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Design and development of smokeless stove for a sustainable growth

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Abstract Air pollution has a serious impact on the health of human beings and is a major cause of death worldwide every year. Out of the many sources of air pollution, the smoke generated from household combustion devices is very dangerous due to the incomplete combustion of fuel. Women from rural areas suffer a lot due to this harmful smoke. Diseases like cancer, throat, and lung infection occur in adults and children due to inhalation of this smoke. The traditional chulha used by rural women is operated by using cow dung, straw, and wood, and the air is blown manually by using small metallic pipes. This paper presents the design and development of an innovative stove to maximize flame temperature and minimize air pollution to overcome the health-related issues of rural women. A smokeless stove is presented, in which wood, straw, and cow dung are taken as primary fuel, and superheated steam as a secondary oxidizer for its operation. In this stove, a forced draft is created by the provision of a small fan, which is operated by solar power thus eliminating the need of creating a forced draft manually by the cook which makes this innovative stove superior to the traditional chulha. Owing to the provision of superheated steam, the flame temperature as well as the burning efficiency increases. The cooking time is reduced due to higher flame temperature as compared to the liquefied petroleum gas stove. The main objective of this work is to minimize air pollution and provide a smoke-free environment to the people using such

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devices as this innovative stove offers complete combustion of fuel. The flame temperature of the designed stove ranges from 595°C to 700°C and its thermal efficiency is 10–17% higher than that of the traditional chulha. The design of this stove is unique, and its maintenance cost is also much less.

Keywords: Combustion; Efficiency; Calorific value; Air pollution; Stove; Fuel; Superheater

Nomenclature

C_v	–	specific heat of container material (aluminum), kJ/kgK
C_w	–	specific heat of water, kJ/kgK
D_1, D_2, D_3	–	diameter of inner, middle, and outer cylinder, m
DR	–	dilution ratio
d	–	diameter of superheater, m
F	–	consumption rate of fuel, kg/s
H	–	height of cylinders, m
H_{fuel}	–	calorific value of primary fuel, kJ/kg
H_k	–	calorific value of kerosene, kJ/kg
h	–	height of superheater, m
M	–	mass of container, kg
m	–	mass of water container, kg
n	–	number of containers
P_o	–	power output, kW
Q_{in}	–	heat input into the stove, kJ
Q_{out}	–	heat output of the stove, kJ
T_1, T_2	–	initial and final temperature of the water, °C
T_3	–	final temperature of water in the last vessel after the test, °C
$\dot{V}$	–	volumetric flow rate, m^3/s
X_{fuel}	–	mass of solid fuel, kg
X_k	–	mass of kerosene, kg
η_{thermal}	–	thermal efficiency of the stove, %.
LPG	–	liquefied petroleum gas

1 Introduction

Smoke from traditional chulha is a major contributor to air pollution which has a great impact not only on the environment but also on the health of human beings using this chulha for cooking purposes. Generally, chulha used by rural women for cooking purposes are placed inside a room. The smoke generated during the operation of chulha causes health-related issues for family members. About 40–50% of families in India are using traditional chulha for the preparation of their food every day. In general, the chulhas of this type are kept inside the home and operated by women. These stoves are operated by using cow dung, straw, and wood. The supply of air to this traditional chulha is done by blowing in the air by mouth continuously using a small cylindrical metallic pipe. The operation of traditional chulha is unsafe due to the generation of harmful smoke as a result of the incomplete combustion of fuel. Women from rural areas suffer a lot due to this harmful smoke. Diseases like cancer, throat infection, eye diseases, and lung infection occur in adults and children due to this harmful smoke [1]. It is found that more than 40% of women using traditional chulha are suffering from many diseases caused by harmful gases released from these stoves during their operation due to the incomplete combustion of fuel. The smoke generated from the traditional chulhas during the preparation of food also creates air pollution which has a serious impact on the environment and is a major cause of death in India. Smoke from the cooking of food using traditional chulha is the major cause of the respiratory problem of rural women [2]. It is reported that more than six *lakh* (six hundred thousand) deaths occur in India due to smoke which is generated by traditional chulha. World Health Organization also estimated that more than one million premature deaths are caused due to indoor air pollution in India every year. The Government from various countries is trying to minimize the use of traditional chulhas by providing a number of other alternatives. But it is found that implementation of these alternative methods is not up to the mark in rural areas.

