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Research Article

Effect of Thermal Mass on Fuel Consumption of Solid Biomass Cooking Stoves

Maman Nazifi Garba Irro[1, *], Coffi Wilfrid Adihou[2], Hassane Ousseyni Ibrahim[3], Abouzeidi Dan Maza[4], Comlan Aristide Houngan[5], Malahimi Anjorin[1]

[1]Applied Energy and Mechanics Laboratory, University of Abomey Calavi, Cotonou, Benin

[2]National Institute of Industrial Technology, National University of Sciences Technologies Engineering and Mathematics, Lokossa, Benin

[3]Polytech, Dan Dicko Dankoulodo University, Maradi, Niger

[4]Department of Physics, Dan Dicko Dankoulodo University, Maradi, Niger

[5]National School of Technical Education, National University of Sciences Technologies Engineering and Mathematics, Lokossa, Benin

Abstract

The use of rudimentary cooking stoves has harmful consequences not only for the health of users but also for the environment. Faced with these problems, studies are being carried out to develop more efficient stoves. The materials used for the construction and/or design of cooker range from heavy materials to light materials. However, cookers built from heavy materials accumulate a portion of the heat produced in their walls. The objective of this study is to demonstrate the influence of thermal mass on the fuel consumption of cookers. The study concerns not only a set of stoves taken from the literature but also a set of stoves that we tested. The two sets of stoves differ in terms of their characteristics: Single-pot wood stove without chimney or skirt, Single-pot wood stove without chimney with skirt, Multi-pot wood stove with chimney, Single-pot charcoal stove without chimney or skirt, etc. The adapted approach consists of classifying all stoves by category. Then, for each category, the mass of the cookers as well as the quantity of fuel necessary for the same cooking task will be compared. It appears that for all the stoves taken from the literature and all the stoves submitted to the test, in each of the categories, the higher the mass of the stove, the more fuel it consumes for the same cooking task.

Keywords

Cooking Stove, Solid Biomass, Thermal Mass, Fuel Consumption

1. Introduction

Approximately 1,860,000,000 m^3 of firewood, charcoal and all other wood based energy sources are consumed each year around the world to meet the need for cooking energy [1]. Around 6,696 million m^3 of this volume are burned in Africa on poor quality

*Corresponding author: garbairromamannazifi92@gmail.com (Maman Nazifi Garba Irro)

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cooking stoves [1]. In Africa, forecasts have shown that, by 2030 if nothing is done, the annual demand for wood energy is expected to double [2]. The use of wood energy through poor quality stoves has harmful consequences on: the environment, the climate, the economy, the health, and the safety of users [3-5].

Faced with these problems, research is increasingly being conducted to develop more efficient cooking stoves. In the literature of efforts on the development of efficient cookers, some authors have been interested in the study of insulation materials for the wall of cookers, while others have been interested in the modeling of this cooking appliance. Memon and al [6], listed in their review articles that: Glass wool, ceramic wool, refractory bricks can be used to insulate the wall of cooking hearths. They also reported that adequate insulation can increase thermal efficiency by up to 8%. Okino and al [7], have created a multi-wall cooking hearth. The walls of the prototype were insulated through two layers of insulating materials: the mixture of sawdust + clay and pure sawdust. Yunusa and al [8], reported in their review article that the wall of a cooking hearth can be insulated with materials such as: wood, air, glass wool, ceramics, cement mixed with other materials. Gandigude and al [9], reviewed parameters that can influence the thermal efficiency of fireplaces. Among these materials are the materials of the fireplace body as well as those of the wall insulation. Dixit and al [10], addressed the effect of insulation on the thermal efficiency of solid biomass cooking stoves. In this study, Dixit and al [10], have listed some materials that can be used to insulate the wall of cooking stoves. They also mentioned that the insulation of a wall has a critical thickness beyond which any increase in thickness contributes to an increase in the conduction resistance and a decrease in the convection resistance of the insulating layer. Suraj and al [11], studied the influence of insulation material on the combustion performance of a hybrid draft stove. In their study, Suraj and al. have shown that there is a critical thickness of insulation beyond which any increase in the latter contributes to the deterioration of the energy performance of the stove thanks to the phenomenon of heat dissipation in the high thermal mass. Date [12], modeled a wood burning cooking stove through a steady-state heat transfer and fluid flow model. He concluded that heat transfer in a cooking hearth is essentially convective. Odesola, Ige and Yunus [13], suggested checking the influence of insulation thickness on thermal efficiency. This study aims to show the effect of thermal mass on the fuel consumption of solid biomass stoves. The study was born from an observation based on the literature, in particular the work of the Aprovecho Research Center [14]. Based on certain information from this work, we will try to demonstrate the influence of thermal mass on the fuel consumption of stoves. After that, tests will be carried out to confirm the effect observed. The information that served as basic data therefore comes from this study by the Aprovecho Research Center, where a set of stoves was characterized under the same test conditions using the water boiling technique.

