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Emissions and thermal performance evaluation of improved cookstove

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Abstract
Biomass is still used in most of the rural household for cooking which are normally burnt inefficiently using traditional cookstove. This effort is made to design and fabricate an improved cookstove to study thermographic behaviour, thermal comfort and its performance using various parameters. WBT was conducted to understand the overall performance of improved cookstove. The novelty of this approach is to work on the improved three-top cookstove with chimney, to assess the thermal comfort of community cookstove by analyzing thermal performance, thermographic behavior and IAQ by taking measurements of different parameters. Thermal Comfort was analyzed by 'CBE Thermal Comfort Tool' using ASHRAE-55 standard and measurements revealed that the worker was exposed to a 'slightly warm-to-hot' environment. The average PMV and PPD value was examined by ASHRAE-55 as 2.99 and 92.04% respectively. Body temperature during WBT was recorded 43.73 °C. During experimentation the thermal efficiency of improved cookstove with Babul wood (*Prosopis juliflora*) was founded as 34.45% and the average power output rating of cookstove was resulted as 1.46 kW. The average CO, CO_2 and Total Particulate Matter (PM2.5) produced during WBT was resulted as 19.06 ppm, 878.69 ppm and 3.04 mg/m^3, respectively. The Karl Pearson's correlation coefficient was positively and highly significant with the body temperature (0.986), air temperature (0.972), and Mean Radiant temperature (0.980) and in case of CO, CO_2, and PM (2.5), the values of correlation coefficient vary in every test. This cookstove saves energy and helpful in reducing pollutant emission which automatically leads to mitigating greenhouse gases. Thus, the institutes, policymaker, government and other related organizations should take step to advertise and implement such a cooking system in needy areas which helpful in reducing the amount of fuelwood used and also preserve our environment.

Keywords: Thermal efficiency, thermal comfort, thermographic behavior

1. Introduction

Even in the 21st century, 2.8 billion people still rely on solid fuels such as wood, dung, crop wastes, charcoal, coal and simple stoves for cooking and heating (WHO, 2014). Studies show that these practices result in very high levels of household air pollution. Global burden of disease estimates that exposure to HAP from cooking results in around 4.3 Million deaths during 2012. The research studies have shown that respiratory diseases, such as asthma, abnormal lung function, and increased lung cancer and mortality among hotel and restaurant/cafe staff, are associated with exposure to pollutants (Svendsen *et al.* 2002) [17]. Most households in developing countries depends on biofuels as a source of cooking energy (Bonjour *et al.,* 2013) [7] and exposure to pollutants from combusting these fuels are responsible for four million premature deaths each year (Lim *et al.*, 2012) [12].

Biofuel is widely used even in the commercial kitchens. India with its huge population has approximately about 7 million restaurants in organized sector and more than 23 million restaurants, Dhabas, thelas etc. in unorganized sector (Apex body of Indian hospitality industry, Times of India, 2020). Workplaces like these having a large number of workforce and the workers were facing various problems like heat stress, heat stroke, uncomfortable environment and various health hazards for longer duration. Workplace heat stress is a well- known occupational health hazard, and climate change characterized by the increased intensity and frequency of extreme heat events has made risks more severe and widespread.

The work environment of Food Service Industry like restaurants, hostel mess/canteen, etc. were considered to be harsh due to working in hot environment in addition to irregular working hours. The main aim of kitchen work is to prepare and produce meals from raw materials. A kitchen worker's work is specifically characterized by long standing hours, constant leaning forward of the body, repetitive upper body movements, lifting heavy items in awkward positions, static postures and heavy workloads etc. Indoor thermal environment of kitchen is depends on the size of the appliances, kitchen area, arrangement of the kitchen zones, number of employees, different environmental conditions during business hours, etc. Due to the production of constant heat in the kitchen, the indoor environment become uneasy for work and the human body is constantly influenced by Thermal comfort.

International Standard EN ISO 7730, explains the thermal comfort as "a condition of mind which expresses satisfaction with the thermal environment". Thermal comfort commonly depends on environmental and personal factors namely; air temperature, humidity, air movement, thermal radiation, the metabolic rate and the level of clothing. Every human needs energy to perform any kind of work/ activity and produces heat energy to maintain an internal body temperature. If the core body temperature increases by more than 1 °C, the person may suffer a heat stroke. Higher the activity level of the individual, more the heat is produced. More amount of heat leads to more amount of body sweat which directly causes discomfort. So, the need is to develop a safer environment for the kitchen worker.