We conducted a survey in a village Mahidharpada in the Cuttack district in the state of Odisha. It was observed that more than 80% of families in this village were using traditional clay chulha for their breakfast, lunch, and dinner. They have installed their stove in a room. Thus, smoke from this stove is accumulated inside the room, which causes serious health-related problems for the occupants. The present government in India has taken a number of initiatives for people belonging to the BPL (Below Poverty Line) category to use LPG cylinders for their cooking. But from our survey, we found that a maximum number of families do not have any BPL card for availing this facility. Some BPL card holders availing of this facility do not have the capability to refill their LPG cylinders due to continuous hikes in the price of LPG cylinders. At the time of the survey, we noticed that 90% of women of the village of Mahidharpada are using traditional chulha and they are exposing themselves for about 4 to 5 hours per day to the harmful smoke during the process of cooking. As many as 40% of rural women are suffering from diseases like chronic obstructive pulmonary disease, eye problems, tuberculosis, stroke, etc. due to their exposure to harmful gases.

This paper demonstrates the designed and developed smokeless stove which can be used for cooking by people residing in rural areas. The main objective of this work is to manufacture a smokeless stove that would not only provide a safe environment but also make the cooking process easy and comfortable. Smoke generated from the cooking process is one of the main sources of air pollution. The harmful gases released from the traditional chulha during the cooking process cause health issues to family members. The smoke generated during the burning of fuel is considerably lower in our designed stove. That has been possible by the use of superheated steam as a secondary oxidizer. The designed stove provides several advantages over traditional chulha. It is easy to transport and its maintenance cost is low. The raw material required for its manufacturing is easily available and hence the cost of the designed stove is low. Few works have been done by researchers to develop smokeless stoves but the studies considering the use of secondary oxidizers are limited in the literature. Onah *et al.* [3] investigated the effect of fuelwood on carbon emissions through the use of improved stoves by selected families in Kwara state and found that such use can help protect forests and may also contribute to reducing CO_2 emissions in Nigeria.

Obi *et al.* [4] studied extensively the performance of fuel blocks driven biomass cooking stoves and found that improved cooking stoves proposed superior thermal efficiency than the conventional cooking stoves. Woldesemayate and Atnaw studied biomass cookers for their project alongside performance and found that the improved cookers showed enhanced performance over conventional cookers [5]. Flores *et al.* [6] studied excessive costs and investigated the cost-benefit of introducing improved cookers in Honduras and found that the costs associated with implementing this related strategy are low. Mekonnen and Hassen [7] examined blueprint, establishment, and evaluation of hybrid biomass cooking stoves driven by solar energy and found that such devices exhibit 5% thermal efficiency enhancement along with 6 g/L declinations in fuel expenditure in comparison to conventional biomass cooking stoves. Jain and Sheth [8] reviewed the energy test plan for a biomass cooking stove and found that this formula increased the run time to about 85 min, representing a 30% overall improvement. Manyuchi *et al.* [9] studied the espousal of eco cooking stoves as a technique of exuberant efficiency enhancement and found that the acceptance of such structures led to energy conservation along with energy efficiency enhancement in comparison to conventional open cooking stoves. Prasannakumaran *et al.* [10] investigated the inclusion of trays to recuperate unwanted heat in an abundance of efficient wood stoves, they demonstrated that such incorporation resulted in increased efficiency while reducing fouling levels. Emetere *et al.* [11] studied properties of heat sink for an effective establishment of exuberance in producing cooking stove for rural people and found that fall down or the rise of the restricted boundaries established by the steel constituents dictates the microstructural proneness, mechanical characteristics, and the chemistry of alloys of the heat sink. Tom *et al.* [12] tested the performance of multi-layered biomass block cooking stove and found that such structure resulted in fine stove performance for quintessential cooking times. Roul and Nayak [13] presented natural convection heat transfer through the internal surface of heated vertical tubes. Other works of Nayak *et al.* [14–16] showed the enhancement of heat transfer in a vertical tube by providing internal rings of various dimensions at different intervals.

