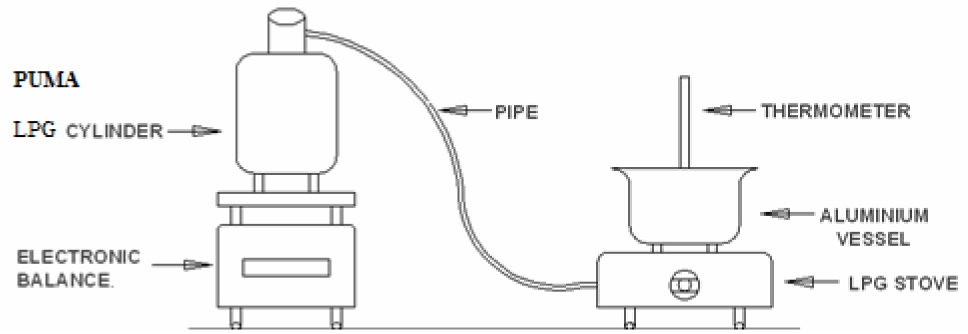

Fig. 3.2. Complete experimental setup of single LPG

3.4 Holding Thermometer in the Pot

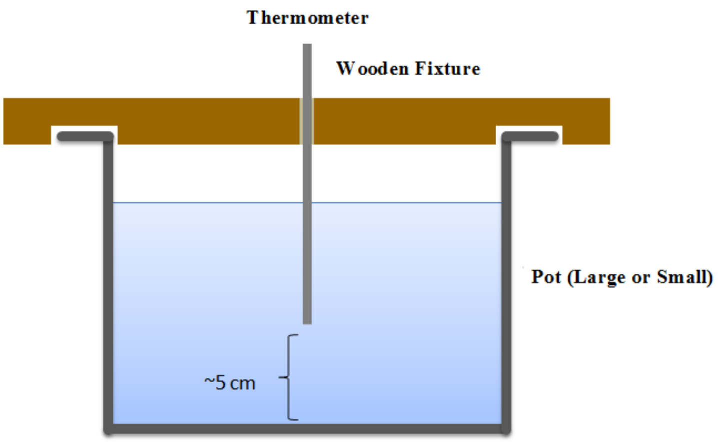

Fig. 3.2. Cooking pot setup

(a) **(b)** **(c)**

Fig. 3.3. (a) Camping valve stove (b) LPG cylinder (c) single gas stove

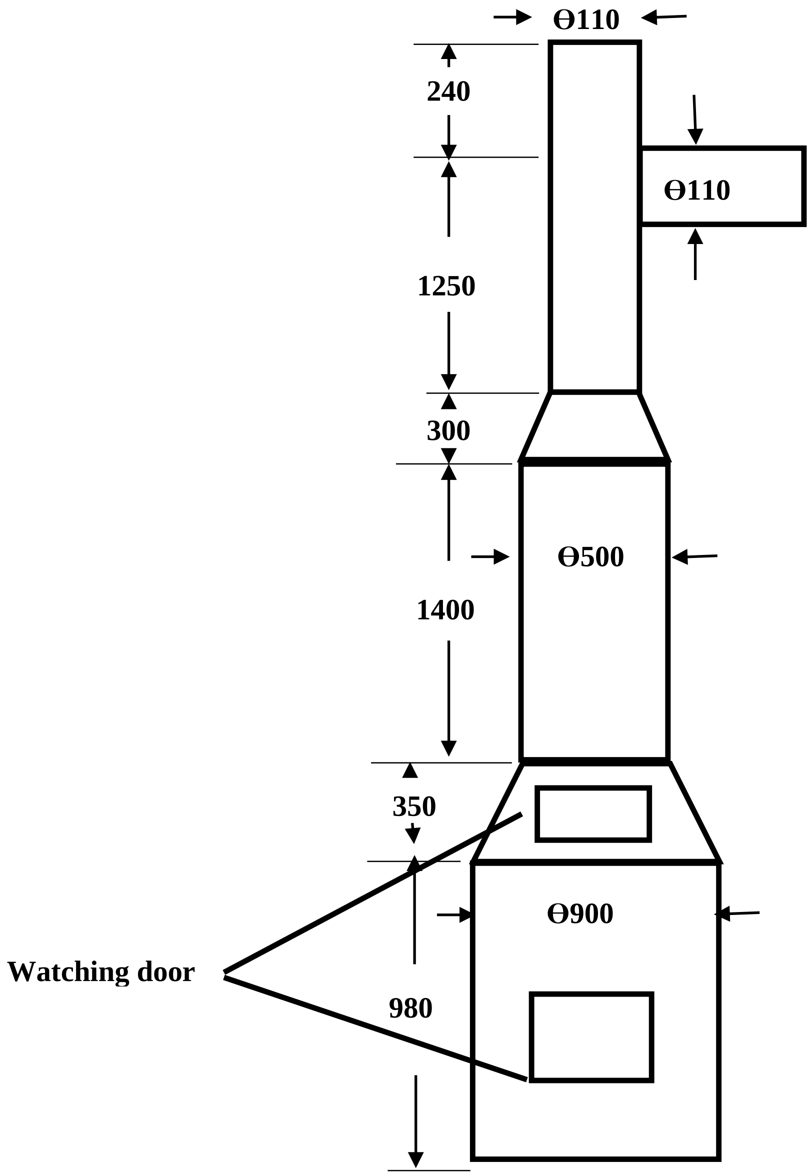

Fig. 3.4. Extraction hood for flue gases

3.5 Emission test for flue gases

Hood method and Flue gas analyser Kane 100-1 & Crypton 295 were used to perform emission test by following WBT 4.2.3 procedure. Two pots and two different cooking stoves were used to perform emission test. Inside hood stove was set with complete setup as shown in (Fig. 3.2) by following WBT procedure. During complete test for different pots readings of CO, HCs and CO2 were also noted to calculate emissions. The flue gas analyser is an automatic machine calibrated to measure the level of emissions initiating as a result of combustion.

3.6 Observation: and calculations

Table 3.1

Summary of thermal efficiencies & emissions data of S_a in HPP

POT	Loading Height	Thermal Efficiency	CO	HCs	CO2
	mm	%	ppm	Ppm	ppm
P_a	15	40.88	200	27	7000
	25	56.13	170	27	8000
	35	58.28	110	20	8500
	45	40.86	210	26	7000
P_b	15	53.95	130	23	6500
	25	62.13	110	20	7000
	35	76.64	90	16	8000
	45	51.18	150	25	6500

Table 3.2

Summary of thermal efficiencies & emissions data of cooking S_b in HPP

POT	Loading Height	Thermal Efficiency	CO	HCs	CO2
	mm	%	ppm	Ppm	ppm
P_a	15	46.63	55	8	6000
	20	55.24	40	2	6500
	25	42.19	73	10	6000
	30	41.22	80	12	5000
P_b	15	50.90	47	5	5000
	20	58.72	30	2	6000
	25	50.02	52	7	5000
	30	43.58	75	10	5000

Table 3.3

Summary of cooking S_a emissions data (LPP)

POT	Loading Height	Thermal Efficiency	CO	HCs	CO2
	mm	%	ppm	ppm	ppm
P_a	15	48.27	140	20	4000
	25	49.35	134	21	5000
	35	53.05	110	17	5000
	45	46.87	126	20	4000
P_b	15	54.54	129	18	4000
	25	55.18	125	19	5000
	35	63.05	93	15	5000
	45	51.88	126	20	4000

Table 3.4

Summary of cooking S_b emissions data (LPP)

POT	Loading Height	Thermal Efficiency	CO	HCs	CO2
	mm	%	ppm	ppm	ppm
P_a	15	34.13	99	8	4000
	20	42.36	70	4	4000
	25	37.45	83	8	4000
	30	31.01	119	9	4000
P_b	15	42.60	64	10	4000
	20	48.80	51	2	4000
	25	45.80	58	7	4000
	30	43.63	67	8	4000

Chapter 4

Results and Discussions

4.1. Thermal Efficiencies of cooking stoves

4.1.1. Thermal efficiency of S_a (HPP)

Performance evaluation of LPG cooking S_a in term of thermal efficiency investigated and thermal efficiency of cooking S_a with P_a found to be increased with increase of loading height from 15 to 25 mm because more heat transfer rate to water through pot. P_a was of capacity 4 liters filled with 2.31 liter water and it was observed that smaller the surface area of pot has lesser thermal efficiency at 15 mm loading height. As its loading height increased from 25 to 35, thermal efficiency increased due to better combustion and approperiate heat transfer to water through pot. It was observed that P_a thermal efficiency increased 42 % at loading height 25mm than at loading height as shown in Fig. 4.1(a). When its loading height increased to 35 mm then its thermal efficiency increased slightly which was 0.4 %. To optimize loading height of cooking S_a with P_a, its loading further increased from 35 to 45 mm and found decrease in thermal efficiency at this loading height. At the end we concluded that at optimum loading height 35 mm, cooking S_a with small pot has maximum thermal efficiency in HPP which was 58.3 %.In other word observation can be concluded that with every 50 % rise in loading height, its efficiency first increased 42 % and then only 0.4 % upto 35mm loading height.

