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Effect of geometric size reduction on the thermal efficiency of a galvanized plate biomass stove

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Abstract

Improving the thermal efficiency of biomass cookstoves remains essential for enhancing energy utilization and reducing fuel consumption in household applications. This study investigates the effect of geometric size reduction on the thermal performance of a galvanized steel biomass stove equipped with a 12 V DC blower. The original biomass stove constructed from galvanized steel plates with dimensions of 50 × 50 × 55 cm^3 equipped with a 12 V DC blower was developed in 2022. Due to its relatively large size, the air–fuel mixture delivered to the combustion chamber was not fully optimized, resulting in a thermal efficiency of only 10%. To address this limitation, the stove dimensions were reduced to 40 × 40 × 40 cm^3. The performance evaluation was conducted using the Water Boiling Test (WBT) method with two water volumes (2 L and 5 L) and three fuel masses (40%, 60%, and 80%). The results indicate that reducing the stove dimensions contributes to a significant improvement in thermal efficiency, reaching up to 14.6%.

Keywords:
Biomass stove, galvanized steel, size reduction, thermal efficiency, water boiling test

1 Introduction

Energy sources utilized in daily life in Indonesia are still predominantly derived from petroleum and coal [1]. The continuous use of non-renewable energy sources ultimately leads to an energy crisis due to their declining availability. Conversely, with economic growth and an increasing population, the national energy demand continues to rise [2].

One of the most common energy uses in daily life is cooking. In Indonesia, cooking activities are still largely dependent on gas or petroleum-based fuels, whose availability is declining while prices are rising annually [3]. Therefore, exploring alternative renewable energy sources is a promising solution to meet the rising energy demand. One such renewable energy source is biomass [4].

Biomass is a renewable energy source derived from organic materials, such as plants, wood, agricultural waste, leaves, and even animal manure [5]. Biomass is utilized as an alternative fuel to reduce dependence on depleting non-renewable fossil fuels. Biomass energy, also referred to as bioenergy, can be converted into gaseous forms (biogas), liquid fuels (biodiesel), or directly utilized in solid form, such as wood or pellets, for combustion [6]. In the context of biomass stoves, solid biomass fuel is used to generate heat through combustion, with thermal efficiency serving as the primary performance indicator [7].

A biomass stove is a device that uses biomass fuel to produce heat through combustion. It can be used for daily cooking activities and may be designed to meet user requirements [8]. The study by Fui Ming developed a galvanized steel biomass stove with a body diameter of 380 mm and a height of 500 mm, and a combustion chamber with a diameter of 280 mm and a height of 450 mm. This stove was equipped with a 12 V DC blower as the combustion air supply system. However, the blower was deemed insufficient in delivering adequate combustion air [9].

A biomass stove model that refers to the Indonesian National Standard for Biomass Stoves (SNI 7926:2023) is the Prime Standard stove developed by the Kopernik Team under the Clean Cooking Alliance program. A biomass stove model, such as the UB 03-01 model [10], has dimensions of 40 × 40 × 40 cm^3, which are smaller than those of the stove designed by Ming, Santoso, and Nurdin (2022) at 50 × 50 × 55 cm^3. The Prime Standard biomass stove achieves a combustion efficiency of up to 45%, significantly higher than the 10% thermal efficiency reported in the study of Fui Ming.

Based on the conditions mentioned above, the present study reduces the stove dimensions of Ming, Santoso, and Nurdin (2022) to 40 × 40 × 40 cm^3 while maintaining the use of a 12 V DC blower as the air supply system for the combustion chamber [11]. The primary function of the blower is to direct airflow into the working system [12], in this case, into the combustion chamber.

Although previous studies have investigated the performance of biomass stoves equipped with blowers, most of them primarily focused on fuel type, airflow characteristics, or construction materials. Limited attention has been given to the influence of stove geometric dimensions, particularly the size reduction of the stove body and combustion chamber, on heat transfer effectiveness and thermal efficiency for galvanized plate biomass stoves. The study by Fui Ming et al. (2022) reported relatively low thermal efficiency but did not examine whether dimensional modification could improve combustion quality and heat utilization. Therefore, this study aims to address this limitation by experimentally evaluating the effect of stove size reduction on thermal performance under identical air-supply conditions.