Sahoo *et al.* [17–19] employed computational fluid dynamics techniques to analyze heat transfer from pin-finned horizontal and vertical plates. Baqir *et al.* [20] carried out the performance evaluation of improved metal stove over traditional mud chulha. They found that the use of improved metal stove resulted in reduced indoor pollutants, reduced fuelwood consumption, and increased thermal efficiencies over traditional mud chulha. Saravanna *et al.* [21] performed modeling and analysis of heating water using waste heat within the hot flue gases exhausted from a stove and found that by the use of stainless steel shell – copper pipe combination waste heat recovery system, the heating time, environmental impact and the cost of energy consumption is reduced. Thakur *et al.* [22] studied the effects of using a low smoke stove over traditional cook chulha with a follow-up time of 1 year. They found that the use of a low smoke stove results in reduced indoor air pollution and an increase in respiratory health for both women and children. Smith and Sagar [23] considered the need and ways to include gas and electric cooking to avoid pollution caused by solid fuel-fired cooking stoves in India. They found that the ministry of health, petroleum, and power ministries engagement can help save the Indian population trapped in the stove trap.

Hanbar and Karve [24] undertook a critical appraisal of the Government of India's National Stove Improvement Program and found that the program mainly focuses on creating resourceful stove models, promoting them, and making them public. They also concluded that this program can provide clean and sustainable use of biomass energy in rural areas. Gowda *et al.* [25] conducted a case study on rural waste management in a village in southern India and found that replacing traditional mud chulha with improved chulha could help families reduce their annual firewood consumption. Their analysis also showed that commercializing the use of rice and coconut biomass could improve the savings of rural families. Wang and Bailis studied the social methods of elimination of traditional stoves in Himachal Pradesh and found that despite decades of effort, extensive acceptance of improved stoves in developing countries is yet to be achieved [26]. They observed that the adoption pathways for improved biomass stoves along with LPG stoves among different socio-economic groups were different. Kammen examined the cook stoves used in Kenya and programs in China and India and indicated that traditional cook stoves using wood, charcoal, and coal are extensively used in most households [27]. The design of new generation stoves has significant consequences not only on energy usage but also on the environment and community health. Asi considered four analytical frameworks in order to analyze extensive learning processes in improved cook stove practice [28]. He found that extensive learning processes lead to collaborative decision implementation. Kshirsagar *et al.* [29] studied the use of robust design parameters to optimize the performance of hybrid draft biomass stove and demonstrated that such optimization procedure resulted in the best overall furnace performance.

From the literature review, it was observed that several researchers have studied the negative effects of traditional chulhas and suggested some improvements to them. However, none of the researchers used the concept of a secondary oxidizer such as superheated steam, to develop a smokeless stove to overcome the harmful effects of traditional chulha. This paper presents a smokeless stove operated by biomass along with superheated steam that has been developed to control air pollution and decrease the health-related issue of rural people. The main advantage of this stove is that it can be easily operated, it is easy to transport and all types of biomass fuels such as wood, cow dung, and straw can be used with the minimum generation of smoke.

2 Experimental setup and procedure

Figure 1 shows the overall setup of the biomass-operated smokeless stove. It consists of external, middle, and internal cylinders. All these cylinders are positioned on a common support. Insulating materials are provided in between the external and middle cylinders to decrease the heat transfer to the outer wall. The flame temperature is maintained at a high level due to the combined effect of the primary fuel and steam supply from the superheater. In this work, glass wool has been used as an insulating material between the external and middle cylinders. The flame temperature can be maintained at a high level by minimizing the heat loss to the environment. The top of external and internal cylinders is covered, and some sort of arrangement is provided on top to support utensils used for cooking purposes as shown in Fig. 1.

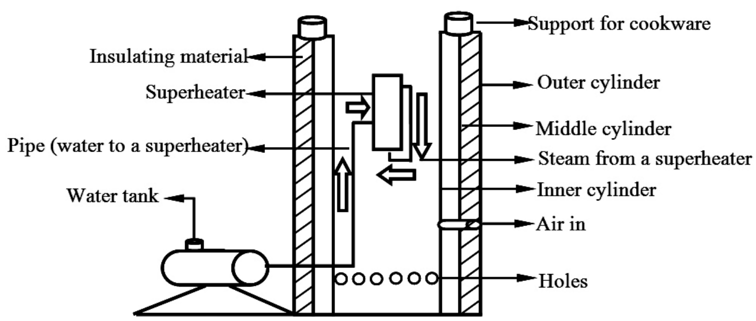

Figure 1: Schematic diagram of the experimental setup.