Similarly with P_b of cooking S_a having larger capacity of 7 liter and surface area. P_b was filled 5 liter of water. At loading height 15 mm, it has thermal efficiency 54 % as shown in figure 4.1(a). As we increased its loading height from 15 mm to 25 mm, heat transfer rate increased due to larger contact area of pot .

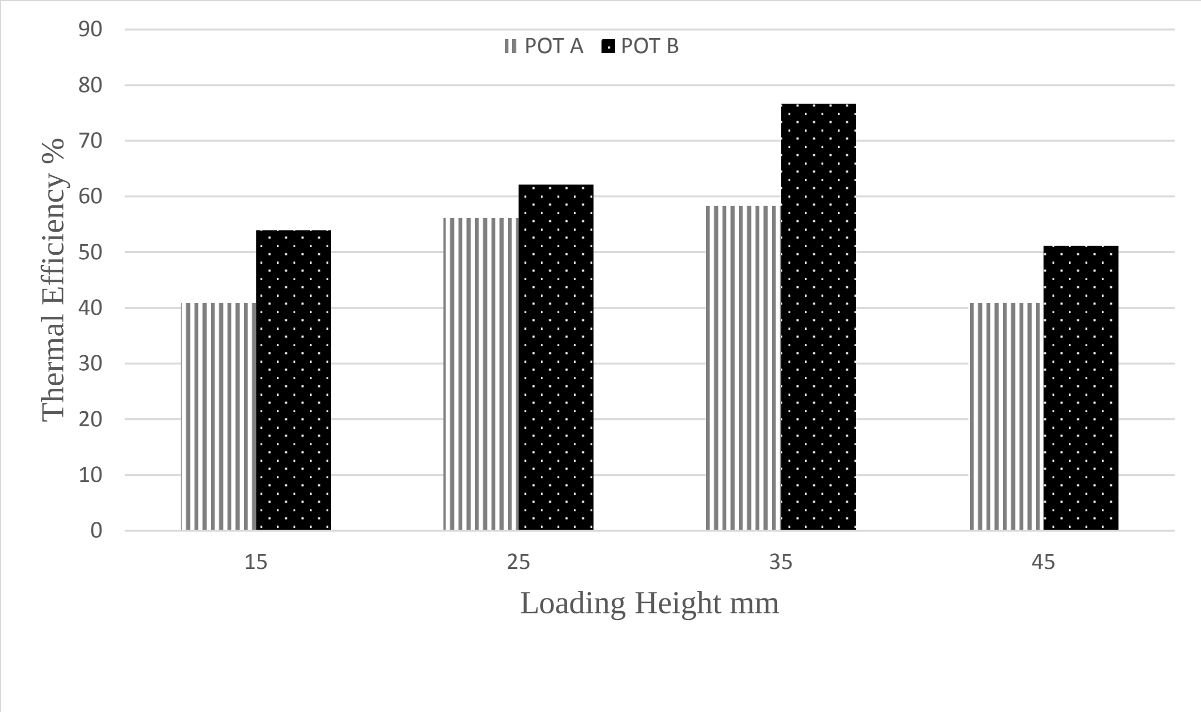

Fig. 4.1(a). Thermal efficiencies comparison of cooking S_a (HPP)

It was observed increase in thermal efficiency from 54 to 62% which was 15 % more thermal efficiency than at 15 mm loading height.When its loading height further increased to 35 mm, heat transfer rate found to be increased to pot and complete combustion occurred resulting higher thermal efficiency 77% which was 25 % more. To optimize its loading height for maximum thermal efficiency,its loading height further increased to 45 mm and found further decrease in thermal efficiency. At the end, it is concluded that at optimum loading height 35mm, S_a has maximum thermal efficiency.

4.1.2. Thermal efficiency of S_b (HPP)

Thermal efficiency of stove S_b with P_a observed higher at loading height 20 mm which means higher heat transfer rate to water through pot as a result of complete combustion. As its loading height increased, thermal efficiency of S_b found to decreased about 28 % due to lower heat transfer and incomplete combustion. P_a was of capacity 4 liters filled with 2.31 liter water and it was observed that smaller the surface area of pot has lesser thermal efficiency at 25 mm loading height. As loading height further increased to 30 mm, its thermal efficiency further found to be decreased about 2 % due to improper combustion and lower heat transfer rate to water through pot. At loading height to 15 mm & 30 mm, thermal efficiency of stove S_b further decreased. At the end of we concluded that at optimum loading height 20 mm, stove S_b with small pot has maximum thermal efficiency of 55%. It is concluded with every rise of 17 % of loading height , thermal efficiency decreased 28 % in first step then 2 % in second step.

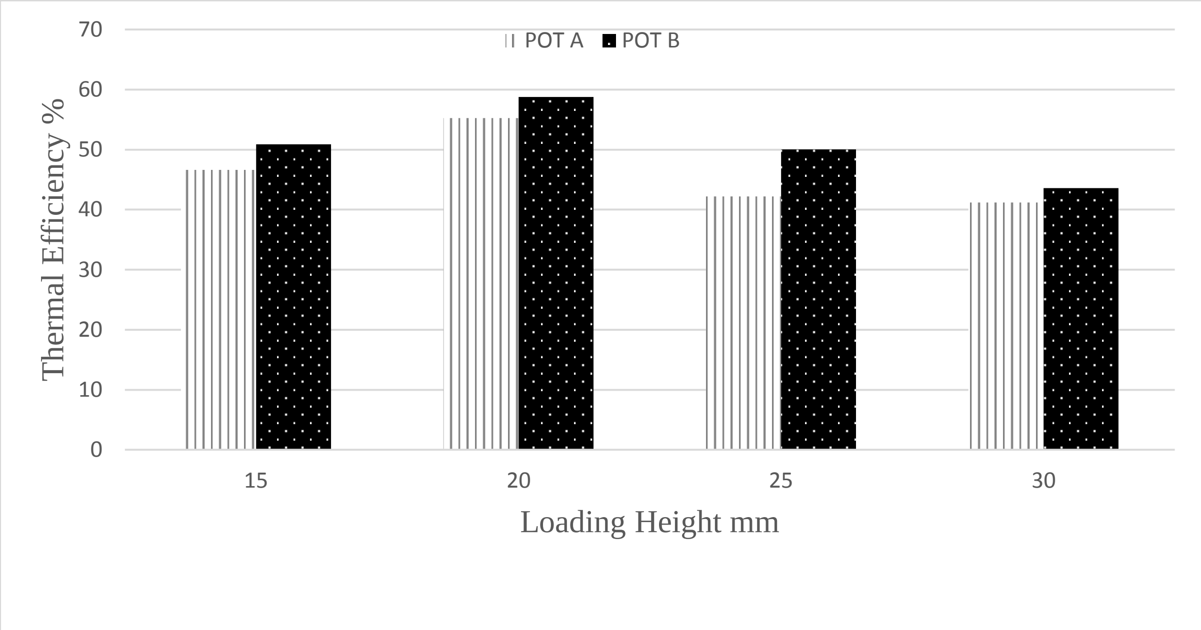

Fig. 4.1(b) Thermal efficiency comparison of cooking S_b in HPP

Thermal efficiency of cooking S_b with P_b observed higher at loading height 20 mm which means higher heat transfer rate to water through pot and complete combustion. As its loading height increased to 25 mm, decrease in thermal efficiency of P_b about 11% was due to lower heat transfer rate and incomplete combustion. It was observed that larger the surface area of pot has higher thermal efficiency at 20 mm loading height. As its loading height increased to 30 mm and observed decrease in thermal efficiency of 13% due to incomplete combustion and lower heat transfer rate. When its loading height decreased from 20mm to 15 mm and found decrease in thermal efficiency. In the end, it is concluded that at optimum loading height 20 mm, cooking S_b for larger pot has maximum thermal efficiency in HPP which was 59%.

4.1.3. Thermal efficiency of S_a (LPP)

Thermal efficiency of cooking S_a with P_a in LPP observed steadily increase as we increased its loading height from 15 to 25 mm which means higher heat transfer rate to water through pot with increase in loading height. One of reason of steadily increased was heating at constant rate in LPP. Test contineoud with remaining water of HPP step and observed same trend that smaller the surface area of pot had lesser thermal efficiency at 15 mm loading height. At loading height 25mm increase in thermal efficiency was observed higher heat transfer rate to water through pot. P_a thermal efficiency found to be increased 2 % at loading height 25mm as shown in Fig.4.1(c). With further increase of loading height to 35 mm, its efficiency found to be increased three time than in first step. To optimize loading height its further increased to 45 mm. At this loading height, decrease in thermal efficiency was observed. So it is concluded that optimum loading height 35 mm of stove S_a with small pot has maximum thermal efficiency of 53% in LPP. In the end of experiment, with every 50 % rise of loading height, 2% increase of efficiency in first step then 8 % in second step and almost 12 % decrease in last step.