2. Materials and Method

2.1. Method

In this work, the effect of thermal mass on fuel consumption is highlighted on a set of stoves taken from the literature [14]. In fact, the information used as basic data comes from the study by the Aprovecho Research Center. In this study from the Aprovecho research center, a set of stoves was characterized under the same test conditions using the water boiling technique where the mass of the stove as well as the quantity of fuel necessary to heat 5 liters of water boiling were evaluated. It is therefore these measurements of mass and fuel consumption of these stoves that we will use to demonstrate the influence of thermal mass on fuel consumption. It should be noted that these stoves differ from each other due to their characteristics: the type of fuel used, the presence of chimney, skirt, number of pots, etc. In order to minimize the influence of this difference in stove characteristics on fuel consumption, it would be ideal to group these stoves as closely as possible into more or less similar categories (fuel used, presence of: chimney, skirt, single or multi pot). For this reason, our methodological approach will initially consist of classifying all the stoves concerned by category. Then, for each category of hearth, the mass of the hearth as well as the quantity of fuel needed to heat 5 liters of water will be compared. In order to confirm or refute the observed effect "effect of thermal mass on fuel consumption", we will evaluate following the same test protocol (water boiling test), the fuel consumption as well as the mass of other stoves having different masses but approximately similar design. In the table 1 below, all the stoves taken from the literature as well as those submitted to the test are presented and then classified by category. Depending on the configurations, the stoves taken from the study by the Aprovecho research center will be classified into: Single-pot wood-burning stove without chimney or skirt; Single-pot wood-burning stove without chimney with skirt; Multi-pot wood stove with chimney; Single-pot charcoal stove without chimney or skirt. However, the stoves that we will submit to the test will be classified into: Single-pot palm nut shell stoves without chimney or skirt, Single-pot wood stoves without chimney with skirt.

2.2. Materials

2.2.1. Scale

A KC AMMRY brand electronic balance with a precision of 20g and a capacity of 100kg is used to weigh the mass of: fuel, water at the beginning and end of the tests. This scale was also used to weigh the weight of the stoves subjected to the test.

Figure 1. KC AMMRY electronic scale.

2.2.2. Thermometer Support

A wooden board is used to hold the thermometer probe 5 cm from the bottom of the pot.

Figure 2. Thermometer support.

2.2.3. Thermometer

Digital liquid immersion probe thermometers with an accuracy of 0.5 ℃ and a range of -50 to 300 ℃ are used for water temperature measurement during the test.

Figure 3. Digital thermometer with liquid immersion probe.

2.2.4. Stopwatch

A stopwatch is used for time measurement during the test.

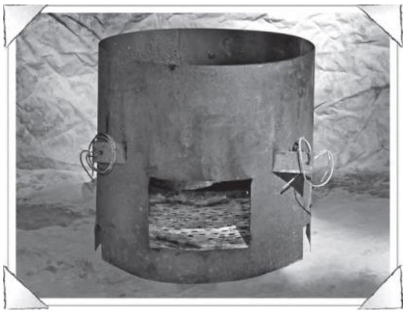
Figure 4. Stopwatch.

2.2.5. Cookers

Table 1 below provides a description of the hearths taken from the literature and those tested.

Table 1. Classification and summary description of cookers (cookers from the Aprovecho research center study as well as those tested).