Small holes are provided on the cylinders to allow higher velocity of the air and higher flow of air to the interior of the stove (combustion space) for complete combustion of fuel. A solar-powered small fan is used to supply air to produce a forced draft inside the stove. The solar panel is used to charge a 12 V battery to supply power continuously to the fan so that the stove can be used during the night. Ash from the stove is removed using an ash tray provided at the bottom of it. Both primary fuel and secondary oxidizer are used in this stove. Cow dung, straw, and small wooden pieces can be taken as primary fuel and superheated steam is taken as a secondary oxidizer. Superheated steam is produced by the provision of a superheater inside the chamber as shown in Fig. 1. A small water tank with a pumping arrangement is provided outside the stove. Water from the water tank is supplied continuously to the superheater through a pipe.

Figure 2 shows the prototype of a smokeless stove. The diameters of the inner cylinder (D_1), middle cylinder (D_2), and outer cylinder (D_3) are 0.3048 m (12 in), 0.3556 m (14 in), and 0.4064 m (16 in), respectively. The height (H) of all the cylinders is 0.6604 m. The solar panel is used to drive the fan to create a forced draft by creating positive air pressure for increasing the rate of combustion and rate of heat transfer.

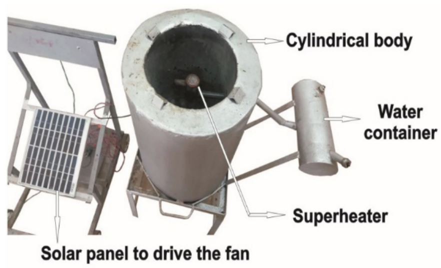

Figure 2: Image of the smokeless stove.

Figure 3 demonstrates the schematic diagram of the superheater. The superheater consists of a cylinder that has a diameter of d =0.0508 m (2 in) and a height of h = 0.1524 m. Two holes are drilled at the side of the cylinder to insert the inlet and outlet pipe. One hole is provided at a distance of 0.0127 m below the top of the cylinder and another hole is drilled at a distance of 0.0254 m above the bottom of the cylinder. The top hole is connected with the nozzle for the supply of superheated steam to the combustion chamber and the bottom hole is connected with the water tank through which water is supplied to the superheater by a manually operated pump. The nozzle is placed below the superheater as shown in Fig. 3. The temperature of superheated steam ranges from 200°C to 250°C which helps in increasing the flame temperature.

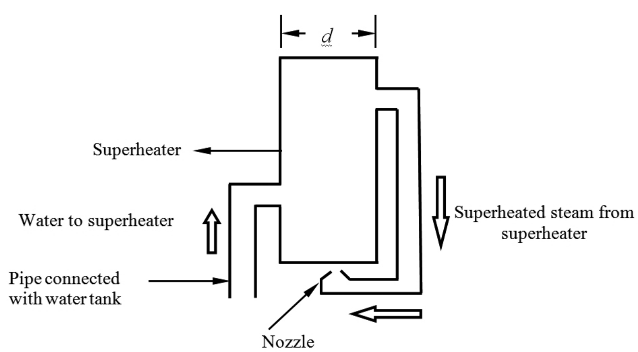

Figure 3: Schematic diagram of the superheater.

Multi-gas analyzer (Horiba Instruments Pvt. Ltd.) is used for continuous measurement of the concentrations of NO_x, CO_2, and CO. Electronic balances (5.1 gm capacity, LC: 0.001 mg, Sartorius ME5, and 30 kg capacity, LC: 1 gm, K-Roy, Kolkata) are used for measurement of the mass of fuel. The automated compensated Isoperibol calorimeter (Parr Instrument IR60,) is used for the determination of the calorific value of a fuel. For analysis of moisture, the Denver Instrument IR60 was used. The total particulate matter is determined with the use of Polltech Instruments Pvt. Ltd. A hotwire anemometer is utilized to measure the flame speed. K-type thermocouples are used to measure the flame temperature, the handle temperature, and the outside wall temperature of the stove. The readings of thermocouples are recorded on a separate computer using the LabView [32] software.

Table 1 shows the details of the designed biomass-operated smokeless stove with specifications of different parameters. The observations have been carried out by considering various factors such as fuel type, geometrical parameters, etc.

Table 1: Details of the biomass operated smokeless stove.

