Journal of Energy Technologies and Policy
ISSN 2224-3232 (Paper) ISSN 2225-0573 (Online)
Vol.8, No.3, 2018

Product Development Using CFD Simulation of Energy Efficient Institutional Bio-char Rocket Stove

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Abstract

Globally, biomass accounts for ten percent of energy production, two-thirds of which is used for cooking and heating purposes in developing countries. Environmental degradation and natural resource depletion are also serious issues as a result of cutting trees to serve as fuel wood; biomass will govern household energy of the countries in the near future and increased afforestation, reforestation, and forest management to increase carbon sequestration in forests and woodlands. This study was product development using CFD simulation, of modified rocket stove that is energy efficient for institutional cooking. The stove design was selected for both the computational fluid dynamic (CFD) simulation and prototype production. ANSYS fluent work bench was used for CFD simulation the wood combustion and pyrolysis of woodchip to form multi-face exhaust holes syngas flow to stove combustion chamber. Gasses start to come out from the pyrolysis chamber through the exhaust outlet after 8 minutes of pyrolysis, and pressurized gasses come out at this time, and start burn in combustion chamber. At 60 minutes pressurized Syngas stops and gives low combustion.

Keywords: stove, CFD, combustion, pyrolysis, Syngas, biochar rocket stove

1. Introduction

Alternatives to fuel-wood as cooking fuel are generally expensive and hardly available in Sub- Saharan Africa. As a result, the demand for fuel-wood in rural communities remains inelastic as long as the resource continues to be available to these communities (Egeru, A.S.2014). Investments in direct fuel saving solutions are thus needed to combat the unsustainable use of fuel-wood. An important strategy is the distribution of improved cooking stoves (ICS) (Lewis, J.et al.2012,Jetter, J. et al. 2012) that allow for significant savings of fuel-wood without the need to introduce energy is expected to be used in domestic cooking activities with no alternative substitute to fire wood (TECSULT International Ltd. 2004). Meanwhile, ICS are increasingly used in fuel-wood-based countries (Ochieng, C. et al. 2013, Carbon Catalog, access February 2017), often supported by carbon funding. Under the Clean Development Mechanism (CDM), there is an increasing number of projects and programs distributing ICS Sophisticated technologies or to change cooking habits.

Globally, biomass accounts for ten percent of energy production, two-thirds of which is used for cooking and heating purposes in developing countries. It's about 2.4 billion people rely on solid fuels like biomass and Coal for their energy needs burning million tons of biomass each day, and this has implications for environmental and human health(Elias Wagari 2016). The pressure on forests, and agricultural productivity, the adverse impact of indoor air pollution and gender related issues in bio-fuel collection, are the challenges issues in our country. In Ethiopia, the forest cover has been reduced from an initial estimate of 40% a century ago to less 3.This bring environmental degradation, natural resource depletion and air pollution as well as associated health risks become serious issues as a result of cutting trees to serve as fuel wood (Morgan.D et al 2006). The influence of particulate matter (PM) by burning of biomass fuel has effect on the air quality, ecosystems and human health for cooking food.

Computational fluid dynamics (CFD) has become a well-known aiding tool in these regards as to characterize the conversion process, optimize the design, visualize the flow fields in the reacting flow environment, and to improve the operating efficiency as a whole (Rahul Shah and A. A. Date, 2011). Thermo-chemical conversion of biomass offers an efficient and economically process to provide gaseous, liquid and solid fuels and prepare chemicals derived from biomass. Design of biomass stoves using CFD for high thermal efficiency and low emissions of toxic gases and particulate matter requires detailed understanding of various fundamental physical phenomena, namely, heat transfer, fluid flow, pyrolysis and combustion, and the complex interaction among them (M.R. Ravi. 2002). All these phenomena are so intimately coupled with one another that a realistic prediction of performance of a biomass stove needs detailed modeling of each of the above phenomena and their coupling.

Design of a biomass stove basically involves the choice of the various geometric dimensions of the stove for achieving a desired range of operating conditions of the stove with the best possible thermal efficiency and the minimum possible harmful emissions. In naturally aspirated wood-burning stoves, the air-flow is driven by buoyancy forces which overcome the flow resistances inside the stove. This air flow, in turn, determines the wood burning rate as well as the overall thermal and combustion efficiencies. The flow and associated heat/mass transfer and combustion phenomena are 3-dimensional and time dependent (Hayat Benndji. 2013). ANSYS fluent is capable of modeling heat transfer and combustion for various fluid flow regimes (laminar and different turbulence models). Its post processor provides color graphics and important flow parameters (mass flow rate, temperature, etc.) by a click of a few buttons.