Stove category	Description of the stove	Photo of the stove
cookers from the study of the Aprovecho research center [14]		
Single-marmite wood-fired stove without chimney or skirt	Name: Ghana Wood 1. Origin: Ghana (Africa) 2. Type of fuel: firewood 3. Weight: 8Kg 4. Fuel consumption: 996g 5. Info on the manufacturer: NA	

Stove category	**Description of the stove**	**Photo of the stove**
Chimneyless wood-fired single-marmite cooker with skirt	1. Name: 20 L Can Rocket 2. Origin: NA 3. Type of fuel: firewood 4. Weight: 6.6 kg 5. Fuel consumption: 733g 6. Info on the manufacturer: Aprovecho Research Center www.aprovecho.org tel: (541) 767-0287	
	1. Name: Mud Sawdust 2. Origin: Africa 3. Type of fuel: firewood 4. Weight: 18Kg 5. Fuel consumption: 793g 6. Info on the manufacturer: NA	
	1. Name: Vita 2. Origin: West Africa 3. Type of fuel: firewood 4. Weight: 2.2 kg 5. Fuel consumption: 689g 6. Info on the manufacturer: Relief International/Enterprise Works-VITA www.enterpriseworks.org tel: (202) 639-8660	

Stove category	**Description of the stove**	**Photo of the stove**
cookers from the study of the Aprovecho research center [14]		
Multi-pot wood stove with chimney	1. Name: Uganda 2-Pots 2. Origin: Uganda 3. Type of fuel: firewood 4. Weight: 36Kg 5. Fuel consumption: 720g 6. Info on the manufacturer: Aprovecho Research Center www.aprovecho.org tel: 541 767-0287	

Stove category	Description of the stove	Photo of the stove
	1. Name: Patsari Prototype 2. Origin: Pátzcuaro, Michoacán, Mexico 3. Type of fuel: wood 4. Weight: 280 kilos 5. Fuel consumption: 1277g 6. Info on the manufacturer: GIRA Centro Comercial El Parián giraac@gira.org.mx Tel: (+0052) (434) 342.32.16	
	1. Name: Onil 2. Origin: Guatemala 3. Fuel type: wood 4. Weight: 280Kg 5. Fuel consumption: 1386g 6. Info on the manufacturer: HELPS International info@helpsinternational.com tel: (972) 386-2901 toll free: (800) 414-3577	

Stove category	Description of the stove	Photo of the stove
cookers from the study of the Aprovecho research center [14]		
Coal-fired mono-marmite cooker without chimney or skirt	1. Name: Malian 2. Origin: Mali (Africa) 3. Fuel type: Coal 4. Weight: 4.2 kg 5. Fuel consumption: 674 6. Info on the manufacturer: NA	
	1. Name: Gyapa 2. Origin: Ghana (Africa) 3. Fuel type: Charcoal 4. Weight: 9 kg 5. Fuel consumption: 73.87 g 6. Info on the manufacturer: Relief International/Enterprise Works-VITA www.enterpriseworks.org tel: (202) 639-8660	
Cookers tested to confirm the effect observed		
Mono-marmite palm nut shell forced convection stove without chimney or skirt	1. Name: Green Light Multi Cooker 2. Origin: Abomey calavi / Benin (Africa) 3. Fuel type: palm nut shell 4. Weight: 25.9 kilos 5. Fuel consumption: 39.65 g 6. Info on the manufacturer: NA	

Stove category	Description of the stove	Photo of the stove
	1. Name: Green Light solar restaurant 2. Origin: Abomey calavi / Benin (Africa) 3. Fuel type: palm nut shell 4. Weight: 17.7 kilos 5. Fuel consumption: 61.52 g 6. Info on the manufacturer: NA	

NA: not available

Stove category	Description of the stove	Photo of the stove
Cookers tested to confirm the effect observed		
Single-pot wood-burning cooker with forced con-vec-tion with chimney and skirt	1. Name: Big Light 2. Origin: Abomey calavi / Benin (Africa) 3. Fuel type: palm nut shell 4. Weight: 87.6 kilos 5. Fuel consumption: 178g 6. Info on the manufacturer: NA	
	1. Name: Small Light 2. Origin: Abomey calavi / Benin (Africa) 3. Fuel type: palm nut shell 4. Weight: 79.65 kilos 5. Fuel consumption: 79.65g 6. Info on the manufacturer: NA	

3. Results and Interpretation

3.1. Resultats

3.1.1. Comparison of Consumption According to Mass: Case of Cookers from the Study of the Aprovecho Research Center

The comparison of fuel consumption of stoves according to their mass is presented in this part. This comparison will be made by category of stoves with similarities in terms of design. The distribution of stoves by category was presented in Table 1 above. It is therefore on the basis of this distribution that the fuel consumption of stoves will be compared.