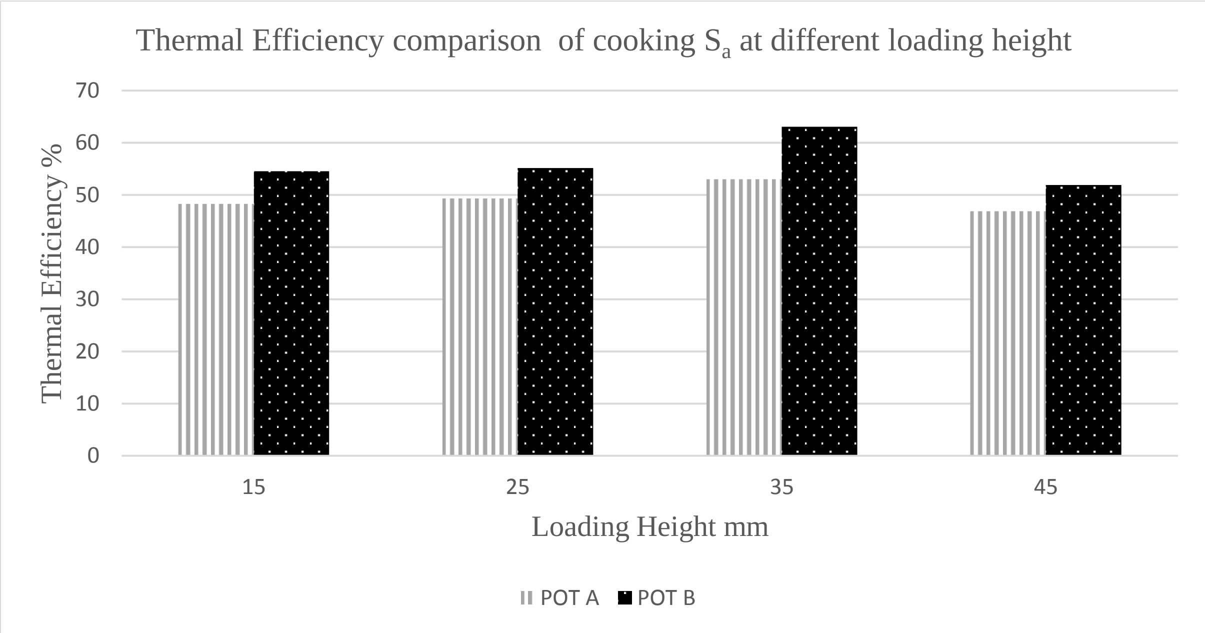

Fig. 4.1(c). Thermal efficiencies comparison of cooking S_a (LPP)

Similarly with P_b of cooking S_a which has larger surface area than P_a. Test contineoud with remaining water of HPP step and it was also observed same trend that larger surface area of pot having lower thermal efficiency at 15 mm loading height but more than P_a at same loading height. At loading height of 15 mm, it has thermal efficiency of 55% as shown in Fig.4.1(c). As its loading height increased from 15 mm to 25 mm, heat transfer rate increased due to larger contact area of pot. It was also observed 1.2% increase in thermal efficiency at this loading height. When its loading height further increased to 35 mm, found higher heat transfer rate due to suffient residence time for flame to burn. So, thermal efficiency reached to value 63% which was observed 12.5 % more thermal efficiency than at loading height 25 mm. To optimize loading height of cooking S_a, its loading height further increased to 45 mm and found decrease in thermal efficieny. At the end with P_b in LPP experiment it was concluded that at optimum loading height 35 mm it has maximum thermal efficiency.

4.1.4 Thermal efficiency of Stove S_b (LPP)

Thermal efficiency of cooking S_b with P_a observed higher at loading height 20 mm which means better heat transfer rate to water through pot and complete combustion. As its loading height increased, thermal efficiency of P_a found to be decreased about 12 % due to improper heat transfer to water and incomplete combustion. In LPP remaining water after HPP was heated at constant temperature of 96 ^{O}C and it was observed that smaller the surface area of pot has lower thermal efficiency at 25 mm loading height. As its loading height increased to 30 mm, thermal efficiency further decreased about 17% due to lower heat transfer to water through pot. To optimize loading height for maximum thermal efficiency, its loading height reduced to 15 mm and found less thermal efficiency than it has at 20 mm laoding height. At the end concluded that at optimum loading height 20 mm, cooking S_b for small pot has maximum thermal efficiency in LPP which is 42%.

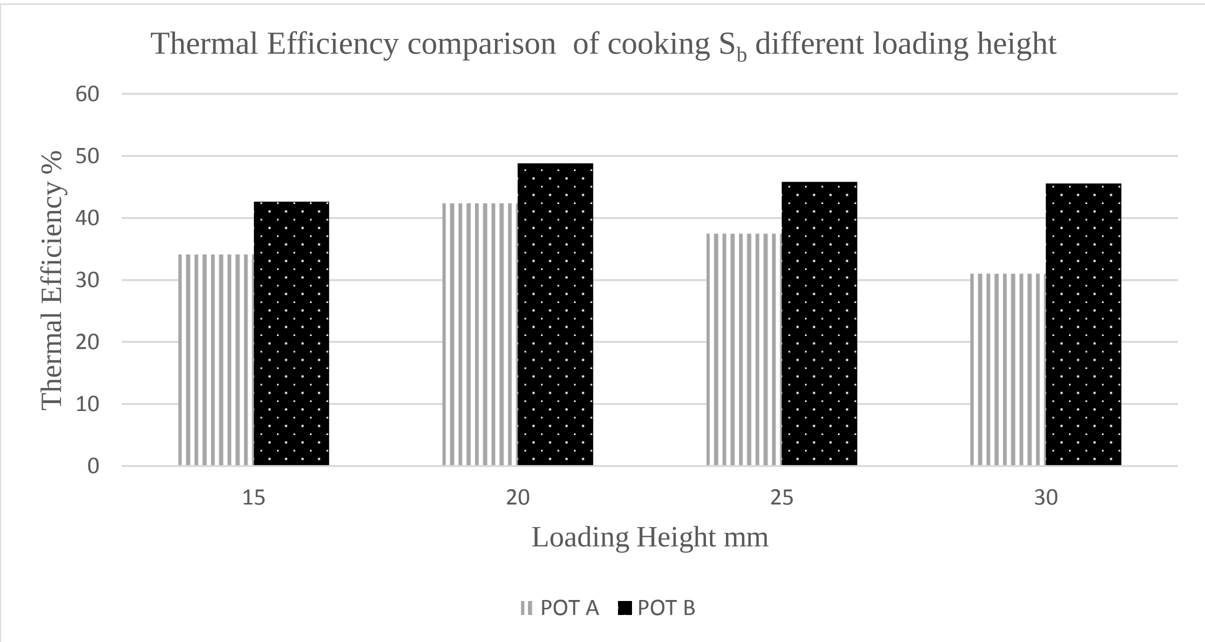

Fig. 4.1(d). Thermal efficiencies comparison of cooking S_b (LPP)

Thermal efficiency of stove S_b with P_b observed higher at loading height 20 mm which means higher heat transfer rate to water. As its loading height increased to 25 mm, thermal efficiency of P_b found to be decreased about 6% due to incomplete combustion. After contineoud heating at 96^{o}C temperature for 45 minutes, it was observed that larger the surface area of pot has higher thermal efficiency at 20 mm loading height. As its loading height further increased to 30 mm, thermal efficiency S_b further decreased slightly about 0.6% due to incomplete combustion and lower heat transfer to water through pot. To optimize loading height it is furhter reduced to 15 mm and found lower thermal efficiency than it has at 20 mm. It is concluded that at optimum loading height 20 mm stove S_b with larger pot has maximum thermal efficiency of 56% in LPP.