Those capabilities make fluent a very valuable tool to analyze the flow and temperature within the cook stove, as well as estimating the performance of the prototypes (Chia-Hsun Hsieh, 2012). The principles of biochar rocket stoves can be applied to increase cooking efficiency of stove as well as this will help us to reduce our ecological footprint, sequester CO2 and produce a greater proportion of our food locally.

2. Materials and Method

2.1. Institutional Bio-Char Rocket Stove Design and Development

2.1.1. Design Consideration

Institutional bio-char rocket stove was designed and developed based on the CFD simulated result for the cost-effectiveness of carrying out multiple parametric studies with greater accuracy allows the production prototype of new system design of high thermal efficiency and low emissions of toxic gases and particulate matter requires detailed understanding of various fundamental physical phenomena, namely, heat transfer, fluid flow, pyrolysis and combustion. The parameters consider designing stove were:

- Non-smokiness
- Safety hygiene
- Ergonomics stability
- Ease of lighting
- Time taken to start fire
- Fire wood consumption
- Speed of cooking
- Socio-cultural fit
- Size
- Cleaning requirements
- Ease of adding more fuel

Detail design of institutional bio-char rocket stove considers the vessel (dist) size and capacity (amount) to hold for purpose it perform. The other thing was the availability of materials locally to reduce cost of production, and maintenance; the materials for the construction of the various component parts were selected on the basis of weight stove as well as the force that would be acting on them, the performance it is expected to perform and the environmental condition in which they would function. As well as by identifying position pyrolysis chamber to modified with rocket stove for achieving a desired range of operating conditions of the stove with the best possible thermal efficiency.

2.1.2. Description of Stove

The configuration this stove in its original form as received from the institutional rocket stove. The stove was medium (60liter), and equipped with a chimney. The stove body is111cm in over-all height, weighed 47kg institutional bio-char rocket stove was constructed from sheet metal of 1.5mm thicknesses. The stove has three sections (figure 2:1), vessel holder, pyrolysis and combustion chambers. This prototype has very similar features to that of rocket stove models. The cook stove consists of two concentric cylinders. A rectangle cut was connected to the inner cylinder to draw the air (primary flow) and inlet of biomass fuel into the cook stove. The inner cylinder is the combustion chamber, where the product of wood combustion and pyrolysis gas mix.

The pyrolysis chamber is slightly higher than that of combustion chamber and this was designed to create a gap between the combustion and the pyrolysis chamber. This gap allows the pyrolysis gas to enter the combustion chamber and mixes with the wood combustion products. The major components of the combustion chamber with inlet of biomass fuel at bottom, pyrolysis chamber at top inlet of biomass(such as wood-chip ,coffee husk, saw-dust etc.) also at bottom outlet of bio char and vessel(Dist) holding chamber as well as chimney at middle holding chamber of vessel. Figure 2:1 gives details of Stove designed, constructed and used in the experiment. The biomass enters a through inlet into combustion chamber section and second section, where pyrolysis is taking place. The volatiles, some Syngas, flue gas are taken out of the pyrolysis chamber through exhaust to combustion chamber wall. The steam, the flue gas and any air exhausts out the top of the stove chimney.

Table2.1:Pertinent dimensions of component parts of stove

Component	Dimensions
Overall size (length × width × height)	(75 x 75 x 111) cm
Vessel(Dist) holding chamber (width × length)	(62x 62) cm
Vessel (Dist) holding chamber inner (diameter)	62cm
Vessel (Dist) holding chamber outer (diameter)	75cm
Combustion chamber (diameter)	32cm
Pyrolsis chamber(diameter)	47cm
Area of combustion chamber ($2\pi r^2 + 2\pi rh$)	7937.92cm^2
(Area of pyrolsis chamber) – (Area of combustion chamber)	3841.79 cm^2
(volume of pyrolsis chamber (πr^2h)) – (volume of combustion chamber (πr^2h))	4735.95cm^3
Stove standing(Length x Height)	(75 x75) cm