Fig 1: Experimental set up for Water Boiling Test

2. Materials and methods

An experimental investigation was conducted by organizing the Water Boiling Test on the improved cookstove at Renewable Energy Engineering department of College of Technology and Engineering, MPUAT, Udaipur. Frequency, Percentage, Average and Karl Pearson Correlation Coefficient test were used for the analysis of data statistically.

2.1 Thermal performance

The performance of the improved cookstove was analyzed by conducting WBT was carried out with *Prosopis juliflora* (Babul wood) having calorific value of 12 MJ/Kg.

$$\text{Thermal Efficiency } \eta = \frac{4.186\times(wr) + 2260\times(wv)}{fd\times LHV}$$

Where,

$w_r = \sum (P_{jf}-P_{ji})^* (T_{jf}-T_{jt})$

$w_v = \sum P_{ji} - w_r$

2.2 Thermographic behavior and IAQ

For analyzing thermographic behavior, temperatures of different zones of stove wall, floor, fuel chamber, ash chamber, walls and human body temperature etc. were measured using Infrared Thermographic camera during combustion process. Indoor Air Quality, Relative Humidity, noise level, Air Temperature and Dew Point was measured by using IAQ Monitor, Hygrometer, Sound Monitor, Fluke Thermographic Camera respectively.

2.3 Thermal Emissivity Analysis

Thermal cameras record thermal information which is then displayed in a way that we can visually interpret it in the form of an image. To make it easier for people to easily analyze a thermal image visually, it is represented using 'false colors' which represent the difference in temperature. These false color visualizations usually do come with a small scale next to the image that show the colors used and what temperature range they cover, otherwise the individual watching a thermal image may get the wrong idea about the actual object temperature.

2.4 Thermal Comfort

On the basis of measurements obtained from the experimentation, thermal comfort was analyzed with the help of 'CBE Thermal Comfort Tool' and 'ASHRAE standard' in the available software "https://comfort.cbe.berkeley.edu/". This web-based tool for measuring thermal comfort according to ASHRAE Standard 55-2020 was developed at the University of California at Berkeley, which is easily accessed by anyone in window software.

2.5 PMV/ PPD

CBE Thermal Comfort Tool' gives those predictions in the form of thermal comfort parameter outputs, specifically predicted mean vote (PMV) and predicted percentage of dissatisfied (PPD).

3. Instrumentations and Measurements

Table 1: Instruments used for the study

S. No.	Instrument	Model	Measurement
1.	Thermographic Camera	Fluke TEX-580	Temperature of different surfaces
2.	Indoor Air Quality Monitor	Gas Probe IAQ	Carbon Monoxide
3.	Indoor Air Quality Monitor	TSI Quest EVM-7	CO_2, PM2.5, Humidity, Air & Room Temperature
4.	Digital stopwatch	mi smart band	Time
5.	Hygrometer		Relative Humidity
6.	Sound Monitor		Noise
7.	Thermometer		Temperature of water

4. Results and discussion

4.1 Thermal efficiency

Results of the experimental study shows that the thermal efficiency of improved cookstove with Babul wood was found to be 34.45% and the average power output rating of cookstove was resulted as 1.46 kW. The thermal efficiency found in the current study was higher than the cookstove tested by the Mehetre (2017) [13], who found thermal efficiency as 29.77% and also higher than the cookstove tested by Panwar (2014) [14] in which Single-pot improved cookstoves thermal efficiency was 20.36%, whereas for the double-pot improved cookstove, it was estimated as 23.45%. And a test on improved stove by Komolafe (2010) [11] shows the thermal efficiency as 34% which is lower than the current investigation.

Table 2: Measurements of different parameters during WBT

S. No.	Parameters	Measurements (average values)
1.	Thermal efficiency	34.45%
2.	power output rating	1.46 kW
3.	CO	19.06 ppm
4.	CO_2	878.69 ppm
5.	PM2.5	3.04 mg/m^3
6.	Back wall temperature	40.73 °C
7.	Chimney	55.74 °C
8.	flame chamber	375.62 °C
9.	left wall temperature	35.46 °C
10.	Relative Humidity	47.93%
11	Dew point	19.43 °C
12.	Air Temperature	39.7 °C
13.	Mean radiant temperature	48.39 °C
14.	Noise	46.28 Decibel
15.	Body temperature	39.91 °C
16.	PMV	2.49
17.	PPD	86.97%