(i). Single Pot Wood Stoves Without Chimney or Skirt

The category of single pot wood stoves without chimney is made up of the stove: roket and ghana wood. For this category, the roket with a mass of 6.6 kg consumes 773 g to bring 5 liters of water to a boil while the ghana wood with a mass of 8 kg requires 996 g for the same cooking task. Figure 5 below illustrates the mass and quantity of fuel needed to bring 5 liters of water to a boil.

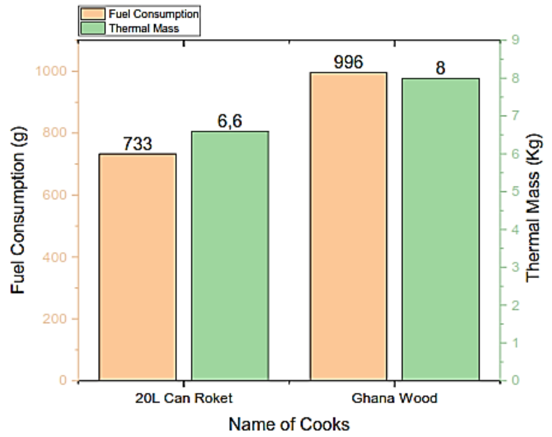


Figure 5. *Quantity of fuel depending on the mass of single pot wood stoves without chimney or skirt caption.*

(ii). Single Pot Wood Stoves Without Chimney with Skirt

The class of single pot wood stoves without chimney with skirt includes the stove: mud sawdust and vita. For this category, the Vita stove with a mass of 2.2 kg consumes 689 g while the Mud Sawdust stove with a mass of 18 kg requires 793 g of wood to bring 5 liters of water to a boil. Figure 6 below shows wood consumption as a function of the mass of stoves for a cooking task which involves bringing 5 liters of water to a boil.

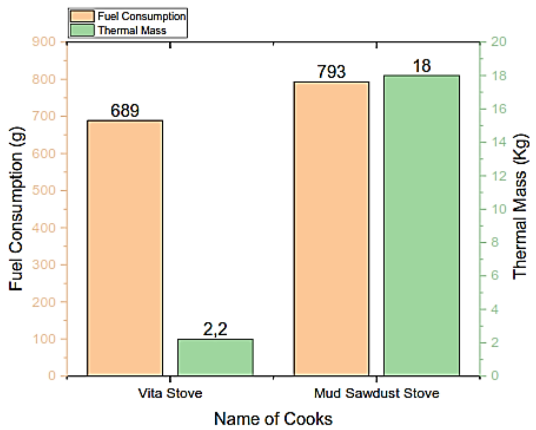


Figure 6. *Quantity of fuel depending on the mass of single pot wood stoves without chimney with skirt.*

(iii). Multi Pot Wood Stove with Chimney

The category of multi pot wood stoves with chimney is made up of: Uganda, Patasri and Onil. For this category, the Uganda stove with a mass of 36 kg consumes 720 g of wood, the Patasri stove with a mass of 280 kg consumes 1277 g while the Onil stove with a mass of 280 requires 1386 g of wood to carry 5 liters of water in boiling. In Figure 7 below, the wood consumption as a function of the mass of hearths for a cooking task, which consists of bringing 5 liters of water to a boil.

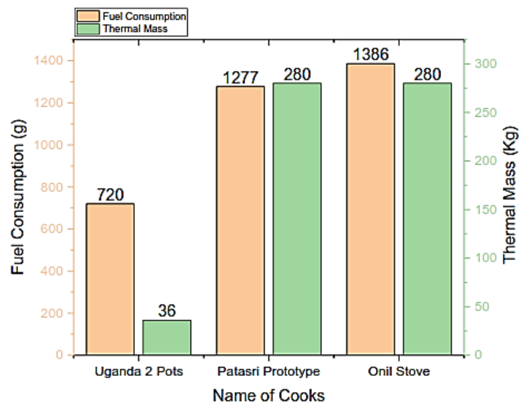


Figure 7. *Quantity of fuel depending on the mass of multi pot wood stoves with chimney.*

(iv). Multi Pot Wood Stove with Chimney

The category of single pot charcoal stoves without chimney or skirt includes the stove: Malien and gyapa. For this category, the Malian cooker with a mass of 4.2 kg needs 674 g while the Gyapa stoves with a mass of 9 kg consumes 694 g of charcoal to bring 5 liters of water to a boil. Figure 8 below shows the fuel consumption as a function of the mass of the stoves.

