The Performance of the High Heat Gas Stove with Emissions and Gasification System

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Abstract. *The performance of a high-heat gas stove with a gasification system was investigated to design a stove with high performance in terms of burner temperature, conduction heat loss, complete combustion, heat usage efficiency, carbon monoxide (CO) and nitrogen oxide (NOx) emissions. The gasifier stove (GS) was compared with the super stove (SS) and the conventional stove (CS). Three types of fuels, tamarind charcoal, Eucalyptus chips, and briquette charcoal, were used. Each fuel sample, weighing 1000 g, was heated to boil 3000 g of water. Temperatures of the burner, water, inner wall and outer wall were recorded using a thermocouple type K. The levels of CO and NOx in the exhaust gases were measured with an exhaust gas analyzer, Testo350 model, both at the start of the fire and when the fuel was fully burned. Additionally, the ash from each sample was recorded after the test was completed. The results showed that the burner temperature of GS was 900°C higher than SS (700°C) and CS (600°C). The conduction heat loss, complete combustion, and heat efficiency of GS were 0.36 MJ, 99%, and 38.37%, respectively. The CO and NOx emissions of GS were 1500 ppm and 97 ppm, respectively. In comparison, SS and CS had heat efficiencies of 33.29% and 29.29%, and CO and NOx emissions in the range of 2392-2765 ppm and 152-163 ppm, respectively.*

Received by	20 June 2023
Revised by	21 August 2023
Accepted by	29 August 2023

Keywords:
gasifier stove, performances of stoves, carbon monoxide, nitrogen oxide

1. Introduction

The overall household cost of living has risen, including the expenses for energy and cooking gas. This escalation may be attributed to various factors, such as the impact of the COVID-19 pandemic and conflicts between major production-exporting countries [1]. The price of LPG has increased significantly, rising by 28.30% during the period of 2563-2565 BE [2]. Consequently, many households have turned to more cost-effective alternatives, such as using biomass in the form of wood chips and charcoal [3]. Additionally, the government has taken steps to promote the use of high-efficiency stoves, like the Super stove (SS), as a substitute for conventional stove household stoves.

The Royal Forest Department [4] has developed a high-efficiency stove with a remarkable burning rate and a heat efficiency of 30.32%. This innovation allows households to save up to 2,000 baht per year on wood chips and charcoal, while also reducing harmful emission. Moreover, the Ministry of Energy has developed the SS, which boasts properties like lightweight construction, smoke-free operation, and the generation of no toxic gases due to its complete combustion. On average, the SS can be used for over two years and is 29% more thermally efficient than CS available in the market. This efficiency translates to substantial savings of 500-600 baht per household per year on firewood and charcoal fuel costs.

According to a survey report by the Department of Alternative Energy Development and Efficiency, Ministry of Energy, approximately 540,000 stoves are produced each month to meet the demands of the Thai people [5]. These stoves are particularly popular in rural areas and are even exported to neighboring countries. The development of biomass furnace technology relies primarily on the thermochemical process achieved through controlled combustion in a limited air environment [6]. This controlled combustion leads to the breakdown of biomass into hydrocarbon compounds in solid and gaseous forms, known as producer gases [7]. These producer gases, including carbon monoxide, hydrogen, methane, carbon dioxide, nitrogen, and others [8], and they can serve as the main cooking fuel for households. Incomplete combustion results in the generation of CO and NOx, which are pollutants harmful to both humans and the environment. Exposure to 690 ppm (parts per million) of carbon monoxide (CO) for more than 3 hours can lead to abnormal and irregular heartbeat, loss of consciousness, and potentially fatal outcomes. Similarly, exposure to nitrogen oxides (NOx) at levels of 200-250 ppm for 1 hour can cause pulmonary edema, difficulty breathing, respiratory failure, and may also lead to fatalities [9]. Most biomass furnaces operate based on gasification reactions, which involve four main processes: drying, pyrolysis, combustion, and reduction [10]. Among the various biomass gasifier systems, the downdraft gasifier system, where biomass and fuel gases move in the same direction (co-current) from top to bottom, is widely favored. This design ensures that air is fed near the combustion zone, creating a hot zone for complete combustion without smoke.