4.2 Emissions from cookstove

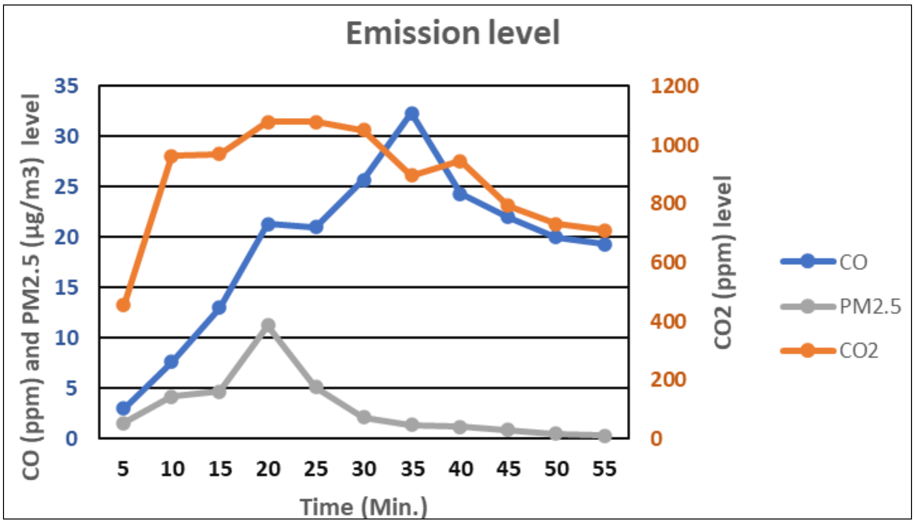

Fig 2: Average Emission level during Water Boiling Test

Carbon Monoxide is basically Colorless, odorless, toxic gas produced by incomplete combustion of carbon-containing materials. As shown in table 2, the average CO produced during combustion was presented as 19.06 ppm, which is much higher than the WHO Standards, 2010. According to the WHO guideline, the CO emission for 24 hours should be less than 7 mg/m^3. A study on 'Indoor air pollution from biomass cookstoves' carried out by Sota *et al.* (2018) [16] found out CO concentrations ranged between 0.01-105 ppm which was much higher than the current study.

Carbon dioxide emissions from non-sustainable use of biofuel also affect the climate, but in this context, this gas does not directly impact the human health. The average CO_2 produced during WBT was calculated as 878.69 ppm. The CO_2 concentration found in the current study was lower than the cookstove tested by the (Mehetre, 2017) [13], who found CO_2 concentration as 3663 ppm.

Particulate Matter (PM2.5) are the particles with aerodynamic diameters of less than 2.5 µm. The average Total Particulate Matter (PM2.5) was assessed as 3.04 mg/m^3 which was much lower than the study conducted by Torres *et al.* (2021) [18] found that levels of PM2.5 during summers in 24 hours levels up-to 510.57 µg/m^3. Results obtained from the study was higher than the WHO

Standards, 2010. According to the WHO guideline, the PM2.5 emission for 24 hours should not be more than 25 µg/m^3, for attaining a healthy life. Emission rates from household fuel combustion should not exceed the WHO guidelines emission rate otherwise it will affects the individual health badly. In young child (under 5 years), these emissions can cause Acute lower respiratory infections, Low birthweight, Stillbirth, Stunting, mortality as well as it impacted the cognitive development (WHO, 2012). In adult's Chronic obstructive pulmonary disease, Lung cancer with coal exposure, Lung cancer with biomass exposure, cardiovascular disease, cancers and Asthma etc. diseases can occur due to these particle emissions.

Table 3: Comparison of Pollutant Emission with WHO Standards/ Guideline

Pollutants	Standards/ Guideline set to protect health	Emission Concentration during WBT	Number of times in excess of Standards/ Guideline
Carbon Monoxide	0.035 ppm	19.06 ppm	543 times
PM2.5	1.0417 mg/m^3	3.04 mg/m^3	3 times

4.3 Thermal Emissivity Analysis

In Fluke TEX-580 Infrared Thermographic Camera, different color palette were presented such as Grayscale, Grayscale Inverted, Blue Red, High Contrast, Hot Metal, Ironbow, Amber, Amber Inverted and Rainbow X. Out of these the researcher used 'High Contrast' color palette where black is for the coldest areas, then dark purple, purple, blue and sky blue for slightly hotter areas, the mid-range of temperatures is usually green, yellow, yellow orange and red and then going to white for the hottest parts. The temperature range that has been recorded by the researcher, in which black (the coldest part) on a thermal image can represent 0 °C or 32 °C or another value and the same goes for the hottest and whitest part it could be 52 °C or 700 °C, It may vary with the temperature distribution during different time zones. In thermal images false colors represents the difference in temperature, there is no specific temperature representing specific color from the color palette used; the colors are just there to make it easy to show the difference in the coldest parts from the hottest parts.