Parameters	Particulars
Type of stove	Forced draft
Combustion chamber of the stove	Cylindrical
Total weight	9.5 kg
Inner diameter (D_1)	0.3048 m
Height of cylinders (H)	0.6604 m
Test duration	4 h
Fuel (primary)	Wood
Secondary oxidizer	Superheated steam
Primary fuel size	0.04 m × 0.04 m × 0.125 m
Diameter of superheater (d)	0.0508 m
Height of superheater (h)	0.1524 m

For the operation of this type of stove, some simple steps need to be followed. The solar-powered fan is connected with the passage of the stove. Some dry woods (primary fuel) are added to the stove. Water is poured into the water tank. Ignition of the primary fuel is done by adding some kerosene into it. The fan is switched on and some more amount of primary fuel is added. When the primary fuel starts burning, water is pumped to the superheater and the superheated steam from the superheater passes through the nozzle to the combustion chamber. Then the cookware is placed on the support for cooking. Pumping of water to the superheater should be carried out with some time intervals for better flame temperature. Primary fuel can be added as and when required.

3 Results and discussion

In this designed stove, superheated steam is used as a secondary oxidizer which provides a number of advantages for increasing the burning efficiency and reducing the generation of smoke. Superheated steam possesses a large amount of heat energy as it carries the latent heat of vaporization of water at higher pressure. Adding water vapor to a high-tem flame can increase the reactivity by catalyzing action. This is in addition to an increase in the concentration of radicals contributing to the reactive gasification of the medium. The associated release of energy will also provide additional heat for the endothermic gasification reactions [30].

By following proper steps and procedures, a number of the tests have been conducted on the biomass-fired smokeless stove. Table 2 shows the test results on the thermal efficiency, formation of carbon monoxide, flame speed, fuel consumption rate, and total particulate matter from this stove. Firewood of size 0.04 m $\times$ 0.04 m $\times$ 0.125 m was used as the primary fuel. Superheated steam which has the property to attract moisture from drying substances and transmit heat to it up to saturation, is used as a secondary oxidizer. Generally, dry fuel (wood) has a maximum heating value compared to wet fuel. In this work, the enthalpy of primary fuel is increased by supplying superheated steam. The drying system, functioning in a self-heat recovery pattern, enables the gathering of steam from the moisture in the raw fuel, followed by the recirculation of its latent and sensible heat for the drying of the rest of the fuel [31]. As a result, the heat of the phase transition is not given off to the ambiance, which results in reducing the energy consumption, thus elevating the thermal efficiency of the system. The property of superheated steam is to avoid reactions during combustion. Thus, the use of superheated steam in the carried out study eliminates the risk of the chances of explosion.

The heat input into the stove is calculated by using the relation:

$$Q_{\text{in}} = X_{\text{fuel}} H_{\text{fuel}} + X_k H_k\,, \tag{1}$$

where X_{fuel} and X_k are the mass of solid fuel and kerosene, respectively, whereas H_{fuel} and H_k represent their calorific values.

Table 2: Test results of biomass operated smokeless stove.

Test No.	Thermal efficiency (%)	CO concentration (ppm)	Flame speed (m/s)	Fuel consumption rate (kg/h)	Calorific value (kJ/kg)	Emission factor for CO (g/MJ)	Total particulate matter (mg/MJ)
Test 1	26.0	291.09	2.41	4.00	18618.60	4.01	145.11
Test 2	26.3	466.03	2.82	3.90	18325.70	4.91	140.01
Test 3	27.5	571.12	2.92	3.70	18115.28	5.00	141.02
Test 4	25.5	271.01	2.31	3.90	18318.8	3.21	142.01
Test 5	27.6	589.99	3.02	3.60	18504.57	4.04	149.03
Test 6	26.1	395.12	2.61	3.70	18118.8	4.93	145.27
Average	26.5	430.73	2.68	3.80	18333.6	4.35	143.74
Standard deviation	0.86	136.09	0.285	0.155	202.26	0.719	3.362

The heat output of the stove is calculated as follows:

$$Q_{\text{out}} = (n-1)\left(MC_V + mC_w\right)\left(T_2 - T_1\right) + \left(MC_V + mC_w\right)\left(T_3 - T_1\right), \quad (2)$$

where n is the number of containers, M and m denote the mass of container and water, respectively, quantities C_v and C_w represent the specific heat of container material (aluminum) and water, respectively, T_1 is the initial temperature of the water, T_2 is its final temperature, and T_3 is the final temperature of water in the last vessel at the completion of the test.