2 Research methodology

The main objective of this research is to reduce the dimensions of the biomass stove previously developed by Fui Ming [9] to obtain a biomass stove with improved heat transfer characteristics and higher thermal efficiency than the earlier design. This study used an experimental approach. No numerical heat transfer simulation, such as Computational Fluid Dynamics (CFD) or Finite Element Method (FEM), was performed before the fabrication of the stove prototype. The design modification was based on empirical design considerations and dimensional benchmarking against commercially available prime-standard biomass stoves. The research framework is presented in Fig. 1.

The initial biomass stove design had dimensions of 50 × 50 × 55 cm^3, which were subsequently reduced to 40 × 40 × 40 cm^3. The main material used is a 1.8 mm-thick galvanized steel plate, which was selected for the stove body and combustion chamber due to its strength and corrosion resistance [13]. The resulting reduced-size stove design is presented in Fig. 2. Fig. 2 illustrates the design of the stove body, which includes a cylindrical combustion chamber for loading biomass fuel. The chamber has a diameter of 280 mm and a height of 400 mm. During testing, variations in fuel load were varied to 40%, 60%, and 80% of the total chamber capacity. The combustion chamber is also connected to a 90 mm-diameter air duct supplying airflow from a DC blower. The blower used in this study operates at 12 V and 0.30 A.

The reduced-size biomass stove prototype was then tested using the Water Boiling Test (WBT) method. WBT is a cooking performance evaluation procedure used to determine how effectively thermal energy is transferred to the cooking vessel when using a stove. The purpose of this method is to quantify the amount of energy delivered to the water and to assess the thermal performance efficiency of the stove during heat transfer [14]. The test utilized a cooking pot filled with water at two volumes: 2 liters and 5 liters. The fuel used in this study was biomass derived from wood waste.