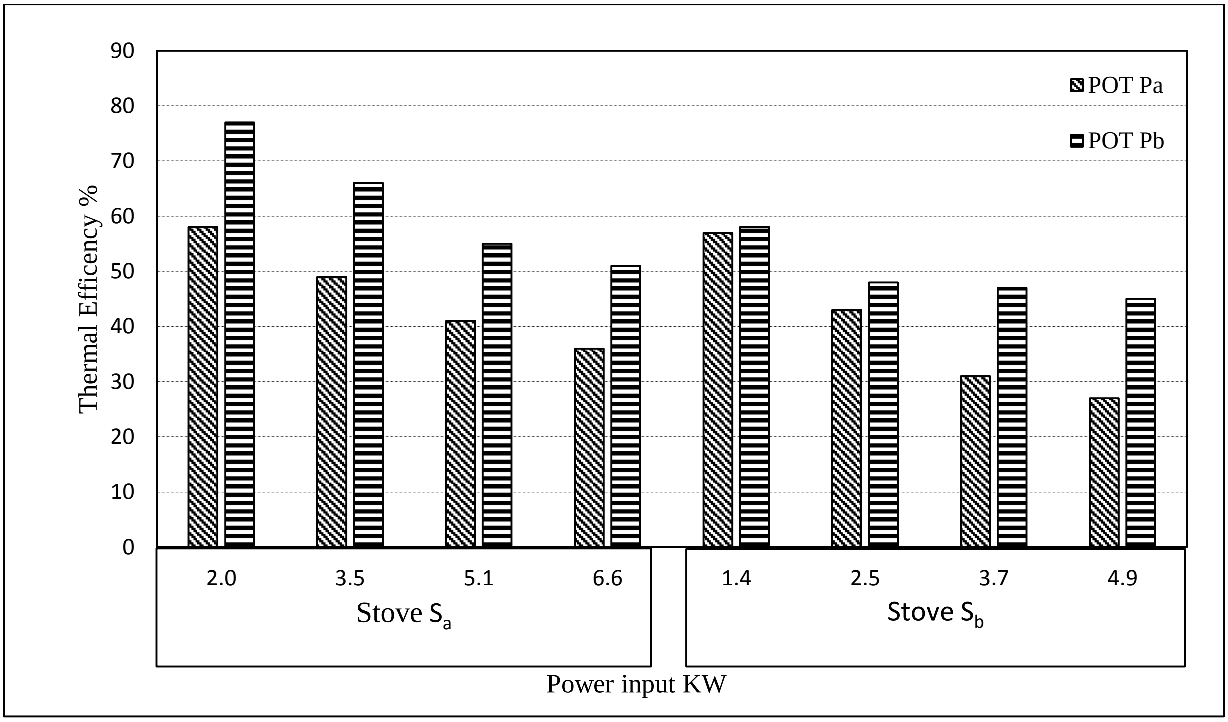

Fig. 4.1(e). Variation in thermal efficiency of stoves along with varying power input.

4.1.5 Variation in thermal efficiency with varying Power Inputs

Fig. 4.1(e). shows variation of thermal efficiencies along with power input at respective optimum loading heights for S_a and S_b respectively. The variations in thermal efficiencies over varying power inputs were evaluated for HPP only as LPP requires the stove to be operated at fixed power inputs. Efficiency of the S_a was evaluated at four different power inputs ranging from 2 to 6.6KW. Consequently, the efficiencies varied from 58 to 36% for P_a and 77 to 51% for P_b. Similarly, thermal efficiencies of S_b were evaulated at four different thermal inputs ranging from 1.4 to 4.9KW. Consequently, the efficiencies decreased from 57 to 27% and 58 to 45% for P_a and P_b respectively. Thermal efficiency decresed for both stoves and both pots as the thermal input to the stoves increased. This can be explained by the increase in flowrate and consequent increase in velocity of the hot flue gases as well as height of the flame with increse in thermal input, resulting in lower contact time between hot gases and pot surface, leading to lower heat transfer to the boiling water and higher loss of heat in flue gases.

4.2 Emission characteristics of cooking stoves

4.2.1 Emission characteristics of S_a (HPP)

Aside from the thermal efficiency, emissions too are given equal significance in any combustion system, because of the growing apprehension about the environment and its adverse effect by the pollutions. At loading height15 mm, cooking stove S_a with P_a CO, HCs and CO_2 emission monitored was 200 ppm, 27 ppm and 7000 ppm respectively. When its loading height increased to 25 mm, emission of HCs remained constant while concentration of CO_2 increased and CO decreased. Increased in CO_2 concentration at loading height 25 was as a result of complete combustion. After further increased in loading height to 35 mm, it was observed higher concentration of CO_2 emission but values of HCs and CO further decreased. Decreased in HCs and CO was indication of better fuel burning which reflecting complete combustion. Furthermore, emission of HCs and CO found higher in concentration and lower CO_2 concentration were observed at loading height 45 mm.

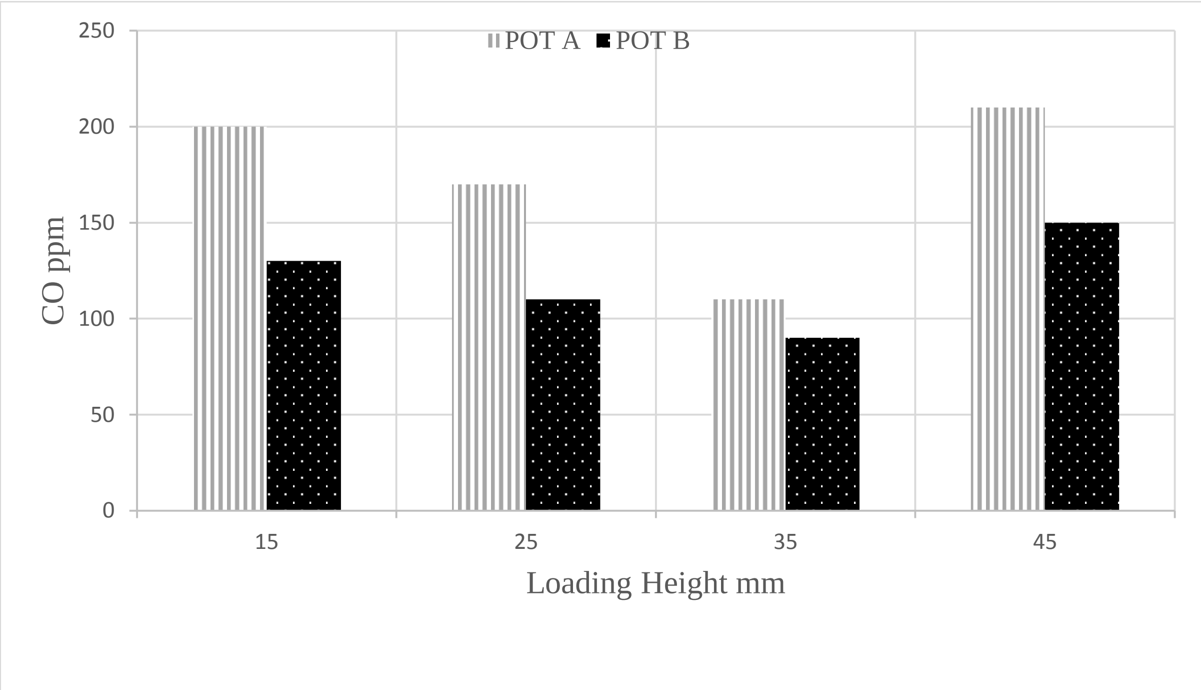

Fig. 4.2 (a). CO emissions comparison of cooking S_a (HPP)

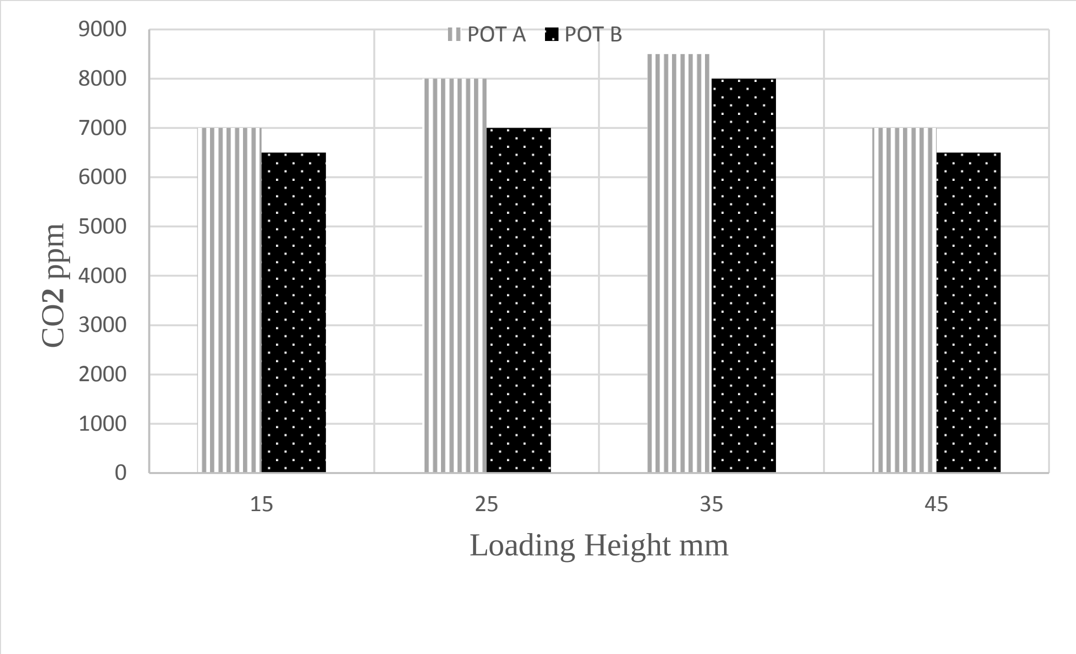

Fig. 4.2(b). CO_2 emissions comparison of cooking S_a (HPP)