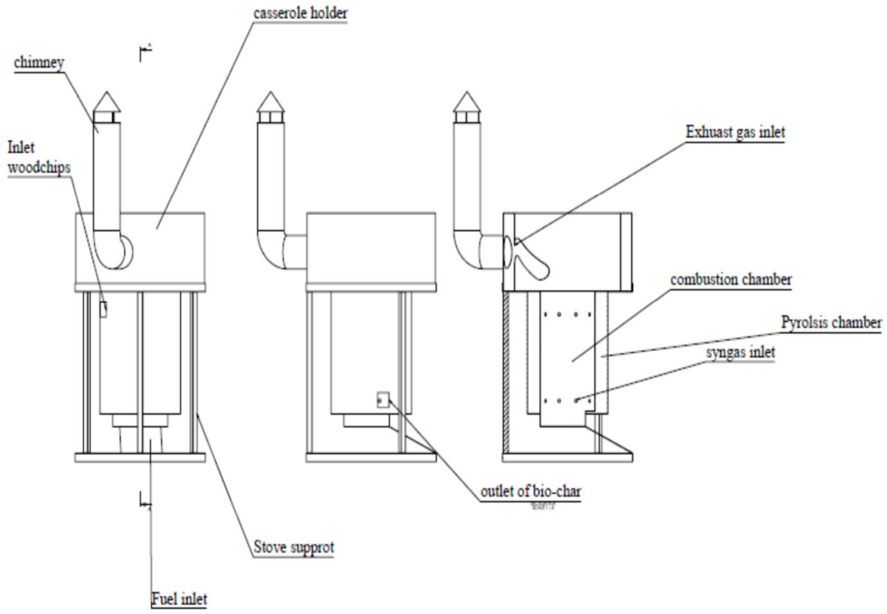

Figure 2.1: Details of the stove

2.2. Numerical Simulation

ANSYS fluent work bench was used for simulation of wood combustion and wood chips pyrolysis the stove. Geometry model was designed using ANSYS fluent and model gets transferred to mesh. The geometry was imported into ANSYS mesher, where the model would be meshed. Body sizing was the primary tool used to create the desired mesh (Nordica Ann MacCarty, 2013).

The mesh in the combustion and pyrolysis chamber was given a finer mesh to fully capture the behavior of the fluid flow. In meshing section parameters of geometry part was defined for better thermal efficiency and gas flow analysis ,under mesh sizing, fining was selected to discrete flow into many elements and updated to recognize the input. Modeling, the bio-char rocket stove system was divided into three zones: the solid phase packed bed zone, the gas phase combustion or flame zone, and the heat transfer zone.