The values of parameters are taken as:

$$\begin{aligned} &C_v = 0.896 \text{ kJ/kgK}, && C_w = 4.2 \text{ kJ/kgK}, && M = 1.310 \text{ kg}, \\ &T_1 = 23°\text{C}, && T_2 = 95°\text{C}, && T_3 = 120°\text{C}, \\ &X_k = 15 \times 10^{-3} \text{ kg}, && H_k = 45000 \text{ kJ/kg}, && n = 4. \end{aligned}$$

The thermal efficiency of the stove can be determined using the formula

$$\eta_{\text{thermal}} = \frac{Q_{\text{out}}}{Q_{\text{in}}} \times 100. \quad (3)$$

Power output (productivity power) of the stove is then given by

$$P_o = \frac{F\, H_{\text{fuel}}\, \eta_{\text{thermal}}}{360000}, \quad (4)$$

where F is the consumption rate of fuel.

By conducting six test series, it was observed that the thermal efficiency of the developed stove ranges from 25.5% to 27.6%, which is 10% to17% higher than that of the traditional chulha. Carbon monoxide (CO) concentration ranges from 270 ppm to 600 ppm. The flame speed ranges from 2.31 m/s to 3.02 m/s. The consumption rate of primary fuel (wood) ranges from 3.60 kg/h to 4 kg/h. The emission factor for CO defined as the emission per unit of energy delivered ranges from 3.21 g/MJ to 5 g/MJ.

Several tests have been conducted to find out the flame temperature, outer cylinder (body) temperature, and the output of the stove during its operation. Measurements were collected simultaneously from undiluted chimney gas, diluted gas drawn directly from the chimney, and plume gas collected from a dilution tunnel above the chimney. Concentrations of CO, CO_2, and O_2, temperature, pressure, and particulate matter (PM) were measured.

The material balance was used for CO_2 to assess the degree of dilution between diluted and undiluted chimney gas. Dilution ratio is defined as the ratio of the rate of flow through the chimney ($\dot{V}_2$) to the rate of flow through the diluted line ($\dot{V}_3$):

$$\mathrm{DR} = \frac{\dot{V}_2}{\dot{V}_3}\,. \tag{5}$$

The outcome of the experimental investigation of the designed stove has been presented in Table 3. It is observed that flame temperature ranges from 595°C to 700°C, the dilution ratio varies from 49.87 to 63.13 and the power output ranges between 4.86 kW and 5.37 kW.

Table 3: Temperature range and power output of the smokeless stove.

Test No.	Thermal efficiency (%)	Stream size (m^3)	Power output (kW)	Dilution ratio (–)	Outside cylinder temperature (°C)	Flame temperature (°C)	Handle temperature (°C)
Test 1	26.0	0.71	5.37	49.87	48	601	45
Test 2	26.3	0.87	5.22	61.01	57	632	52
Test 3	27.5	0.83	5.12	61.01	52	640	49
Test 4	25.5	0.99	5.06	60.12	49	595	43
Test 5	27.6	1.33	5.10	60.79	50	700	43
Test 6	26.1	1.01	4.86	63.13	51	670	44
Average	26.5	0.96	5.122	59.32	51.17	639.67	46
Standard deviation	0.856	0.213	0.169	4.739	3.188	40.272	3.688

Figure 4 demonstrates the operation of the designed biomass-burning smokeless stove. The flame temperature and flame velocity are higher than in the traditional chulha.

a) b)

Figure 4: Functioning of the designed smokeless stove.

Table 4 shows the comparison between the traditional chulha and the designed stove. The designed stove has many advantages over traditional chulha. It is easy to operate and it can be transported easily due to the

Table 4: Comparison of traditional and the designed stove.

Parameters	Traditional chulha	Designed stove	Remark
Flame temperature	200–300°C	595–700°C	More than double
Flame velocity	Low	Almost double	Due to forced draft
Smoke	More	Less	Due to the complete burning of fuel
Fuel used	Primary (wood)	Primary (wood) and secondary oxidizer (superheated steam)	Higher flame temperature, higher efficiency, lower smoke
Efficiency	10–15%	27.6%	Saves cooking time and cost
Combustion	Inadequate	Improved	Complete combustion due to superheated steam

flexibility of its design. The cost of the designed device is also very low as the material required for its manufacturing is easily available. The use of the developed stove provides an environment having zero-emission and zero health issues for rural women, whereas cooking with traditional chulha causes serious health problems and environmental pollution. In addition, it has higher flame temperature and higher efficiency due to the use of superheated steam. Due to the complete combustion of fuel, the smoke and ash formation is also reduced which makes the stove environment-friendly and energy-efficient.