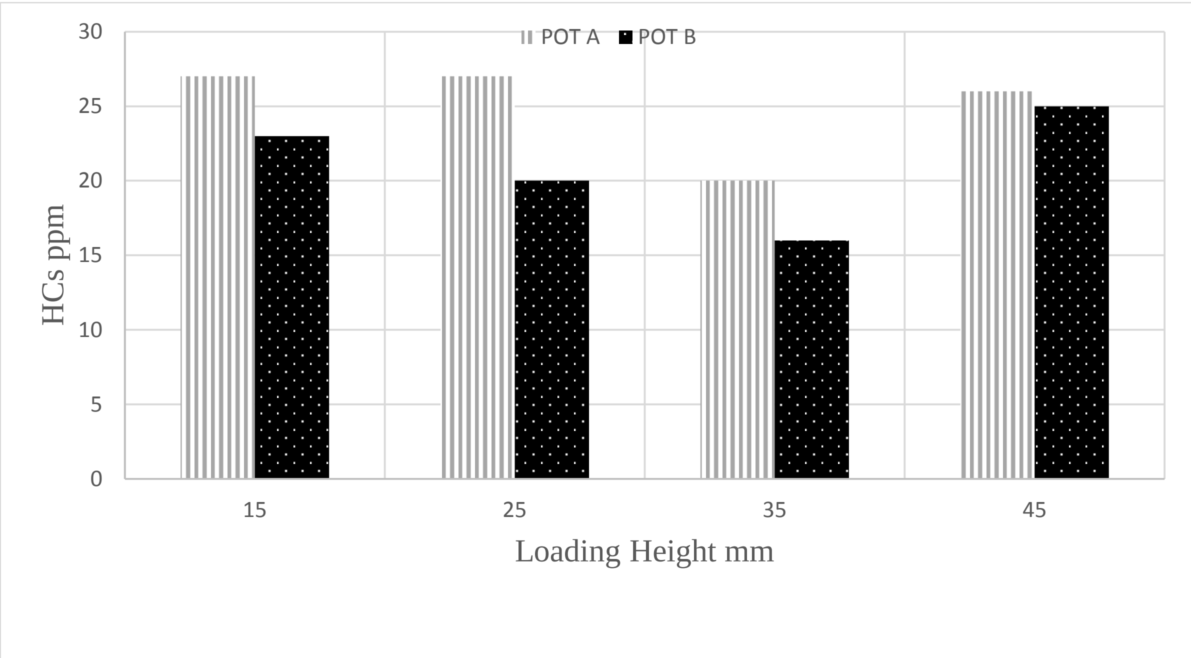

Fig. 4.2(c). HCs emissions comparison of cooking S_a (HPP)

At loading height 15 mm, cooking stove S_a with P_b CO, HCs and CO_2 emission monitord was 130 ppm, 23 ppm and 7000 ppm respectively. When loading height increased to 25 mm higher CO_2 concentration was observed, while emission of flue gases HCs and CO found to be decreased. Increase in CO_2 emissions at loading height 25 was due to complete combustion

/better fuel burning. After further increased in loading height to 35 mm, higher CO_2 was observed, where as values of HCs and CO further decreased. Decreased in values of CO and HCs due to complete combustion. When its loading height increased to 45, emission of HCs and CO increased and lower CO_2 concentration was observed.

4.2.2 Emission characteristics of S_b (HPP)

At loading height 20 mm, cooking stove S_b with P_a CO, HC and CO_2 emissions were 55 ppm. 2 ppm and 7000 ppm respectively.When its loding height increased to 25 mm emissions of flue gases such as CO and HCs increased, while value of CO_2 flue gas decreased. Decreased in values of CO_2 due to incomplete combustion than at loading height 20 mm.While increased in value of CO due to incomplete combustion/improper burning of fuel in term high HCs value in flue gases as HCs values were more than at loading height 20 mm. At loading height 30mm, it was observed decreased values of CO_2 and increase in values of HCs and CO. Increased in values of HCs indicated poor fuel burning/incomplete combustion. At loading height stove S_b, showed higher concentration of HCs and CO while lower CO_2 concentration was observed.

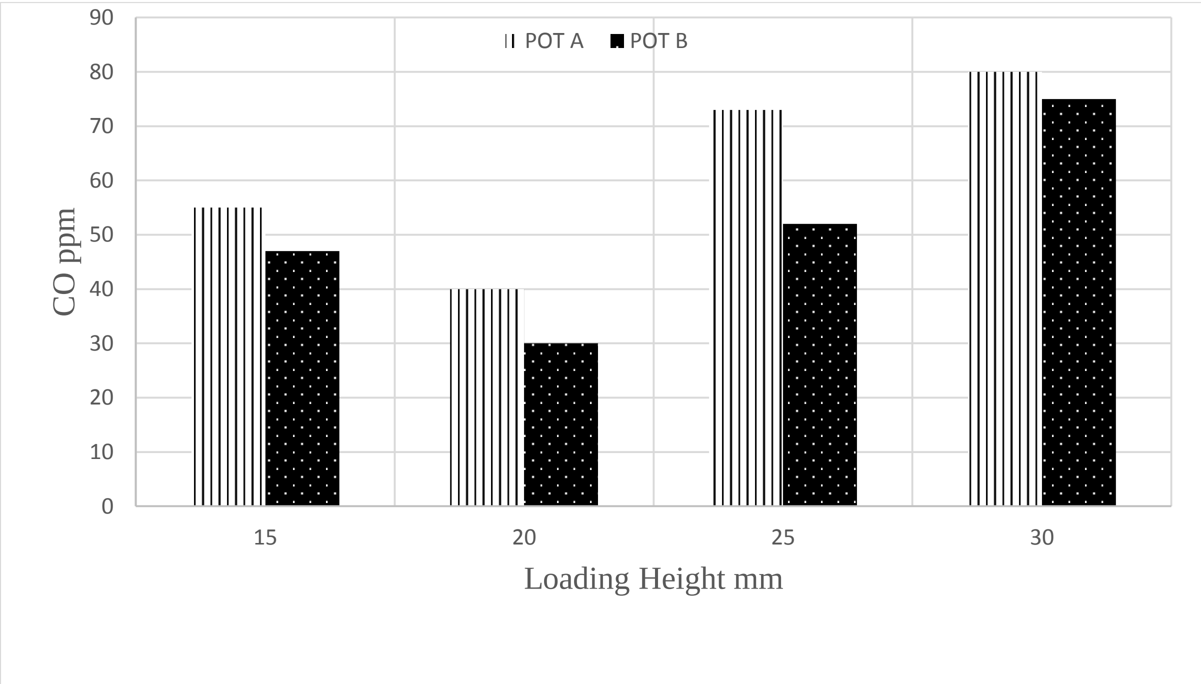

Fig. 4.2(d). CO emissions comparison of cooking S_b (HPP)

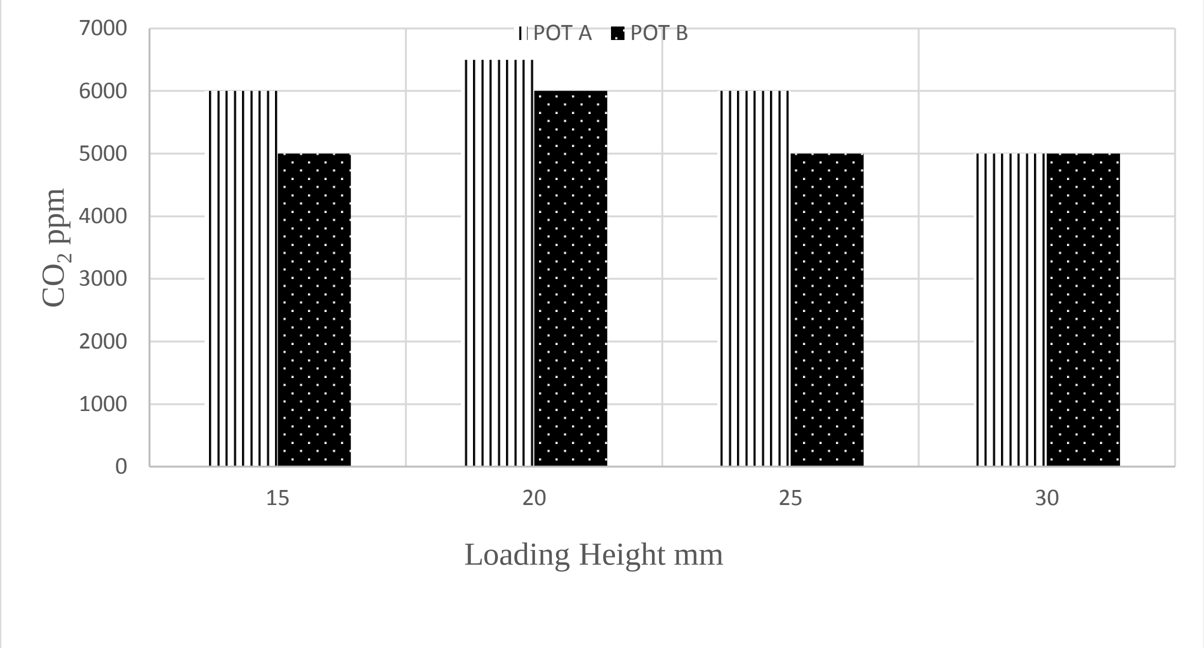

Fig. 4.2(e). CO_2 emissions comparison of cooking S_b (HPP)