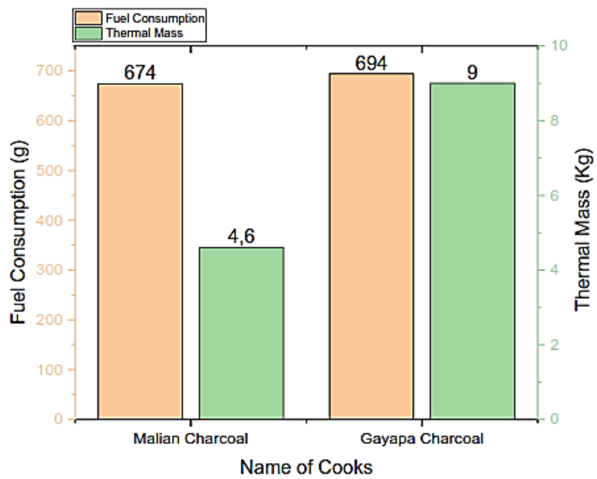


Figure 8. *Quantity of fuel depending on the mass of single pot charcoal stoves without chimney or skirt.*

3.1.2. Test results of Tested Cookers

In order to confirm the observed effect "effect of mass on fuel consumption", four stoves two by two identical in terms of design which only differ by their mass were tested using the same test protocol as that used in the study of the Aprovecho research center (water boiling technique). These stoves are briefly described in table 1. The test results, including the fuel consumption of these stoves are presented in table 2 below:

Table 2. Test result of the four stoves tested.

Test Parameter	Green light solar	Green light multi cooker	Big Lightning	Small lightning
TE (min)	57.89	67	79	78
Vc1 (g/min)	39.82	28.19	133.66	86
PCU1 (%)	0.38	0.44	0.17	0.16
CS1 (gc/kg)	43.13	39.65	127	124
P1 (kW)	15.59	11.04	60.28	27.92
Vc2 (g/min)	19.45	23.79	57	39
PCU2 (%)	0.35	0.36	0.15	0.24
CS2 (gc/kge)	18.39	34.22	51	35
P2 (kW)	7.62	9.32	18.68	12.81

3.1.3. Comparison of Consumption According to Mass: Case of the Cookers Tested

Here, too, the consumption of the stoves tested can be compared by category. The breakdown of these ranges by category is also shown in Table 1.

(i). Single Pot Palm Nut Shell Stoves Without Chimney or Skirt

The category of single-pot palm nut shell stoves without chimney or skirt includes the stove: green light multi cooker barbecue and green light solar restaurant. For this category, green light multi cooker barbecue mass 25.9 Kg needs 73.87g while the green light solar restaurant mass 17.7 Kg, consumes 61.52 g of palm nut shell for the same cooking task (bring 5 L of water to the boil then simmer for 45 min). Figure 9 below shows the fuel consumption as a function of the mass of the stoves.

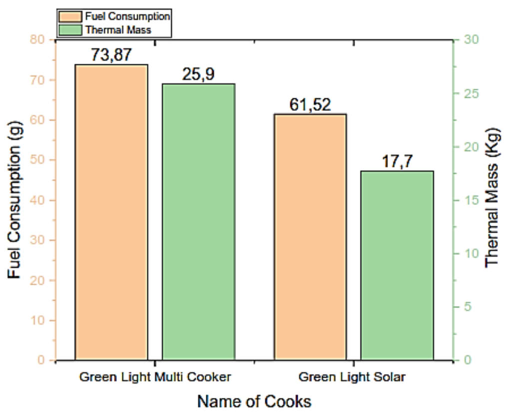


Figure 9. Quantity of fuel depending on the mass of single pot palm nut shell stoves without chimney or skirt.

(ii). Single pot Forced Convection Wood Stoves with Chimney and Skirt

The class of single-pot wood-burning stoves with forced convection with chimney and skirt includes the stove: small light and big light. For this category, the small light stove of mass 79.65 Kg, consumes 159 g while the big light stove of mass 87.6 Kg needs 178 g of wood to carry 5 liters of boiling water then simmer them for 45 minutes. Figure 10 below shows the wood consumption as a function of the mass of stoves for the same cooking task which consists of bringing 5 liters of water to the boil and then simmering them for 45 minutes.