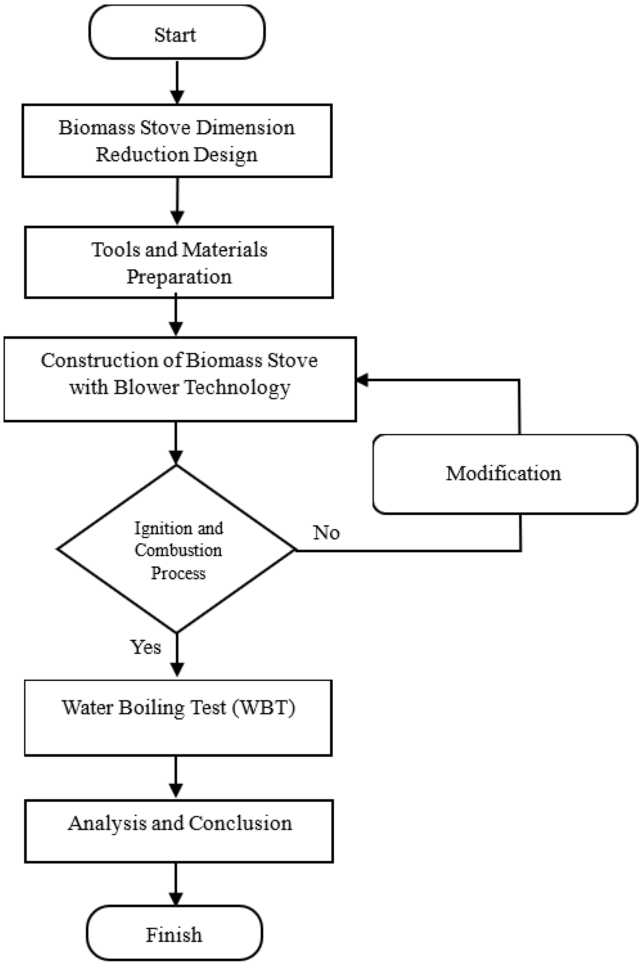

Fig. 1. Experimental flowchart of the research

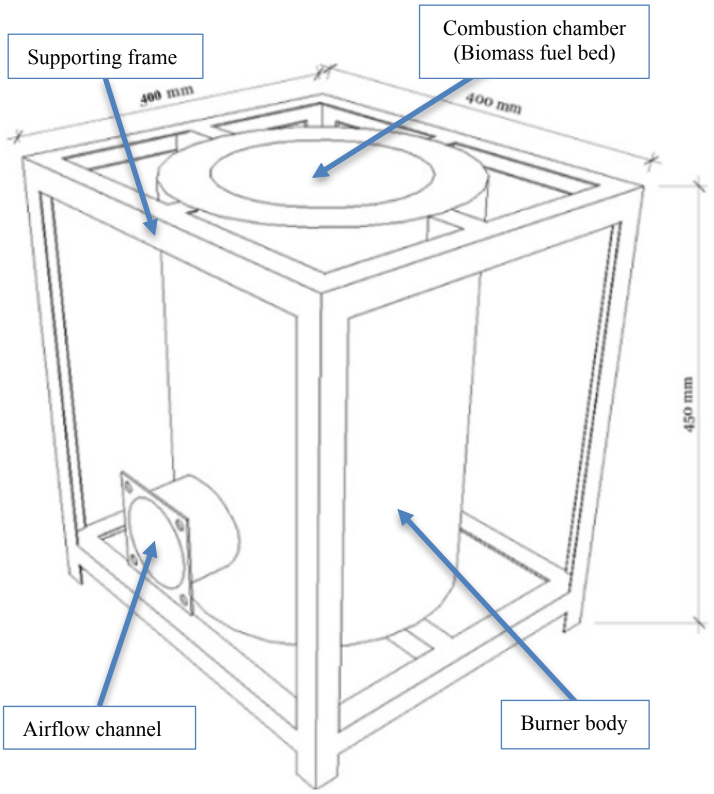

Fig. 2. Design of the reduced biomass stove

The water volumes of 2 liters and 5 liters were selected to represent typical small- and medium-scale household cooking activities, such as boiling beverages, preparing instant foods, and meal preparation. According to Insusanty, as cited in Purnomo [15]Comparisons of water boiling times across different fuel variations are commonly based on a minimum reference volume of 2 liters of water. This practice is consistent with studies reporting that the average daily drinking water requirement for adults is approximately eight glasses (230 mL per glass), equivalent to about 2 L per day [16]. In various other WBT studies, WBTs have been conducted using a water volume of 5 L [17], [18], [19]. This 5-liter volume remains relevant, as the typical capacity of standard household cooking pots is 5 liters. This volume applies to both conventional pots and pressure cookers.

Meanwhile, in research on the performance of biomass gasification stoves fueled by solid materials, fuel variation may be determined based on the fuel filling height relative to the combustion chamber [20]. Three filling levels are commonly used, corresponding to chamber volume fractions of approximately 40%–80%. In this study, fuel loading levels of 40%, 60%, and 80% of the combustion chamber capacity were selected to represent low, moderate, and high fuel utilization conditions. These variations were also intended to control flame overflow and to identify potential unstable combustion behavior.

The selection of variations in the water volume to be boiled and the fuel loading level enables the evaluation of stove performance under practical operating conditions commonly encountered in daily use. Each experimental condition was repeated three times to ensure data reliability and reproducibility, and the reported results represent the average values of the measurements. The reduced stove prototype and the WBT testing process are shown in Fig. 3.

Fig. 3. Results of stove dimension reduction and WBT Testing

To analyze the thermal efficiency of the biomass stove during the water-boiling process using the WBT method, the following data are required:

1. Fuel consumption

   Fuel consumption is calculated by subtracting the mass of the remaining fuel from the initial fuel mass loaded into the combustion chamber of the biomass stove [9], calculated using Eq. (1).

$$WF = BBM - BBS \tag{1}$$

where *WF* is fuel consumption (kg), *BBM* is the initial fuel mass (kg), and *BBS* is the remaining fuel mass (kg).

2. Sensible Heat
   Sensible heat is the thermal energy required to increase the temperature of water, measured before and after boiling [7], calculated using Eq. (2).

$$SH = M_w \times C_p \times \left(T_f - T_i\right) \tag{2}$$

where *SH* is sensible heat (kcal), M_w is the initial mass of water (kg), C_p is the specific heat capacity of water (1 kcal/kg°C), T_f is the final water temperature / Boiling temperature (°C), and T_i is the initial water temperature (°C).