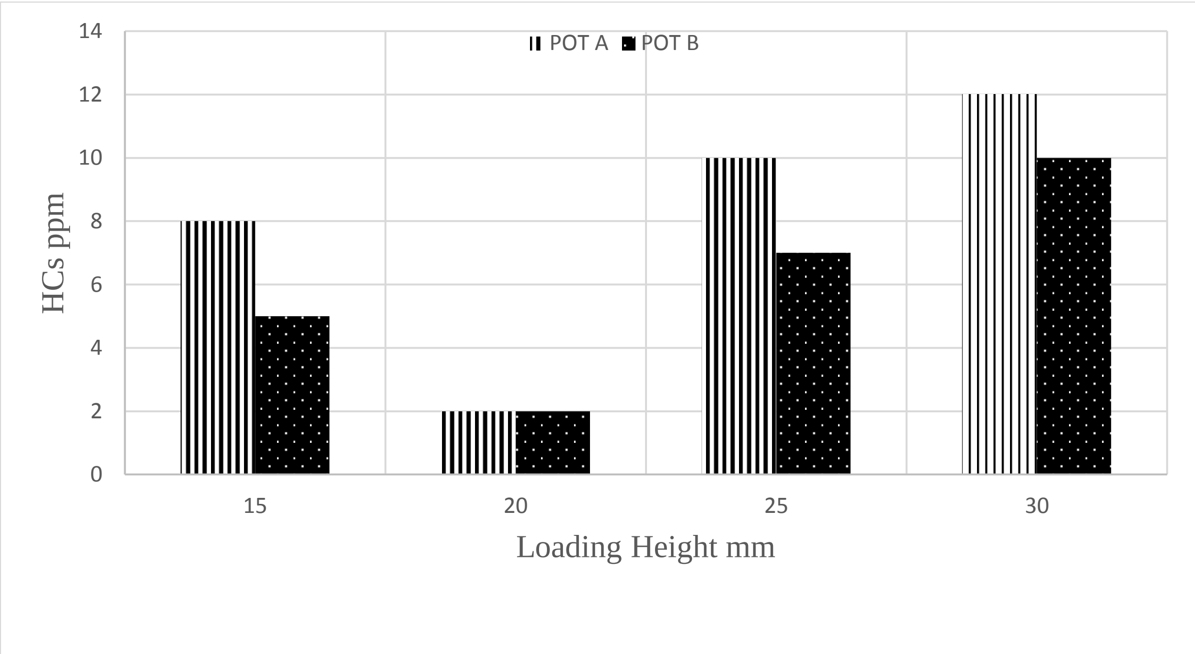

Fig. 4.2(f). HCs emissions comparison of cooking S_b (HPP)

At loading height 20 mm, stove S_b with P_b , concentration of CO, HCs and CO_2 obseved was 47 ppm, 2 ppm and 5000 ppm respectively. With increase of loading height to 25mm concentration of flue gases in term of CO and HCs increased while concentration of CO_2 decreased. Lower CO_2 concentration was due to incomplete combustion at this loading height. While increase in concentration of HCs and CO was observed. When loading height increased to 30mm, increase in concentration of CO along with HCs and CO_2 was observed. Increased in values of HCs and CO indicated poor fuel burning and lower heat transfer rate. At loading height of 15 mm, higher concentration of HCs and CO while lower CO_2 was observed.

4.2.3 Emission characteristics of S_a (LPP)

Concentration of CO, HCs, and CO_2 of stove S_a with P_a monitored at loading height 15mm was 140ppm, 20ppm and 4000ppm respectively. At loading height of 25mm, concentration of CO and CO_2 decreased while HCs concentrationfound to be increased. Insufficinet air available for combustion caused higher concentration of HCs and CO resulting lower CO_2. It was also observed CO_2 concentration remained constant where as concentration of HCs and CO further decreased at loading height of 35mm. Decreased in HCs and CO concrentration means better burning of fuel resulting complete combustion. However, concentration of HCs and CO increased and decrease in CO_2 concentration were observed at loading height 45 mm.

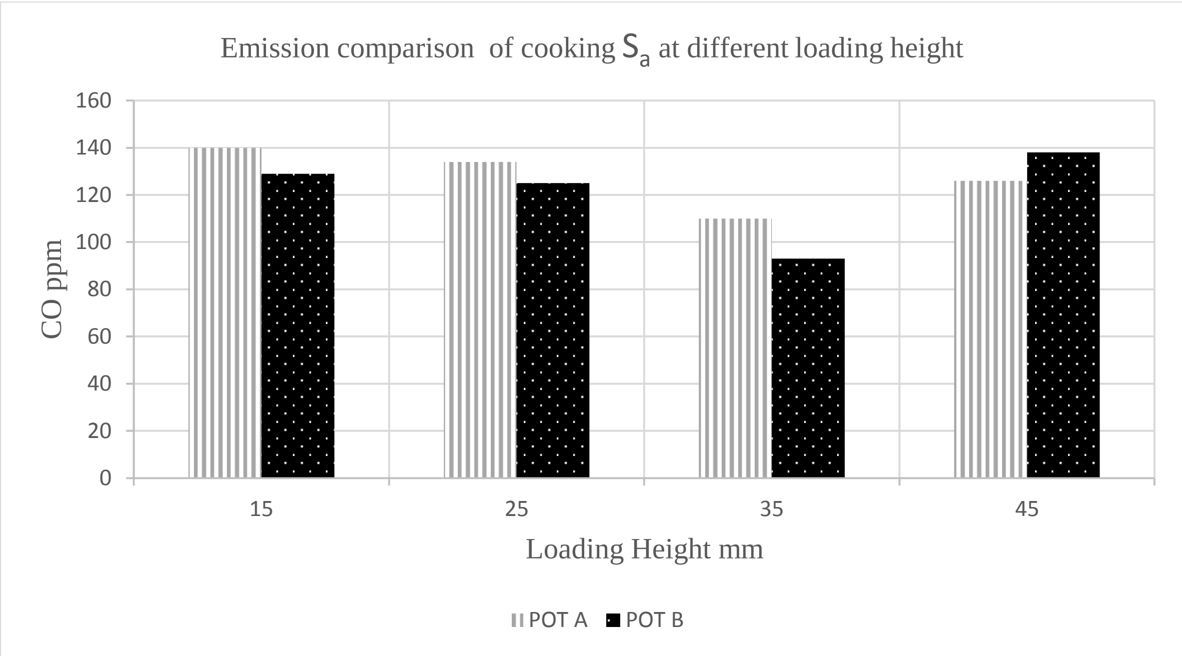

Fig. 4.2(g). CO emissions comparison of cooking S_a (LPP)

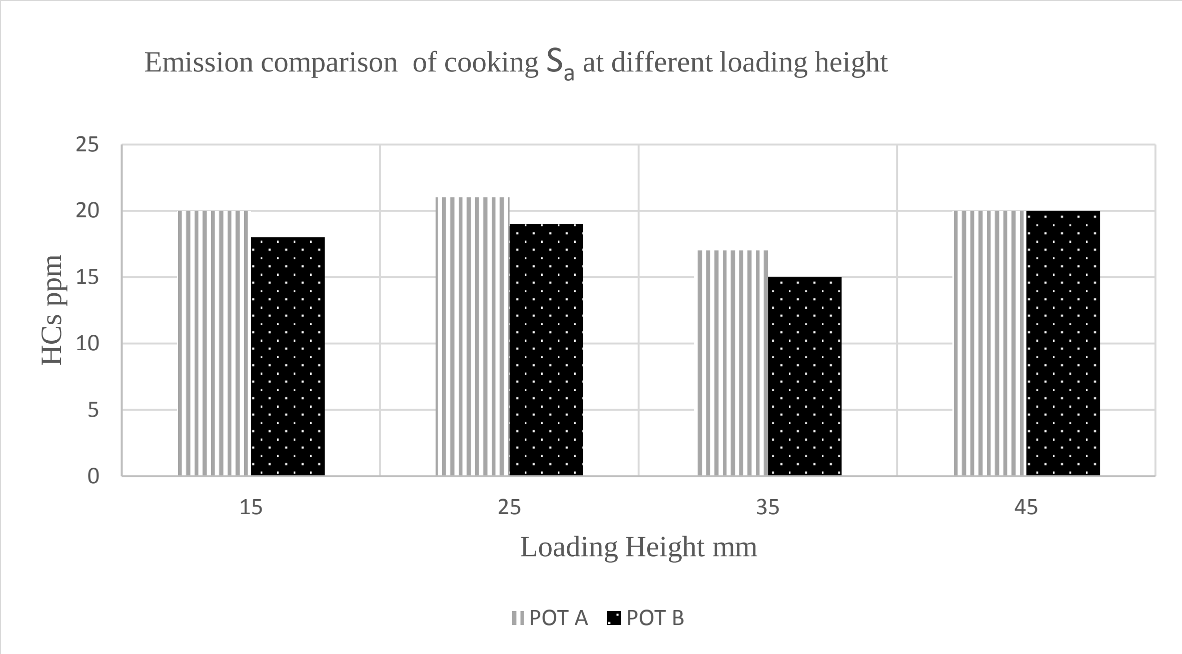

Fig.4.2(h). HCs emissions comparison of cooking S_a (LPP)