Despite the availability of high-efficiency cooking stoves and the promotion of sustainable solutions (SS) to conserve energy, reduce costs, and mitigate health risks associated with cooking smoke, there is room for the development of even more advanced high-efficiency and modern stove models. Perhaps modern users are more drawn to convenience and modernity, overlooking the potential benefits of these cooking stove innovations. Consequently, the researcher aims to develop a high-heat stove without pollution and this is defined as a condition or state in which no harmful substances or pollutants are released into the environment as a result of a process or activity. The gasifier stove promises complete combustion, no smoke emissions, ease of ignition, lightweight construction, and exceptional heat resistance, making it a durable and health-conscious stove option for households.

2. Materials and Method

2.1 Concept Designed Gasifier Stove

The design of gasification cooking stoves is based on the gasification process to ensure suitability for use and compatibility with local fuel types [11]. Fig.1 shows that the GS frame consists of an inner jacket and an outer jacket. The inner jacket's combustion chamber has a diameter of 15 cm, a height of 30 cm, and a wall thickness of 2.5 cm. The outer jacket has a diameter of 42 cm, a height of 40 cm, and a wall thickness of 2.5 cm. Fig. 2 shows the components of the inner jacket and the sieve plate (1), which are made from refractory clay to provide strength and durability. The outer jacket (2) and stove base (3) are made from fiber cement mixed with cement and light concrete to insulate, strengthen, accommodate the fuel insertion (4), and facilitate air flow and ash cleaning (5). The heat is in direct contact with the cookware at the top of the stove. The conduction heat loss through the stove walls is important. Therefore, testing the cooking stove under real-use conditions should focus on design to prevent heat loss from the stove walls.

Procedures for using GS are as follows. First, put fuels in the sieve of the stove (1). Then, ignite the fuel and place the cooking load on top of the stove (6). As needed, fill the fuel compartment (4) and clean the ash (5) when necessary.

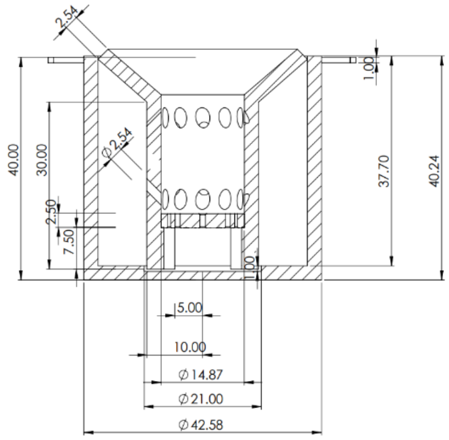

Fig. 1 Dimension (cm. unit) of GS model

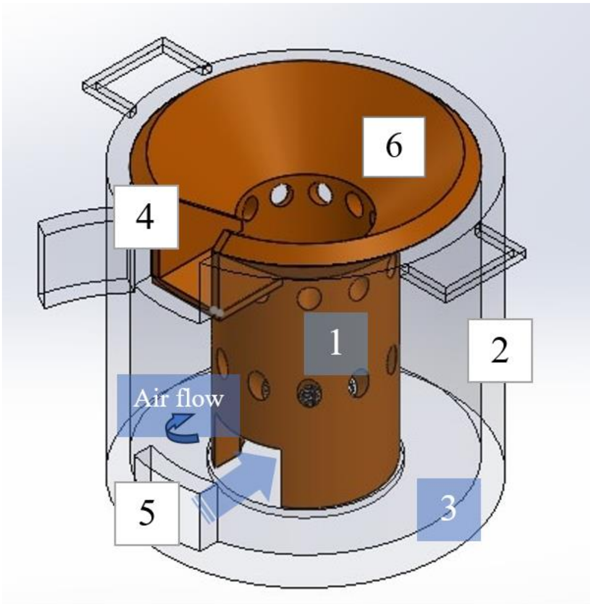

Fig. 2 GS model in 3D

1) inner jacket and the sieve plate, 2) outer jacket, 3) stove base, 4) the fuel insertion, 5) ash cleaning, and 6) cooking load