3. Latent Heat
   Latent heat is the amount of energy required to vaporize water [21]. In this study, the latent heat of vaporization is assumed to be 539.4 kcal/kg [9]. The latent heat is calculated using Eq. (3).

$$LH = W_e \times H_{fg} \tag{3}$$

where LH is the latent heat (kcal), We is the mass of evaporated water (kg), and Hfg is the latent heat of vaporization of water (539.4 kcal/kg).

4. Thermal Efficiency
   Thermal efficiency is generally calculated using a standard equation based on the WBT method, as expressed in Eq. (4) [7].

$$\eta = \frac{SH + LH}{HHV \times WF} \times 100\,\% \tag{4}$$

where *HHV* is the higher heating value of the fuel (4622 kcal/kg), and η is the thermal efficiency (%).

3 Results and discussion

This research focuses on the performance analysis of a galvanized-steel biomass stove, which was evaluated through systematic data collection and objective analysis. The detailed procedures are presented in Table 1 and Table 2. The water-heating test results show differences between using 5 liters of water (Table 1) and 2 liters of water (Table 2) under varying fuel load conditions (40%, 60%, and 80%).

Table 1. Experimental data for the 5-liter water test

(Average of three repetitions)

Fuel capacity	Fuel mass (kg)		Water temperature (°C)		WF (kg)	WE (kg)
	Before combustion	After combustion	Before heating	After heating		
40%	0.8	0.038	26	80.8	0.762	0.27
60%	1.2	0.082	26.3	98.1	1.115	0.73
80%	1.6	0.100	27.4	98.1	1.5	0.87

Table 2. Experimental data for a 2-liter water test

(Average of three repetitions)

Fuel capacity	Fuel mass (kg)		Water temperature (°C)		WF (kg)	WE (kg)
	Before combustion	After combustion	Before heating	After heating		
40%	0.8	0.11	28.9	89.8	0.691	0.53
60%	1.2	0.168	29	90.8	1.032	0.5
80%	1.6	0.143	29	94.7	1.423	0.82

In the 5-liter water test, the initial water temperature ranged from 26°C to 27.4°C, and after heating, it reached 98.1°C. Meanwhile, in the 2-liter water test, the initial water temperature ranged from 28.9°C to 29°C, and after heating, it reached 94.7°C.

In Table 1 and Table 2, it can be observed that the amount of fuel used in the WBT process is directly proportional to the amount consumed during the water boiling process for both 5 liters and 2 liters of water. This relationship can be further visualized in the graph shown in Fig. 4.

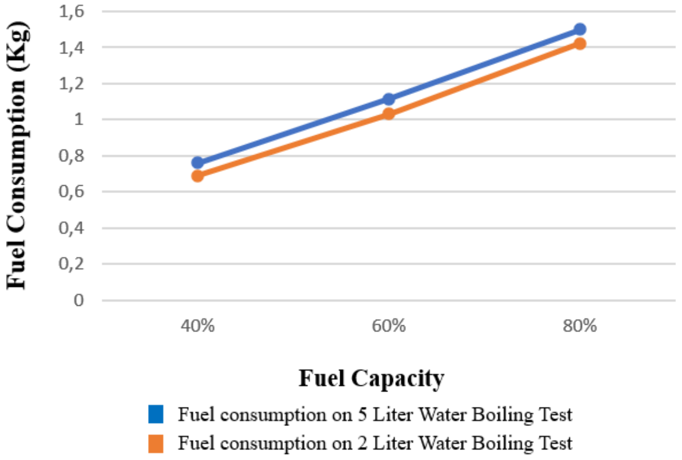

Fig. 4. Fuel consumption on 5-Liter and 2-Liter WBT

Fig. 4 illustrates the fuel demand for water boiling, indicating that a larger volume of water requires a proportionally higher amount of fuel, as greater energy input is needed to increase the temperature of a larger water mass. These data are consistent with trends reported in other studies on stove testing and biomass fuel utilization [7], [20], [22], which indicates that larger water volumes require greater fuel consumption.