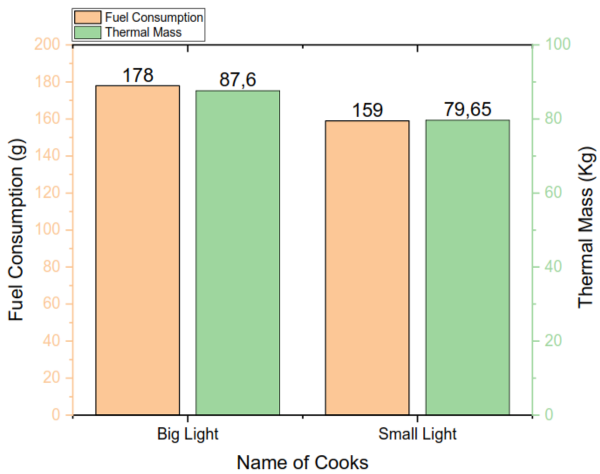


Figure 10. Quantity of fuel depending on the mass of single pot wood stoves with forced convection with chimney and skirt.

3.2. Interpretation

The fuel consumption of the stoves was determined in the same test environment for the same cooking task. In addition, this fuel consumption of the stoves was determined following the same test protocol. Fuel consumption based on the mass of stoves was compared by category of stoves with more similarity in terms of characteristics (type of fuel, presence of chimney, presence of skirt, etc.) that could influence this consumption. Taking all these aspects into account, it was noted, for the same cooking task, in each of the categories, stoves with very high masses consume more fuel than those with lower masses. There is therefore certainly an aspect which is at the basis of this state of affairs. From our analysis, two reasons may be at the origin. On the one hand, heavy materials around the fire deprive the pot of a certain amount of energy, which contributes to the heating of these materials as mentioned in the design principles of the Aprovecho research center [15]. For example, in the case of the Onil Stov and Big Light stoves, it is not profitable to heat 280 kg and 87.6 kg respectively to cook a quantity of food with a significantly lower mass. This interpretation was confirmed by E.Chica and al [16], in their article in which they stated that when materials with high thermal mass are used around the fire, the combustion gases tend to heat these materials instead of the pot and its contents. On the other hand, for cylindrical shaped stoves, when the thickness of the insulation goes beyond the cove thickness (equation 1), the excess insulation contributes to further increasing the mass of the stove. For these cylindrical shaped homes, it clearly appears through figure 11, this excess insulation contributes At the same time, the thermal resistance of conduction (equation 2) increases while that of convection (equation 3) decreases. However, in a cooking hearth, the trades thermals are essentially convective [12-17]. As a result, convective heat losses will be very significant. It is therefore for one or other of the above reasons that in each category, the stove that weighs more consumes more fuel for the same cooking task and under the same operating conditions.

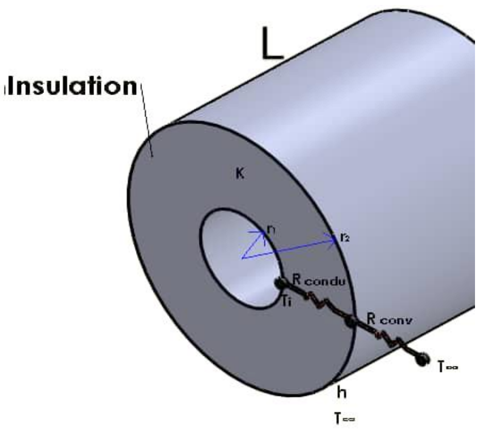


Figure 11. *Illustration of the increase in conduction thermal resistance and decrease in convection thermal resistance around a cylinder, when the insulation thickness exceeds the critical thickness.*

$$T_c = \frac{K}{h} \quad (1)$$

$$R_{cond} = \frac{\ln(\frac{r_2}{r_1})}{2 \times \pi \times K \times L} \quad (2)$$

$$R_{conv} = \frac{1}{h \times 2 \times \pi \times L \times r_2} \quad (3)$$

4. Conclusions and Recommendation

In this present study, the influence of thermal mass on the fuel consumption of stoves was highlighted based on an observation made from the literature. This observation was confirmed through a test. It appears that the mass of the materials used around the fire as well as their thickness affects in one way or another the performance of the stoves. It is therefore important to take these two parameters into account in the design and/or construction of a cooking stove. To do this, materials suitable for wall insulation must be developed. Methods for choosing materials for stove insulation must be developed and studied. These must take into account the technical, environmental, economic and safety aspects of the use of materials.