2.2 Methodology

The biomass stove used in this study was designed to operate with a gasification process, resulting in complete biomass combustion and consequently, high heat generation and low pollution levels. The study also focused on improving and developing the materials used in production to minimize heat loss and enhance heat retention capabilities. Therefore, the materials and methods of testing were as follows. Three types of stoves (GS, SS, and CS) and three types of fuels (tamarind charcoal, Eucalyptus chips, and briquettes charcoal) were utilized. The full factorial experiment [12] was designed with 27 trials and 3 replications. A water quantity of 3000 grams was used to test the evaporation rate by the different biomass fuels (tamarind charcoal, Eucalyptus chips, and briquettes charcoal) as shown in Table 1. The position at which exhaust gas was measured (6) is shown in Fig 2. The levels of CO and NO_x in the exhaust gases were measured with an exhaust gas analyzer, Testo350 model, both at the start of the fire and when the fuel was fully burned. Additionally, the ash from each sample was recorded after the test was completed.

Moisture content refers to the amount of water present in the fuel. Higher moisture content can hinder combustion as energy is needed to evaporate the water before actual burning occurs, leading to lower heating efficiency. Volatile matter represents the proportion of combustible gases and liquids released during heating. Fuels with higher volatile matter content ignite easily and burn faster, resulting in rapid combustion. After volatile matter is driven off during combustion, fixed carbon remains as the non-combustible part of the fuel. Higher fixed carbon content promotes stable and efficient combustion. Also called calorific value, HHV indicates the heat energy released per unit of fuel mass during complete combustion. Fuels with higher HHV provide more energy, leading to better overall combustion efficiency. After complete combustion, incombustible residue known as ash remains. High ash content can cause clinker and slag formation, affecting the performance of the stove or furnace.

Property	Fuel type		
	Tamarind Charcoal	Eucalyptus Chip	Briquette Charcoal
Moisture (%)	5	4.3	7.13
Fixed Carbon (%)	1	1.51	3.74
Volatile matter (%)	14	79.1	13.47
Ash (%)	85	15.09	82.73
HHV (MJ/kg)	7.170	4.436	7.276

Table 1 Properties of fuels

Remark: Proximate Analysis as Received [13],[14]

Temperature measurements were recorded using a thermocouple type K at various positions, including the inner wall, outer walls, combustion chambers, and water container [15]. A biomass fuel sample weighing 1000 g was ignited to heat the water in a surrounding temperature of about 29°C, *and* the temperature was recorded every minute during firing, and observed until the firing room temperature had dropped to 90°C. The produced CO and NOx were measured using an exhaust gas analyzer, Testo350 model, during both the ignition and fully firing stages. After the experimental testing was completed, water retention and ash content were recorded.

2.3 Indications of Stove Evaluation

Conduction heat transfer is a type of heat transfer that occurs through materials as a heat transfer medium when there is a temperature difference between both surfaces of a solid. Thermal conductivity depends on several factors, including the area, thickness, material type, and temperature difference, as described by Fourier's law of conduction [16], equation (1).

$$\text{Conduction heat loss} = \frac{kA(\triangle T)}{\triangle x} \times \Delta t \quad (1)$$

Symbol is

- k = Thermal Conductivity
- A = Area of material
- $\triangle T$ = Difference of temperature
- $\triangle x$ = Thickness of material
- $\triangle t$ = Consideration period