4 Conclusions

The main objective of this work is to design and develop a smokeless stove to improve thermal efficiency and reduce air pollution that will not only reduce the cooking cost but also provide a better environment for rural women. The significant conclusions derived from the analysis can be reckoned as follows:

- The thermal efficiency of the designed stove is 10–17% higher than that of the traditional chulha.
- The flame temperature of this stove ranges from 595°C to 700°C, which not only reduces the cost of cooking but also reduces the cooking time.
- Due to the provision of secondary oxidizer (superheated steam), complete burning of primary fuel occurs, as a result of which ash formation, as well as the formation of harmful gases, reduce.
- The maximum heating value of the primary fuel contributes to an increase in combustion efficiency.
- Due to the provision of insulating layers, the temperature of the body and handle of the designed stove is low, so it can be handled easily.
- It provides a safer environment due to less formation of harmful gases.
- By utilizing the battery and solar power system, the designed stove can be used at night.

- In the stove, the forced draft is created using a small fan, which is operated by solar power thus eliminating the need of creating forced draft manually by the cook which makes this innovative stove superior to the traditional chulha.

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References

[1] James B.S., Shetty R.S., Kamath A., Shetty A.: *Household cooking fuel use and its health effects among rural women in southern India — A cross-sectional study.* PLoS ONE **15**(2020), 4, e0231757.

[2] Balakrishnan K.: *Examining health effects of air pollution in India.* ICMR Cent. Adv. Res. Environ. Health, New Delhi 2013.

[3] Onah I., Ayuba H.K., Idris N.M.: *Estimation of fuelwood-induced carbon emission from the use of improved cook stoves by selected households in Kwara State, Nigeria.* Clim. Change **160** (2020), 3, 463–477.

[4] Obi O.F., Ezema J.C., Okonkwo W.I.: *Energy performance of biomass cookstoves using fuel briquettes.* Biofuels **11** (2020), 4, 467–478.

[5] Woldesemayate A.T., Atnaw S.M.: *A review on design and performance of improved biomass cooks stoves.* L. N. Inst. Comp. Sci. Soc.-Inf. Telecomm. Eng. LNICST **308**(2020), 557–565.

[6] Flores W.C., Bustamante B., Pino H.N., Al-Sumaiti A., Rivera S.: *A national strategy proposal for improved cooking stove adoption in Honduras: Energy consumption and cost-benefit analysis.* Energies **13**(2020), 4, en13040921.

[7] Mekonnen B.Y., Hassen A.A.: *Design, construction and testing of hybrid solar-biomass cook stove.* L. N. Inst. Comp. Sci. Soc.-Inf. Telecomm. Eng. LNICST **274** (2019), 225–238.

[8] Jain T., Sheth P.N.: *Design of energy utilization test for a biomass cook stove. Formulation of an optimum air flow recipe.* Energy **166**(2019), 1097–1105.

[9] Manyuchi M.M., Mbohwa C., Muzenda E., Mpeta, M.: *Adoption of eco cook stoves as a way of improving energy efficiency.* In: Proc. Int. Conf. on Industrial Engineering and Operations Management, Pilsen, July 23–26, 2019, 35–39.

[10] Prasannakumaran K.M., Karthikeyan M., Sanjay Kumar C., Premkumar, D., Kirubakaran V.: *Integration of cooking trays for waste heat recovery in the energy efficient wood stove.* Indian J. Environ. Prot. **39**(2019), 1, 69–73.

[11] Emetere M.E., Okonkwo O.D., Jack-Quincy S.: *Investigating heat sink properties for an efficient construction of energy generating cook stove for rural settler.* Int. J. Manuf. Mater. Mech. Eng. **8**(2018), 3, 12–22.

[12] Tom S., Shuma M.R., Madyira D.M., Kaymakci A.: *Performance testing of a multi-layer biomass briquette stove.* In: Proc. Conf. Ind. Commer. Use Energy ICUE (2017), 8068008.