The relationship between fuel consumption and the water-boiling process needs further analysis in relation to the effects of the fuel's higher heating value and the Mass of evaporated water, which are related to the stove's thermal efficiency during the water-boiling process. The calculated output parameters from the 5-liter and 2-liter WBTs can be observed in Table 3 and Table 4.

Table 3. Output parameters of the 5-liter WBT

(Average of three repetitions)

No	WF (kg)	SH (kcal)	LH (kcal)	Thermal efficiency (%)
1	0.762	274	145	11.13
2	1.115	359	393.7	14.6
3	1.5	318.5	469.3	11.4

Table 4. Output parameters of the 2-liter WBT

(Average of three repetitions)

No	WF (kg)	SH (kcal)	LH (kcal)	Thermal efficiency (%)
1	0.691	121.8	286	12.8
2	1.032	123.6	269.7	8.2
3	1.423	131.4	442.3	8.7

Based on Table 3, the 5-liter boiling test shows that increasing fuel quantity does not consistently lead to a linear improvement in thermal efficiency; in fact, efficiency tends to decrease when more fuel is used. In contrast, Table 4 indicates that in the 2-liter boiling test, increasing the fuel quantity may reduce the thermal efficiency. Across the two experimental variations, the thermal efficiency of the biomass stove ranged from 8.2% to 14.6%.

At higher fuel loads, the combustion chamber experiences excessive fuel packing density, which restricts effective oxygen diffusion and reduces combustion completeness. This condition increases unburned carbon losses and sensible heat losses through the exhaust gases. Similar phenomena have been reported for several types of biomass stoves using solid fuels, such as the Berkeley Air Injection stove, Ace-1, Mini Moto, Oorja stove, and SSM, which utilize solid biomass fuels derived from wood, agricultural waste, wood waste, and crop residues [23]. In addition, excessive flame height may cause heat to bypass the pot surface, leading to increased convective and radiative heat losses to the surroundings. Consequently, although more chemical energy is supplied, the fraction of that energy converted into useful heat absorbed by the water decreases, resulting in lower thermal efficiency.

The efficiency test results for boiling 5 liters and 2 liters of water, as presented in Table 3 and Table 4, respectively, are illustrated in the graphs shown in and .