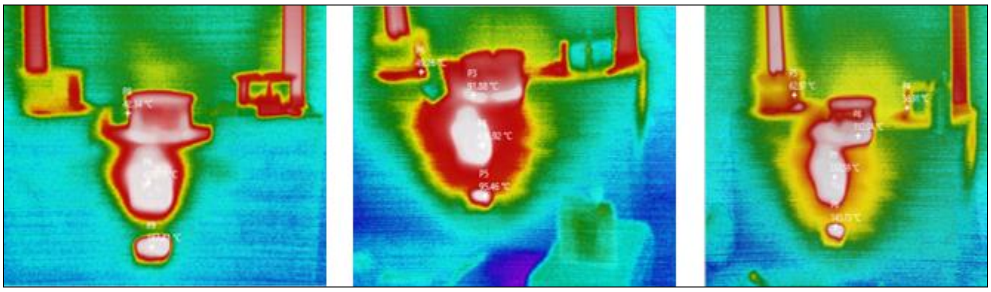

Fig 3: Distribution of temperature during cooking

As shown in the fig. 3, before starting the WBT, lower areas of the cookstove was comparatively cooler than the back wall. In next figure, small amount of radiation was started with the rise in temperature. As the temperature rises in the next figures, thermal emissivity/ MRT were also increased with it. The temperature of walls, floor, flame chamber, ash chamber and stove exit etc. was also increased along with time.

The temperature difference was clearly shown in each figure by just examining the color variation, especially from the red color. The red color differentiated the coldest part of the cookstove to the hottest parts. After 40-45 minutes, thermal emissivity was highest so the thermal radiation during this period was also increased rapidly, due to this, the worker was started to feel thermally uncomfortable. More thermal radiation makes the worker to feel more heat. If the worker was regularly exposed to more radiation, this can cause numerous health problems.

4.4 Thermal Comfort

Thermal Comfort was analyzed by 'CBE Thermal Comfort Tool' using ASHRAE-55 standard and the physical measurements revealed that there is a wide range of kitchens environments and confirmed that occupants were exposed to a 'slightly warm-to-hot' environment. Study predicted that the measured ranges of activities as well as the temperatures were outside the range as recommended by ASHRAE 55 standard. According to (ASHRAE-2009), the warm/hot environment in the cooking area exposing the workers to temperatures higher than the 88°F, may leads to negative health consequences of kitchen workers. Khaiwal, 2019 [10] found in their experiment that the thermal comfort sensation was slightly cool to neutral during winter, neutral during pre-summer and slightly warm during summer according to PMV method.

4.5 PMV/PPD

The findings of the study indicated that the predicted mean vote/percentage people dissatisfied (PMV/PPD) index is not directly appropriate for all thermal conditions in commercial kitchens. The average PMV value for the cold start was 2.49 and for the hot start it was 3.98 and the PPD was evaluated for the cold start and hot start as 86.97% and 97.57% respectively. Rahmillah *et al.* (2017) [15] concluded in her study that the thermal comfort sensation in residential kitchen was in warm/hot condition with the PMV value ranges between 1.73 up to 2.36 and PPD between 63% until 90%.

Table 4: Karl Pearson's Correlation Coefficient of different parameters with time

S. No.	Parameters	TIME					
		Test I	Test II	Test III	Test IV	Test V	Test VI
1.	Body Temp.	0.988**	0.996**	0.994**	0.986**	0.991**	0.973**
2.	Air Temp.	0.993**	0.968**	0.876**	0.972**	0.931**	0.981**
3.	RH	-0.980**	-0.999**	-0.980**	-0.817**	-0.978**	-0.872**
4.	Dew Point	0.285	0.346	0.095	-0.029	0.322	-0.029
5.	MRT	0.832**	0.986**	0.826**	0.980**	0.920**	0.980**
6.	CO	-0.247	0.709**	0.814**	-0.229	0.680**	0.816**
7.	CO_2	0.011	0.255	-0.333	0.001	0.065	-0.254
8.	PM2.5	-0.670**	-0.471	-0.468	-0.557*	-0.462	-0.387
9.	PMV and PPD	0.978**	0.959**	0.970**	0.810**	0.921**	0.741**