[13] Roul M.K., Nayak, R.C.: *Experimental investigation of natural convection heat transfer through heated vertical tubes.* Int. J. Eng Res Appl. **2**(2012), 6, 1088–1096.

[14] Nayak R.C., Roul M.K., Sarangi S.K.: *Experimental investigation of natural convection heat transfer in heated vertical tubes with discrete rings.* Exp. Tech. **41**(2017), 585–603.

[15] Nayak R.C., Roul M.K., Sarangi S.K.: *Experimental investigation of natural convection heat transfer in heated vertical tubes.* Int. J. Appl. Eng. Res. **12**(2017), 2538–2550.

[16] Nayak R.C., Roul M.K., Sarangi, S.K.: *Natural convection heat transfer in heated vertical tubes with internal rings.* Arch. Thermodyn. **39**(2018), 4, 85–111.

[17] Sahoo L.K., Roul, M.K., Swain R.K.: *CFD analysis of steady laminar natural convection heat transfer from a pin finned isothermal vertical plate.* Heat Transf. – Asian Res. **46**(2017), 840–862.

[18] Sahoo L.K., Roul M.K., Swain R.K.: *Natural convection heat transfer augmentation factor with square conductive pin fin arrays.* J. Appl. Mech. Tech. Phys. **58**(2017), 1115–1122.

[19] Sahoo L.K., Roul M.K., Swain R.K.: *CFD analysis of natural convection heat transfer augmentation from square conductive horizontal and inclined pin fin arrays.* Int. J. Ambient Energy **39**(2018), 840–851.

[20] Baqir M., Bharti S.K., Kothari R., Singh, R.P.: *Assessment of an energy-efficient metal stove for solid biomass fuel and evaluation of its performance.* Int. J. Environ. Sci. Technol. **16**(2019), 11, 6773–6784.

[21] Saravanna J.Y., KantamnenR., Fasil N., Sivamani S., Hariram V., Micha Premkumar T., Mohan., T.: *Modelling and analysis of water heating using recovered waste heat from hot flue gases of stove.* ARPN J. Eng. Appl. Sci. **12**(2017), 21, 6164–6171.

[22] Thakur M., Boudewijns E.A., Babu G.R., Winkens B., de Witte L.P., Gruiskens J., Sushama P., Ghergu C.T., van Schayck O.C.P.: *Low-smoke stove in Indian slums: Study protocol for a randomised controlled trial.* BMC Public Health **17**(2017), 1, 454.

[23] Smith K.R., Sagar A.: *Making the clean available: Escaping India's Stove Trap.* Energy Policy **75**(2014), 410–414.

[24] Hanbar R.D., Karve, P.: *National Programme on Improved Stove (NPIC) of the Government of India: an overview.* Energy Sustain. Dev. **6**(2002), 2, 49–55.

[25] Gowda M.C., Raghavan G.S.V., Ranganna B., Barrington S.: *Rural waste management in a south Indian village – A case study.* Bioresour. Technol. **53**(1995), 2, 157–164.

[26] Wang Y., Bailis R.: The revolution from the kitchen: *Social processes of the removal of traditional cookstoves in Himachal Pradesh, India.* Energy Sustain. Dev. **27**(2015), 127–136.

[27] Kammen D.M.: *Cook stoves for the developing world.* Sci. Am. **273**(1995), 1, 72–75.

[28] Asi E.M.: *An integrated analytical framework for analysing expansive learning in improved cook stove practice.* Learn. Cult. Soc. Interact. **26**(2020), 100414.

[29] Kshirsagar M.P., Kalamkar V.R.: *Application of multi-response robust parameter design for performance optimization of a hybrid draft biomass cook stove*. Renew. Energy **153**(2020), 1127–1139.

[30] Koroll G.W., Mulpuru S.R.: *The effect of dilution with steam on the burning velocity and structure of premixed hydrogen flames*. Symp. (Int.) Combust. **21**(1988), 1, 1811–1819.

[31] Mujumdar A.S.: *Superheated steam drying*. In: Handbook of Industrial Drying (3rd Edn.). CRC Press, Boca Raton 2006.

[32] Potter D.: *Measuring Temperature with Thermocouples – A Tutorial*. National Instruments Application Note 043, Nov. (1996).