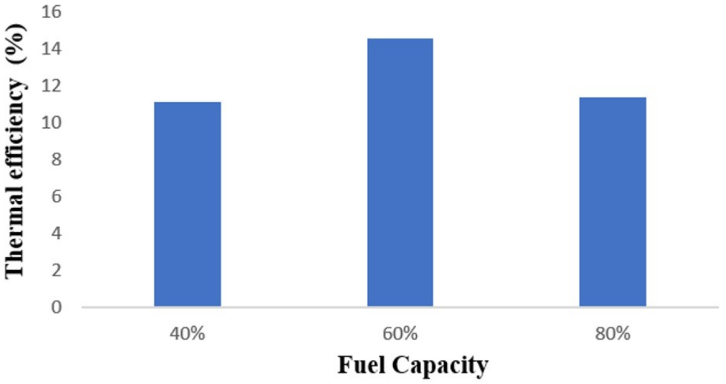

Fig. 5. Correlation of thermal efficiency values in the 5-liter WBT

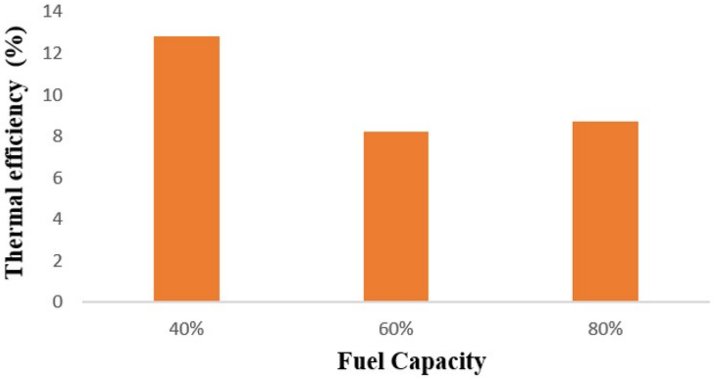

Fig. 6. Correlation of thermal efficiency values in the 2-liter WBT

 and present bar charts illustrating the relationship between thermal efficiency and the variation in fuel volume percentage under two testing conditions: boiling 5 liters and 2 liters of water. In the 5-liter water test (), the highest thermal efficiency was obtained at 60% fuel volume, reaching 14.6%. Meanwhile, the 40% and 80% fuel volumes produced thermal efficiencies of 11.13% and 11.4%, respectively. This indicates that for a larger water volume, the optimal thermal efficiency is achieved with a moderate fuel supply, whereas too low or too high a fuel supply tends to reduce efficiency. In contrast, for the 2-liter water test (), the highest thermal efficiency was achieved at 40% fuel volume, reaching 12.8%. Increasing the fuel volume to 60% and 80% resulted in lower efficiencies of 8.2% and 8.7%, indicating that increasing fuel volume does not necessarily improve efficiency when the boiled water volume is small. Overall, both graphs show that the combination of fuel volume and water quantity strongly influences the thermal efficiency of the biomass stove. Selecting the proper fuel-to-water ratio is essential to achieve optimal combustion performance.

The contrasting trends observed between the 2 L and 5 L WBTs are mainly attributed to differences in thermal load and heat utilization. For the larger water volume (5 L), a moderate increase in fuel input improves heat absorption because a greater portion of the released thermal energy is utilized to raise the water temperature, resulting in higher thermal efficiency. This finding is consistent with previous studies using the WBT, which reported that moderate increases in fuel input and water volume can enhance thermal efficiency, as a larger fraction of the released thermal energy is absorbed by the water rather than lost to the surroundings. For instance, WBT results showed that increasing the water volume from 1 L to 2 L increased the measured thermal efficiency due to the greater sensible heat absorbed by the water [20][24]. In contrast, for the smaller water volume (2 L), excessive fuel loading leads to rapid boiling, after which heat losses through exhaust gases and stove walls become dominant. Furthermore, higher fuel loads increase fuel packing density in the combustion chamber, restricting oxygen diffusion and reducing combustion completeness, thereby increasing unburned carbon and sensible heat losses. As a result, although more chemical energy is supplied, the fraction of that energy converted into useful heat absorbed by the water decreases, producing lower thermal efficiency.

The obtained data were then compared with those from a previous study by Ming et al. This comparison was carried out because the present research focuses on redesigning the biomass stove used in the earlier study, reducing its dimensions from 50 × 50 × 55 cm³ to 40 × 40 × 40 cm³. The comparison results are shown in Table 5 and Table 6, which present the boiling performance tests for 5 liters and 2 liters of water, respectively.

Table 5. Comparison of the research results in the 5-liter WBT

Fuel volume variations	Thermal efficiency of the previous study (%)	Thermal efficiency of the reduced stove (%)
1	8	11.13
2	8	14.6
3	10	11.4

Table 6. Comparison of the research results in the 2-liter WBT

Fuel volume variations	Thermal efficiency of the previous study (%)	Thermal efficiency of the reduced stove (%)
1	6	12.8
2	9	8.2
3	7	8.7

The data presented in Table 5, which compares the results of the previous study (A) with those of the reduced stove volume study (B) during the 5-liter water-boiling process, are shown in . The data presented in Table 6, which compares the results of the previous study (A) with those of the reduced-stove-volume study (B) during the 2-liter water-boiling process, are shown in .

In Study A [9], the highest thermal efficiency was recorded in the 5-liter water-boiling test using 80% of the fuel capacity, yielding an efficiency of 10%. Under the same testing conditions, Study B (the present study) demonstrated a higher thermal efficiency of 11.4%. The highest thermal efficiency in Study B occurred at 60% fuel loading during the 5-liter boiling process, reaching 14.6%. These results clearly indicate the success of reducing biomass stove size in improving thermal efficiency. Considering findings from other studies that also implemented stove reduction with a redesign focus on a downdraft continuous-system biomass stove, similar efficiency improvements were reported [17]. The increase in efficiency suggests that reducing the stove dimensions influences the effectiveness of air supply from the 12 V DC blower, thereby enhancing flame fluidity and heat distribution to the cooking pot.