The three types of stoves were of similar size, approximately 0.3 square meter. However, they were made from different materials, resulting in different heat loss and affecting their efficiency and heat levels. GS was made from glass fiber insulation, with a thermal conductivity of 0.035 W/m. °C. This low thermal conductivity means that GS had a low heat loss and was more efficient at retaining heat. SS was covered with straw insulation, which predominantly consists of lightweight materials and has a thermal conductivity of 0.08 W/m. °C. Compared to GS, SS had a higher heat loss due to its higher thermal conductivity. CS was made from fired clay, with a high thermal conductivity of 0.473 W/m. °C. As a result, CS experienced significant heat loss, making it less efficient at retaining heat compared to both GS and SS [17-18]. The percentage of complete combustion was calculated as the ratio of the difference between the initial fuel consumption and the actual fuel consumption to the difference in the initial fuel amount and the mass of ash, as shown in equation (2).

$$\text{Complete combustion (\%)} = \frac{(m_{initial}-m_{actual})}{(m_{initial}-m_{ash})}\text{x}100 \quad (2)$$

Heat efficiency as usage efficiency tested water-boiling [19] as eq (3).

$$\eta\ (\%) = \frac{m_{wi}c_{pw}\,(T_b-T_i)+m_{evap}h_{fg}}{m_f \times HV_f}\text{x}100 \quad (3)$$

Symbol is

- η = Usage efficiency
- m_{wi} = Water volume
- c_{pw} = Specific heat of water
- T_b = Temperature of boiling water
- T_i = Temperature initial of water
- m_{evap} = Steam volume
- h_{fg} = Heat of evaporating water
- m_f = Mass of fuel
- HV_f = Heating Value of fuel

Moreover, CO and NO_x levels were measured using an exhaust gas analyzer, specifically the Testo350 model, both during the start of firing and when the gasifier stove was in full operation, to assess its performance [20].

2.4 Data Analysis

The performance of the GS was evaluated in comparison to the SS and CS using indicators such as temperature behavior, conduction loss, complete combustion, usage efficiency, and exhaust gas emissions of CO and NOx. The data were statistically analyzed using the Duncan method with the Statistical Package for the Social Sciences (SPSS) program. The statistical differences were analyzed at a confidence level of 95%.

3. Result and Discussion

3.1 Fuel Combustion Behavior

The performances of all three types of stoves, namely the GS, SS, and CS, were tested by boiling 3000 grams of water using 1000 grams of fuel, which was tamarind charcoal, Eucalyptus chips, or briquette charcoals. Throughout the test, temperature readings were recorded to study the combustion and vaporization behavior of the water.

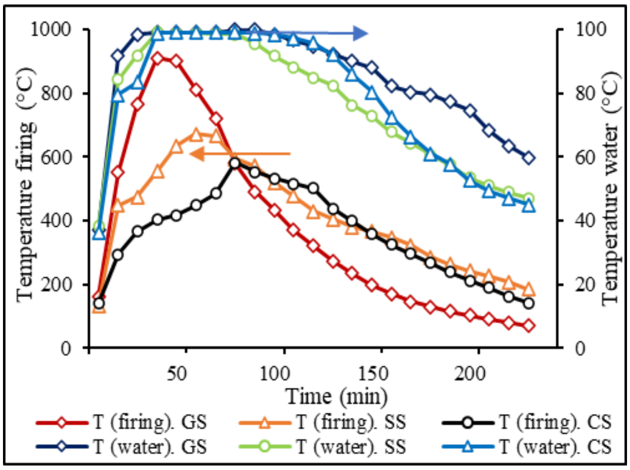

Fig. 3 The temperature behavior of the combustion chamber and water temperature over time

The results are depicted in Fig. 3, illustrating the temperature behavior of the combustion chamber and the water temperature over time. The temperature of GS showed a rapid increase, reaching a peak temperature of 900°C at 30 minutes, while peak temperature SS was 700°C at 60 minutes and CS was 600°C at 80 minutes. This indicates that GS had a higher air flow, leading to a more efficient and rapid complete combustion, resulting in a higher heat temperature compared to SS and CS, which took twice as long to reach their peak temperatures. The boiling time for GS was 12 minutes, whereas SS and CS took 32 minutes to boil the water. The high temperature achieved by GS makes it suitable for grilling or frying and highly practical for household use. However, the rapid combustion in GS also led to a quicker depletion of fuel, causing its temperature to be lower than that of SS and CS after 80 minutes.