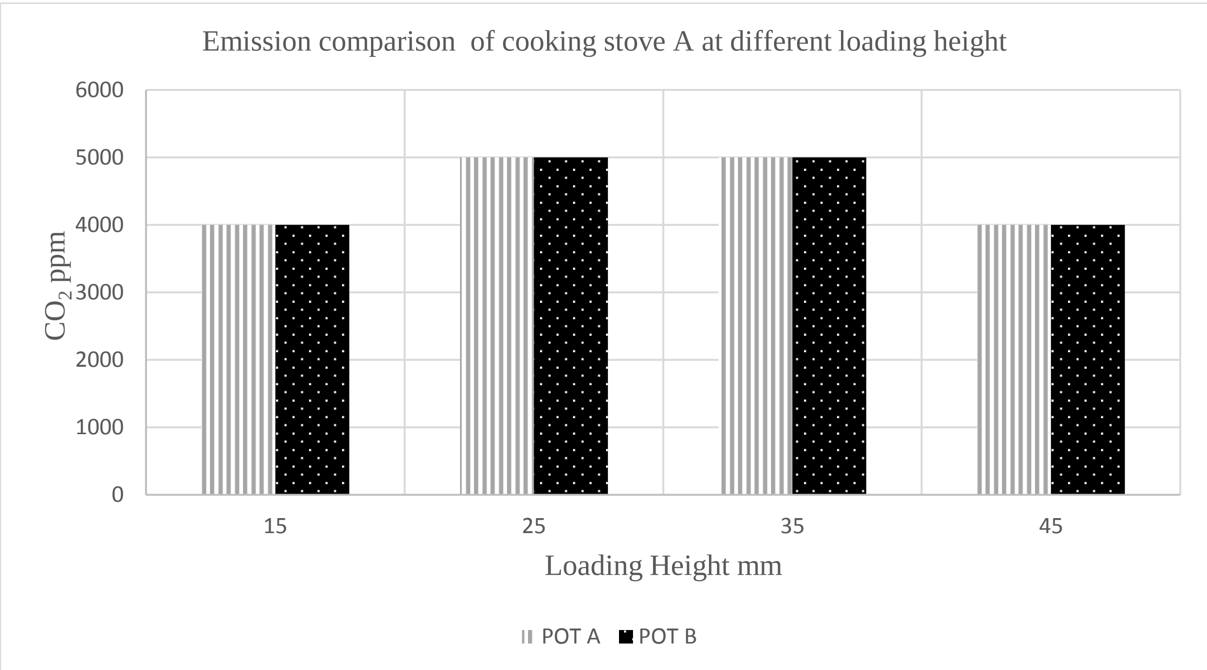

Fig. 4.2(i). CO_2 emissions comparison of cooking S_a (LPP)

At loading height 15 mm, stove S_a with P_b having concentration of CO 129ppm, HCs 18ppm and CO_2 4000ppm respectively. When loading height increased to 25 concentration of CO and

HCs decreased, while CO_2 increased. Increased in concentration of HCs due to incomplete combustion at this loading height. while lower value of CO due to complete combustion. At loading height 35 mm, lower HCs and CO was observed. Lower concenetration of HCs and CO as a result of complete combustion. However, higher concentration of HCs and CO and lower CO_2 concentration was also observed at loading height 45 mm.

4.2.4 Emission characteristics of S_b (LPP)

Emissions monitored of cooking stove S_b with P_a at loading height 20mm were CO 99ppm, HCs 8ppm and CO_2 4000ppm respectively. When its loading height increased to 25 mm emissions monitored of flue gasses CO and HCs found to be increased but CO_2 decreased. Increased in values of CO and HCs and lower CO_2due to incomplete combustion at this loading height At loading height 30 mm , lower concentration of CO_2 and higher concentration of HCs and CO was observed. When loading height further decreased to 15 mm, concentration of HCs and CO found to be increased while concentration of CO_2 decreased.

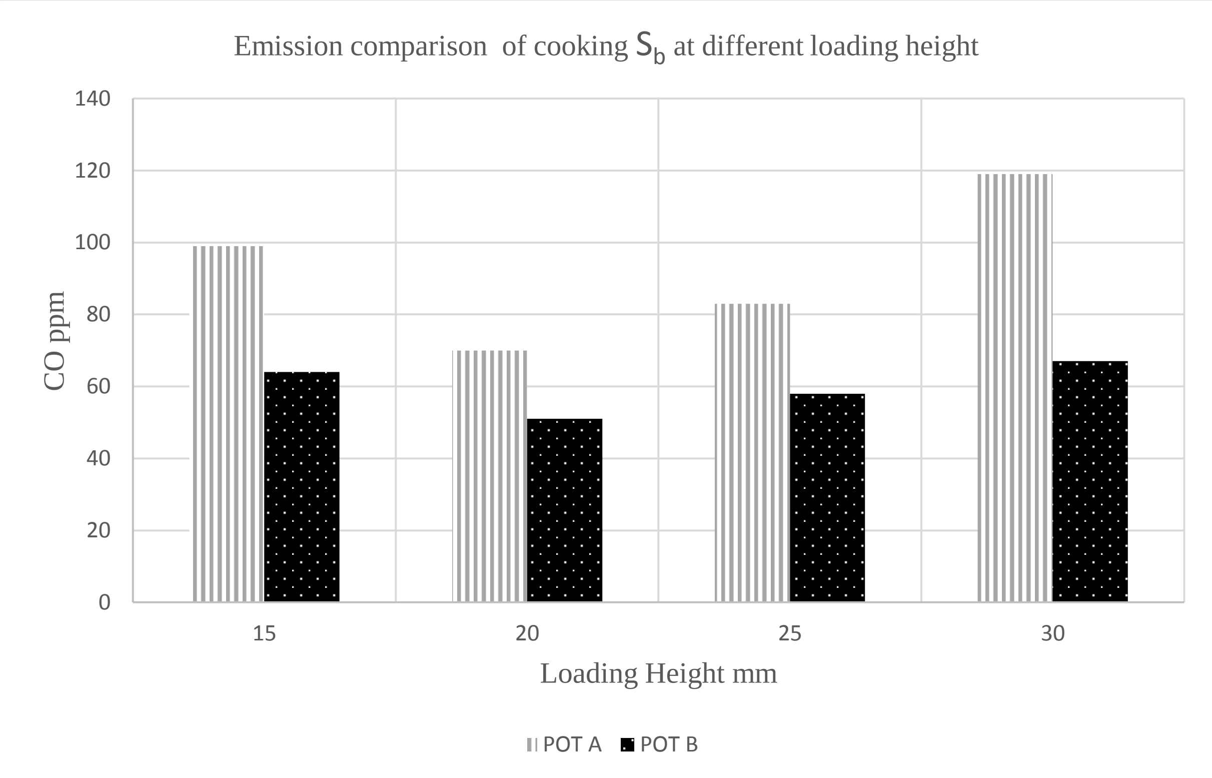

Fig. 4.2(j). CO emissions comparison of cooking S_b (LPP)

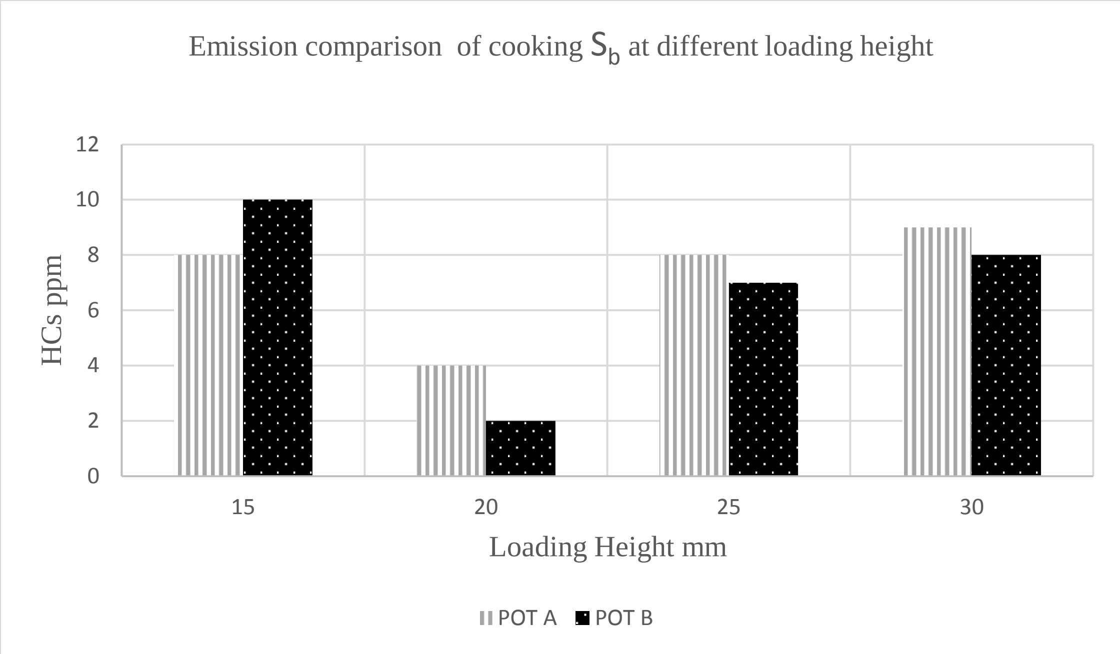

Fig. 4.2(k). HCs emissions comparison of cooking S_b (LPP)