According to the data analyzed, the body temperature, air temperature and mean radiant temperature were correlated with time, which means that the values of these parameters were simultaneously increased with time. In this, positive and high correlation coefficient was found out at 5% level of significance. Relative humidity, dew point, CO, CO_2 and PM 2.5 shows both negative and positive correlation because their value varies along with time. Table 4 revealed that the values of correlation coefficient for PMV were obtained above 0.7 so the PMV was positive and highly significant with the PPD for the entire test. So, the result suggested that the values of PPD were significantly increasing in relation to PMV values.

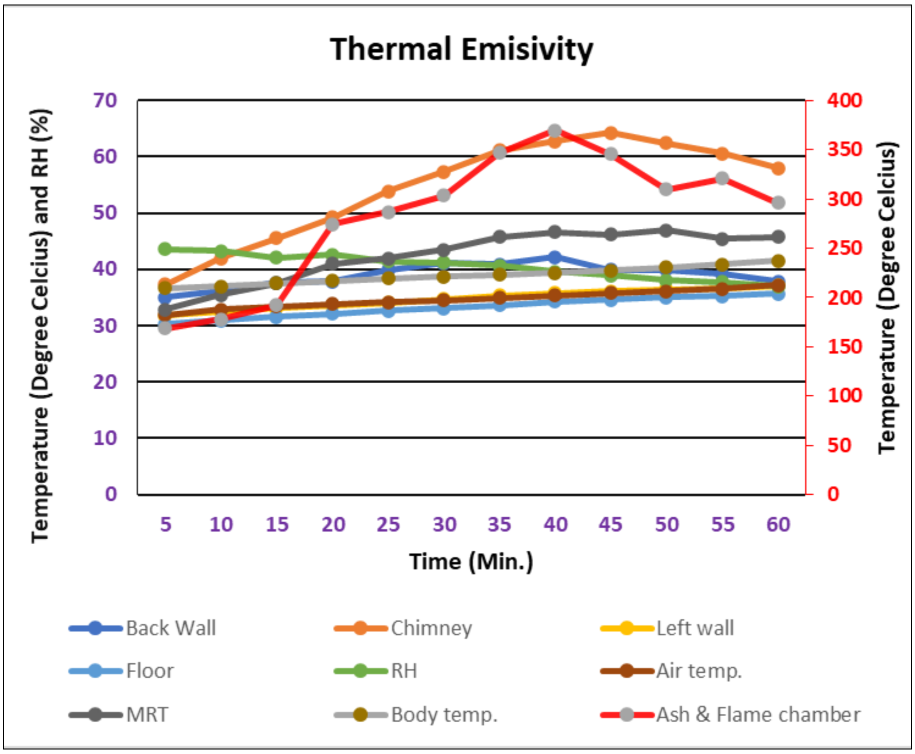

Fig 4: Temp distribution of different zones of the cookstove during WBT

5. Conclusion

The improved cookstove was more thermally efficient and able to save valuable amount of fuel and produce lesser radiant heat when compared to traditional cookstove. Experimental data indicated that there is positive and high correlation coefficient between time and temperature (body temperature, air temperature and mean radiant temperature), which means the increase in temperature was directly proportionate to the time involved during cooking. A 'slightly warm-to-hot' thermal environment was examined during the WBT and the warm/hot environment in the cooking area exposed the workers to temperatures approximately 43 °C, that leads to negative health consequences of kitchen workers. Developed cookstove saves considerable amount of CO, CO_2 and PM (2.5) emission as compare to traditional cookstove. As it is a three-pot cookstove, which saves both time and energy in comparison to the others. The rural and needy people can easily afford or build the developed cookstove. So, for all those reasons it is valuable to use.

Abbreviations

ASHRAE	American Society of Heating, Refrigerating and Air Conditioning Engineering
BIS	Bureau of Indian Standard
CBE	Center for Built Environment
Fd	corresponds to the equivalent dry fuel consumed (g)
HAP	Household air pollution
LHV	Low heating value of biomass (J/g).
MRT	Mean Radiant Temperature
H	number of pots used in the test
Pjf-Pji	weight difference of the pot at the beginning and end of the test (g)
Tjf - Tji	temperature change in each pot (°C)
w_r	mass of liquid water presents in the pots after the test (g)
w_v	amount of water evaporated during the test (g)

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