3.2 Conduction Loss, Complete Combustion and Heat Efficiency

An excellent property of stoves is their ability to retain heat, have low heat loss through the walls with good insulation, and facilitate efficient air flow for complete combustion. Natural air flows into the stove without the assistance of any forced air ventilation or mechanical devices, which is an advantageous design. These factors significantly influence the heat efficiency of stoves. Table 2 displays the conduction heat loss through the walls of GS, SS, and CS. The heat loss test through conduction reveals the values for the stoves in Table 2. It is observed Eucalyptus chip fuel that the GS had a conduction heat loss of 0.36 MJ, which was lower than the heat losses of SS and CS, which were 0.55 MJ and 4.60 MJ, respectively. These differences are statistically significant at a 95% confidence level. The reason for the lower heat loss in GS is attributed to its design, which includes a wide 11 cm gap between the outer and inner walls. This allows the combustion gas to circulate through the wall, acting as an effective heat insulator with lower thermal conductivity compared to other materials. In contrast, SS and CS stoves rely on other types of insulation, such as rice husk ash, to enhance strength, lightness, etc. It is worth noting that the properties of cooking stoves may vary when using different fuels, leading to different performance characteristics.

Fuel	Stove		
	GS	SS	CS
Tamarind Charcoal	0.94	1.84	10.47
Eucalyptus Chip	0.36	0.55	4.60
Briquette Charcoal	1.18	0.82	11.71

Table 2 Total conduction heat loss (MJ) through side wall of stoves

The calculation of the combusted values according to Equation 2 is presents and compared in Figure 4. Eucalyptus chip fuel exhibited the highest combustion integrity at 99%. There were no statistical differences observed between GS, SS, and CS stoves.

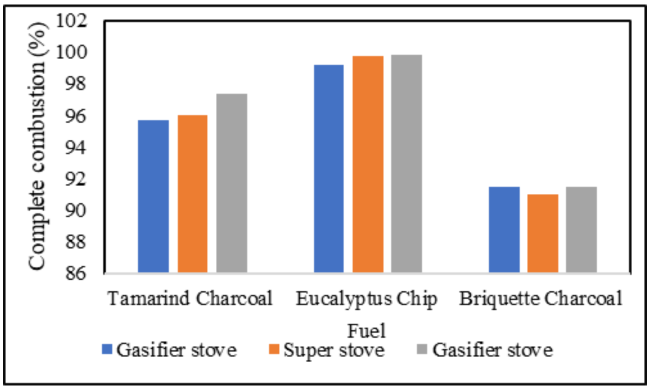

Fig. 4 Complete combustion of stove types with various fuels

However, tamarind charcoal and briquette charcoal had slightly lower complete combustion percentages, ranging from 96.02% to 97.34% and 91.03% to 91.52%, respectively. The complete combustion of fuel is influenced by its fiber content and low ash content, as indicated by the properties of the fuel. Fuels with low ash content result in minimal ash production during burning, thus contributing to higher combustion completeness [21]. For instance, Eucalyptus chip had an ash content of 15.09%, while tamarind charcoal and briquettes had ash contents of 85% and 82.73%, respectively.

Furthermore, other fuel properties, such as moisture content, fixed carbon and volatile matter, as well as the surrounding management conditions, also play a role in determining the level of complete combustion achieved.