Abbreviations

TE	Time to Boil
Vc1	Burning Rate for the High-Power Phase
PCU1	Thermal Efficiency for the High-Power Phase
CS1	Fuel Consumption for the High-Power Phase
P1	Power of High-Power Phase
Vc2	Burning Rate for the Simmering Phase
PCU2	Thermal Efficiency of The Simmering Phase
CS2	Fuel Consumption for the Simmering phase
P2	Power for the Simmering Phase
Tc	Critical Thickness of Insulation
K	Thermal Conductivity of Insulation
h	Convective Heat Exchange Coefficient
Rcondu	Conduction Thermal Resistance
r2	Radius of Outer Cylinder
r1	Radius of Inner Cylinder
L	Cylinder Length
Rconv	Convective Thermal Resistance

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http://www.pciaonline.org/files/Test-Results-Cookstove-Perf

ormance.pdf. which allowed us to carry out this study.

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Data Availability Statement

The data that support the findings of this study can be found at: http://www.pciaonline.org/files/Test-Results-Cookstove-Performance.pdf. which allowed us to carry out this study.

Conflicts of Interest

The authors declare no conflicts of interest.

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Biography

Maman Nazifi Garba Irro was born in Zinder, Niger, on October 04, 1992. He obtained a professional master's degree in renewable energies and energy systems and a research master's degree in energy efficiency and renewable energies from the University of Abomey calavi in 2020 and 2021 respectively. He is currently a doctoral student at the same university's Doctoral School of Engineering Sciences.

Coffi Wilfrid Adihou was born in Zogbodomey, Bénin, on April 04, 1982. He obtained a professional master's degree in renewable energies and energy systems then a research master's degree in energy efficiency and renewable energies from the University of Abomey Calavi in 2012 and 2014 respectively. He is currently an Assistant Professor in Heat and Mass Transfers and Fluid Mechanics at the Higher Institute of Industrial Technology of Lokossa since 2022.

Hassane Ousseini Ibrahim was born in Niamey, Niger, on June 10, 1980. He obtained a state engineering diploma in electromechanics at the University of Boumerdes in Algeria then a doctorate in engineering science in the specialty electrical engineering at the University of Abomey Calavi in Benin in 2006 and 2023 respectively. He is currently a teacher-researcher at the Dan Dicko Dankoulodo University of Maradi in Niger.

Abouzeidi Dan Maza was born on January 1 in Djibballé, Niger. He holds a master's degree and a doctorate in thermal transfer from Cheikh Anta Diop University in Dakar, Senegal. He is currently an Assistant Professor of Heat and Mass Transfer and Fluid Mechanics at Dan Dicko Dankoulodo University in Maradi, Niger.

Comlan Aristide Houngan was born in Houegbo in the Republic of Benin on October 5, 1974. He obtained the M.Sc. in Benin in 1999 and the doctorate in Energy and Environment at the University of Agro ParisTech / ENGREF in Nancy (FRANCE) in 2008. He has been a Full Professor in Energy Engineering at CAMES/Industrial Science and Technology (STI) since 2020. Also, he is currently the Vice-Rector in charge of University Research at UNSTIM/Abomey/Benin since 2021.

Malahimi Anjori was born in Porto-Novo in October 11th 1953 in Benin Republic. Received the M.Sc. in Moscow and Ph.D. degrees in Heat Transfer from INPL of Nancy in 1993 (FRANCE). He is currently Professor in the Department of Mechanical Engineering of the Polytechnic School of the University of Abomey-Calavi (UAC) in Benin.

Research Field

Maman Nazifi Garba Irro: Solar thermal, Heat and mass transfer, Energy efficiency, biomass energy, Energy diversification and renewable energy systems.

Coffi Wilfrid Adihou: Solar thermal, Heat and mass transfer, Energy efficiency, biomass energy, Energy diversification and renewable energy systems.

Hassane Ousseini Ibrahim: Solar thermal, Energy efficiency, Energy diversification and renewable energy systems.

Abouzeidi Dan Maza4: Solar thermal, Heat and mass transfer, Energy efficiency, biomass energy, Energy diversification and renewable energy systems.

Comlan Aristide Houngan: Solar thermal, Heat and mass transfer, Energy efficiency, biomass energy, Energy diversification and renewable energy systems.

Malahimi Anjorin: Solar thermal, Heat and mass transfer, Energy efficiency, biomass energy, Energy diversification and renewable energy systems.