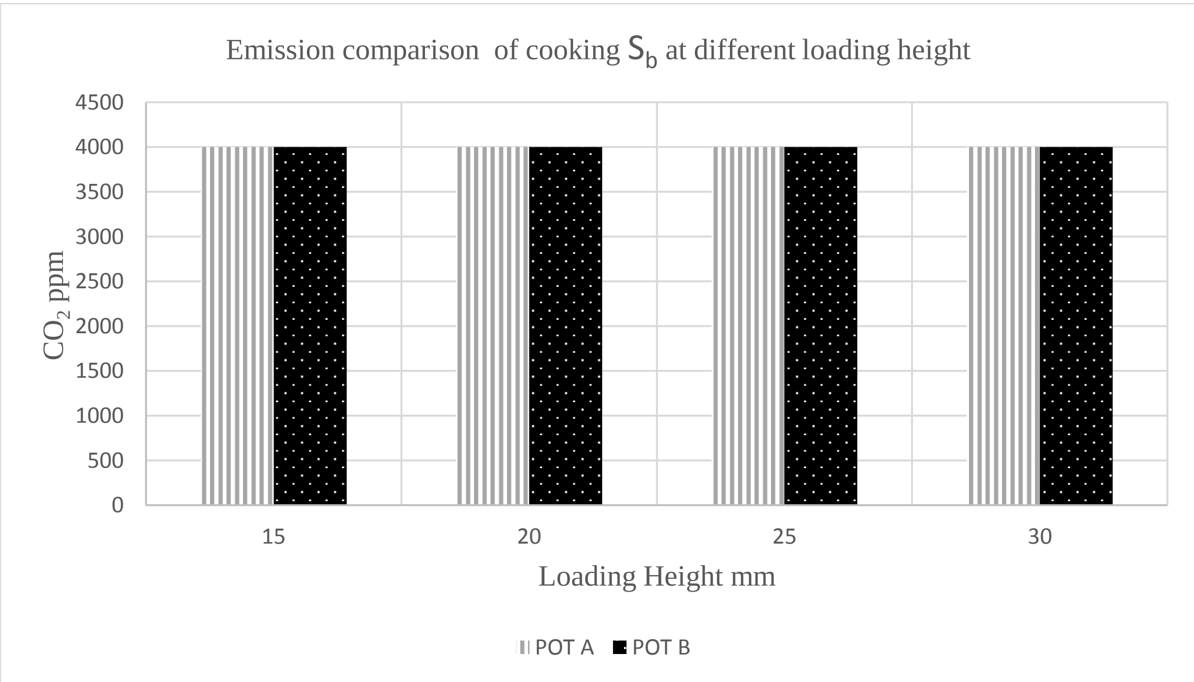

Fig. 4.2(l). CO_2 emissions comparison of cooking S_b (LPP)

Concentration of stove S_b with P_b in term of CO, HCs and CO2 monitored at loading height 20 mm, was 64 ppm, 2 ppm and 4000 ppm respectively. When its loading height increased to 30 concentration of flue gasses CO and HCs found to be increased and CO_2 concentration decreased. When loading height further increased to 30 mm, concentration of CO_2 remained constant where as values of HCs and CO further increased. When loading height decreased to 15mm, higher concentration of HCs and CO were observed.

Conclusions and Recommendation

5.1 Conclusions

Perfomance of LPG cooking stoves in term of thermal efficiency and emission characteristic domestically available in Pakistan experimentally investigated. Cooking stove S_a in HPP has lower thermal efficiency with both P_a and P_b at loading height 15 mm because of lower heat transfer rate as a result of more heat loss to sorounding. However concentration of CO 200 ppm, HCs 27 and CO_2 7000 ppm were monitored respectively. The amount of heat utilized at this loading height was higher, which indicated that more heat was used to bring water to boil and less conversion of fuel resulting higher HCs and CO (insufficient air available for combustion) in flue gases. When loading height increased to 25 mm thermal efficiency was observed more than it was at loading height 15 mm. Then concentration of CO_2 monitored at this loading height found to be increased and CO concentration found to be decreased. The amount of heat utilized to bring water to boil was less at this loading height, resulting lower heat loss to sorounding. When loading height further increased to 35 mm, emission was monitored was CO 110, HCs 20 and CO_2 8500 ppm respectively. From given data, it was observed that at loading height 35 mm S_a has a maximum thermal efficiency of cooking S_a because of minimum heat loss to surounding and lower concentration of CO and higher concentration of CO_2 and HCs.

Cooking stove S_a in LPP has lower thermal efficiency with both pots at loading height 15 mm because of lower residence time and more heat loss to suroundings. Concentration of flue gases, monitored were CO 140ppm, HC 20ppm and CO_2 4000ppm respectively. The amount of heat utilized at this loading height was maximum, which indicated that more heat was used to bring water to boil and less conversion of fuel resulted higher HCs and CO in flue gases. When loading height increased to 25mm, thermal efficiency was found to be increased. Emission monitored at this loading height was higher concentration of CO_2 and lower CO. The amount of heat utilized to bring water to boil was less than heat utilized at loading height 15 mm, which showed higher heat transfer rate and conversion of fuel. When loading height further increased to 35 mm, emission was CO 110 ppm, HCs 17 and CO_2 5000 ppm respectively. From given data, it was observed that at loading height 35mm, S_a has a maximum thermal efficiency and higher concentration of CO_2 and lower concentration of HCs and CO as a resulte of complete combustion/efficient burning of fuel. Thermal efficiency found to be lower and higher concentration of CO and lower of HCs and CO_2 at loading height 45mm.

Cooking stove S_b in HPP has maximum thermal efficiency at loading height 20 mm because minimum heat loss to suroundings due to complete combustion and higher residence time. Emission monitored at this loading height was CO 40 ppm, HCs 2 ppm and CO_2 6500 ppm with P_a and CO 30 ppm, HCs 2 ppm and CO_2 6000 ppm with P_b . Increased of loading height to 25mm, thermal efficency found to be decreased. In emissions CO_2 concentration decreased and HCs was five time more than as it was at loading height 20 mm. When loading height further increased to 30 mm, thermal efficiency of cooking S_b with both pots further decreased. At this loading height emissions were monitored and found lower concentration of CO_2 and higher concentration of HCs and CO due to incomplete combustion and more heat loss to suroundings .

Similarly cooking stove S_b in LPP showed maximum thermal efficiency at loading height 20 mm because minimum heat loss to suroundings as result of complete combustion and efficient fuel conversion. Emissions monitored at this loading height were CO 70 ppm, HCs 4 ppm and CO_2 4000 ppm with P_a and CO 51 ppm, HCs 2 ppm and CO_2 4000 ppm with P_b respectively. Increased in loading height to 25 mm, thermal efficency found to be decreased. In emissions CO_2 concentration found to be decreased and HCs was two time more than as it was at loading height 20 mm with P_a and three time more with P_b. When loading height increased to 30mm, thermal efficiency of cooking S_b with both pots further decreased. At this loading height emission was monitored and found same value of CO_2 and increase in concentration of HCs and CO which resulted incomplete combustion and more heat loss to suroundings. The same trend of decreasing value of thermal efficiency was found when loading height decreased from 20 to 15mm. So at the end it was observed cooking S_b has maximum thermal efficiency at optimum loading height 20 mm, where efficient burning of fuel occurred and minimum heat loss to suroundings due to higher residence time.

The variations in thermal efficiencies over varying power inputs were evaluated for HPP only as LPP requires the stove to be operated at fixed power inputs. Efficiency of the S_a was evaluated at four different power inputs ranging from 2 to 6.6KW. Consequently, the efficiencies varied from 58 to 36% for P_a and 77 to 51% for P_b. Similarly, thermal efficiencies of S_b were evaulated at four different thermal inputs ranging from 1.4 to 4.9KW. Consequently, the efficiencies decreased from 57 to 27% and 58 to 45% for P_a and P_b respectively. Thermal efficiency of both stoves at respective optimum loading height found to be decreased with increase of power input (KW). This can be explained by the increase in flowrate and consequent increase in velocity of the hot flue gases as well as height of the flame with increse in thermal input, resulting in lower contact time between hot gases and pot surface, leading to lower heat transfer to the boiling water and higher loss of heat in flue gases.

5.2 Recommendations

1. Optimization and Performance evaluation of cooking stoves other than fueled by LPG.
2. Optimization of cooking stoves performance by modification of burners.
3. Evaluation the performance of cooking stoves by varying power rating**.**

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