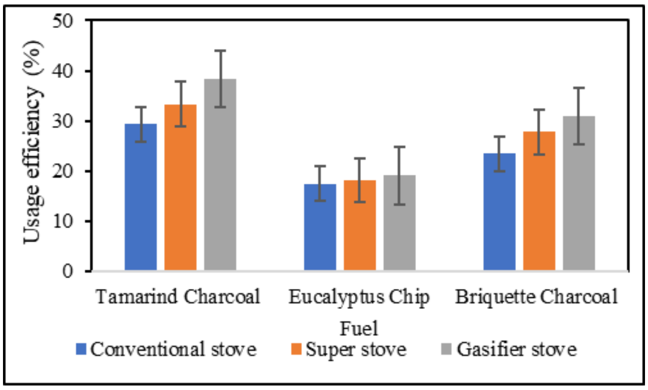

Fig. 5 Usage efficiency of stove types with various fuels

Fig.5 illustrates the evaluation of actual use efficiency by boiling 3000 g of water with different types of fuel. The usable thermal efficiency of boiling 3000 g of water using 1000 g of fuel was assessed, and it was observed that the efficiency varied depending on the type of cooking stove and fuel used. When GS was tested with tamarind charcoal, it showed a thermal efficiency of 38.37%, significantly higher than SS and CS, which had thermal efficiency values of 33.29% and 29.29%, respectively. Similarly, when using briquettes as fuel, GS achieved a thermal efficiency of 30.93%, while SS and CS had thermal efficiencies of 27.74% and 23.42%, respectively. On the other hand, Eucalyptus chip fuels demonstrated the lowest heating efficiency, around 18%, primarily due to the lower calorific value of the fuel. Tamarind charcoal, briquettes, and Eucalyptus chip had calorific values of 7.17, 7.27, and 4.44 MJ/kg, respectively. While tamarind charcoal and briquettes had similar calorific values, the thermal efficiency of the GS stove varied significantly. This difference can be attributed to other components of the fuel that contributed to the overall thermal efficiency under actual test conditions.

The study's results on thermal conduction through the wall, complete combustion, and usage efficiency of GS revealed values of 0.36 MJ, 99%, and 38.37%, respectively, which were found to be superior to SS and CS depending on the fuel being tested. It is important to note that these values may vary depending on the specific conditions and types of fuel used in the experiments.

3.3 Carbon Monoxide (CO) and Nitrogen Oxide (NO_x)

The main sources of nitrogen oxide emissions are power stations, motor vehicles, and commercial and industrial operations. Carbon monoxide emissions primarily arise from motor vehicle exhaust, while hydrocarbon emissions come mainly from motor vehicles and stationary non-combustion sources. Incomplete combustion in cooking stoves can also lead to pollution, although not on the same scale as engine combustion pollution. However, regular use of household cooking stoves can result in the accumulation of toxic air and negatively affect health. Therefore, measuring carbon monoxide gas and nitrogen oxides is crucial when evaluating and selecting cooking stoves.