Compared to the previous stove design (50 × 50 × 55 cm³), the reduced stove (40 × 40 × 40 cm³) consistently exhibited higher thermal efficiency under similar operating conditions and identical air supply specifications. The improvement ranged from approximately 3% to 7%, depending on the water volume and fuel loading. This confirms that geometric size reduction enhances heat transfer effectiveness by improving flame–pot interaction and reducing internal heat losses within the combustion chamber. These findings demonstrate that stove dimensional optimization is a critical design parameter for improving biomass stove performance.

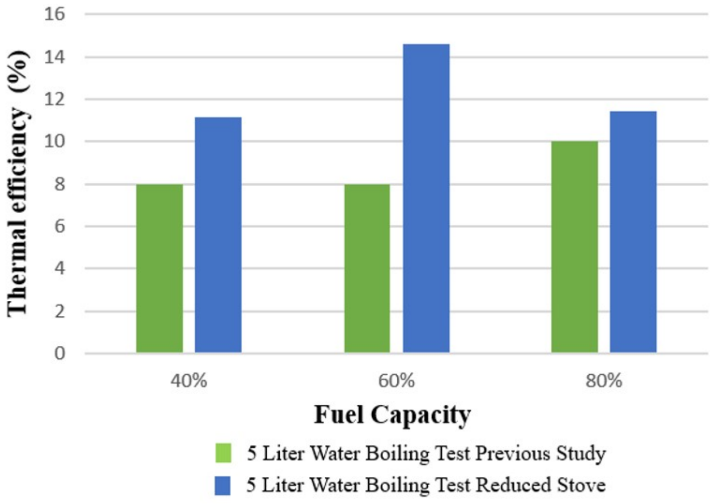

Fig. 7. Comparison of thermal efficiency in the 5-liter WBT between the two studies

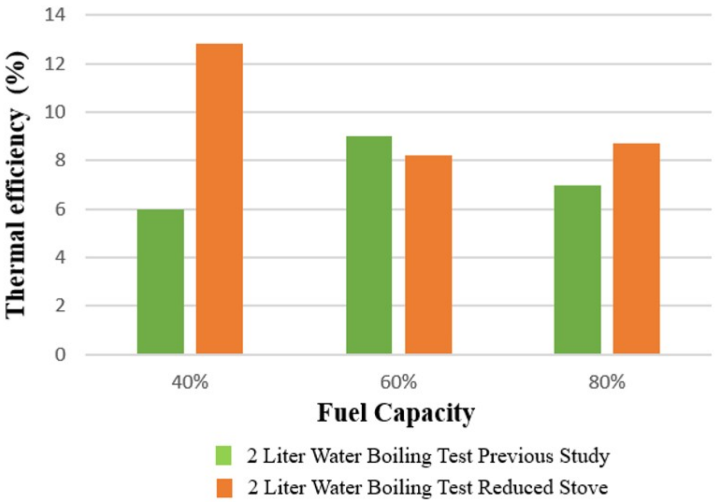

Fig. 8. Comparison of thermal efficiency in the 2-liter WBT between the two studies

4 Conclusions

Optimizing stove geometry plays a crucial role in improving combustion efficiency and heat transfer performance in biomass cookstoves. This study demonstrates that reducing the dimensions of a galvanized steel biomass stove from 50 × 50 × 55 cm^3 to 40 × 40 × 40 cm^3 leads to measurable improvements in thermal efficiency. Based on Water Boiling Test results, the modified design achieved a maximum efficiency of 14.6%, compared to 10% in the original configuration under comparable operating conditions. The improvement is primarily attributed to enhanced air–fuel interaction, improved flame stability, and reduced heat losses within the combustion chamber. Although the efficiency gain is significant, the overall performance remains below international clean cookstove benchmarks, indicating substantial room for further optimization. Future research should focus on improving thermal insulation, refining forced-air distribution, and applying computational heat transfer and combustion modeling to systematically enhance performance and achieve higher efficiency levels suitable for sustainable household energy applications.

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