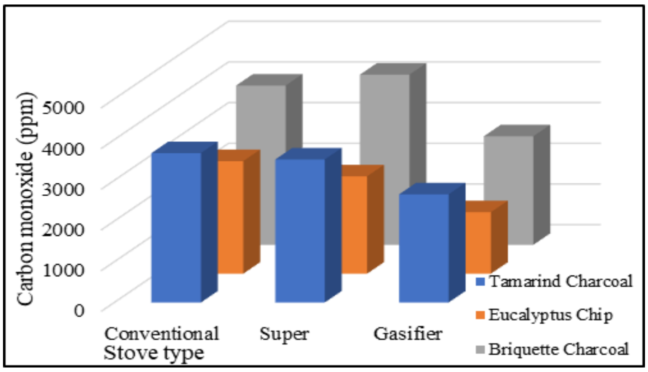

Fig. 6 Carbon monoxide content of cooking stove and type of fuel

Fig.6 displays the carbon monoxide content of different cooking stoves and types of fuels. It was found that GS had lower CO emissions compared to SS and CS for each type of fuel. The minimum CO emission value for eucalyptus fuel was 1500 ppm, and for tamarind charcoal and briquettes, it was 2650 ppm. For SS and CS, the corresponding CO emission values for eucalyptus fuel were 2400 and 2765 ppm, respectively. In contrast, tamarind charcoal and briquettes produced similar CO values ranging from 3500 to 4200 ppm. The differences in CO emissions were related to the properties of each type of fuel, such as the content of volatile substances and ignition temperature. Fuels with higher volatile matter content tended to have lower ignition temperatures and produce less waste, making them easier to burn with faster-spreading flames. For instance, eucalyptus wood had a volatile matter content of 79.1%, while tamarind charcoal and briquette charcoal had volatile matter contents of 14.0% and 13.47%, respectively. As a result, the oxygen consumption rate and heat release intensity were lower, making them less likely to burn.

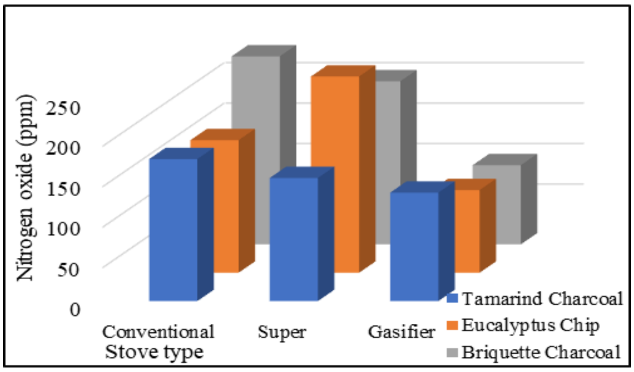

Fig. 7 Nitrogen oxide content of cooking stove and type of fuel

Nitrogen oxides (NO_x) are highly reactive gasses composed of nitrogen and oxygen in various ratios. They are colorless and odorless, excepting nitrogen dioxide. The main source of NOx is the combustion of different types of fuels at high temperatures, such as automobile engine fuel, power plants, various industries, and household fuel combustion. Automobiles contribute to about 55% of the total NOx emissions.

Fig.7 illustrates that GS had similar NO_x emissions for nearly all tested fuels, ranging from 97 to 134 ppm, which were the lowest compared to the emissions from SS and CS, which ranged from 152 to 242 ppm for all tested fuels. This indicates the excellent performance of the stoves with various biomass fuels, as they achieved complete combustion with low emissions of toxic gases, which is beneficial for the health of household users. This is especially important for modern families who cook in rooms with limited ventilation, as poor ventilation can be harmful to health.

4. Conclusion

The performances of a high heat gas stove with emissions and gasification system were investigated to design a stove with high performances in terms of burner temperature, conduction heat loss, complete combustion, heat efficiency, and carbon oxide (CO) and emissions of nitrogen oxides (NO_x). The GS had several advantages over other types of stoves. It had a higher temperature burner, complete combustion, and heat efficiency, which means it can cook food faster and more efficiently. Additionally, it produces lower CO and NOx emissions, which are harmful to human health and the environment. The gasifier stove was also designed to be smokeless and safe for health. The GS was compared with the SS and CS. Three types of fuels, namely tamarind charcoal, Eucalyptus chips, and briquette charcoal, were used. The results showed that GS achieved a high temperature of 900°C in a quick time of 30 minutes. The conduction heat loss, complete combustion, and usage efficiency were measured at 0.36 MJ, 99%, and 38.37%, respectively. CO and NO_x emissions were recorded at 1500 ppm and 97 ppm, respectively. All indicators of GS's performance were better than those of SS and CS. Therefore, GS should be produced and promoted for use in households as it will benefit both the economy and reduced fuel costs, while also promoting good health.

Acknowledgements

This research was financially supported by the Science Park (UIC), Mahasarakham University, Thailand.

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