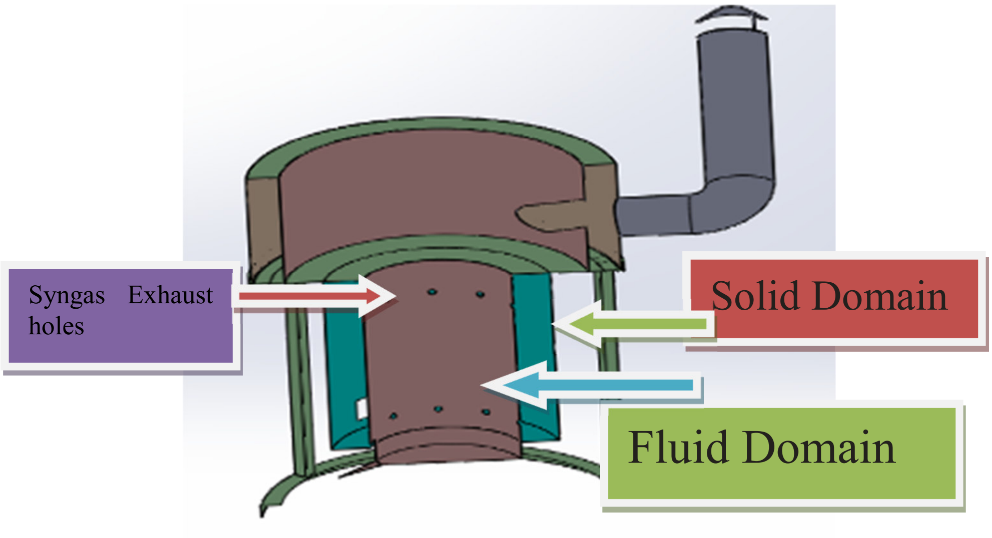

Figure 2.2: Sectional view of stove

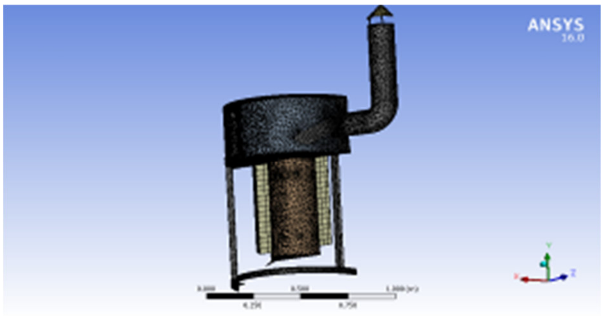

Figure 2.3:3D model view with mesh grid

2.2.1. Boundary Conditions

The fluent model was used six of boundary conditions to simulate stove but Syngas outlet from pyrolysis is twenty holes. Those boundary conditions were temperature, Wood volatile velocity, syngas flow, wall surface, pressure inlet and Pressure outlet the same as atmospheric pressure.

Table 2.2: List of boundary conditions

Boundary Name	Boundary Type	Boundary condition
Case wall	Surface	$H_{wall\ ext}$=7.41 w/m^{2}k Ambient T=300k
Wood-volatile gas velocity inlet	Wood-volatile velocity inlet	V=0.04m/s and T=873k
Syngas(from exhaust hole to combustion chamber through 20 holes)	syngas velocity inlet	V=3m/s and T= 723k

Model assumptions

The following assumptions were made:

- The operation is transient state.
- Combustion is assumed to be complete (Ragland et al, 2011).
- There is ax- symmetric, one-dimensional, vertical airflow within the combustion chamber.
- The radiation temperature is neglect.

2.3. Prototype Production of Stove

Figure 2.4: Combustion, Vessel holder Cylinders and Pyrolysis Cylinder

Figure 2.6 stand up and upside down

3. Results and Discussion

3.1. CFD Simulation Result

CFD-model has been taken from process simulation results that balanced the data gained from the condition of experiments. The convective part was solved together with the solution of the flow field. The diffusive mass transfer contains laminar diffusion (using Diffusion coefficients and Fick´s laws) and turbulent diffusion that was calculated using turbulence parameters generated by turbulence modeling.

The design of the biochar rocket stove with the cooking vessel considering of the vessel gap for the simulation was cut into half (half section) to reduce the time of convergence for the selected mesh size and to observe the temperature increase due to heat transfer within the woodchip packed bed and to the cooking vessel. Figure below shows the temperature gradient in the woodchip packed bed of the symmetrical view. The heat transferred from the inner surface which was around the maximum 600^{o}c to the outer surface which was around the minimum 30^{o}c.

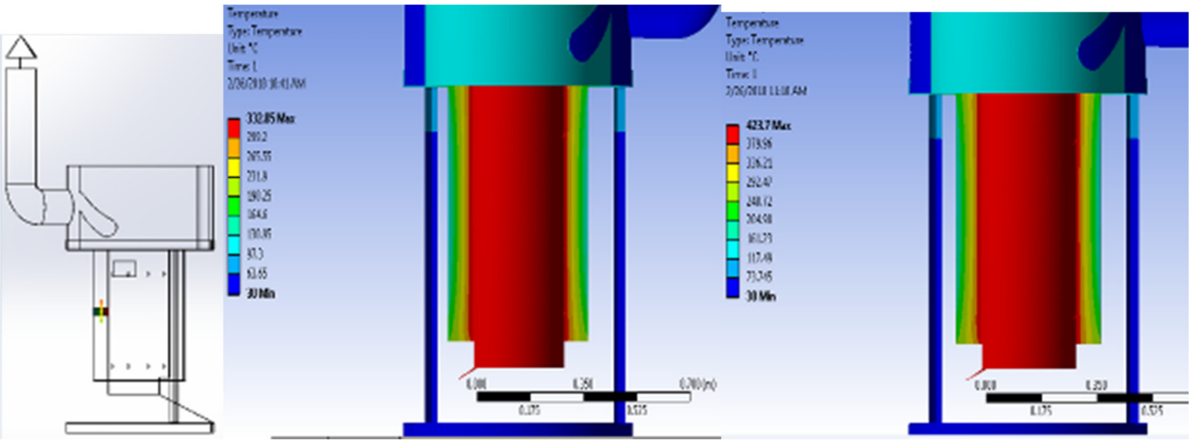

Figure 3.1: Temperature distribution with in biomass bed at 15 minute and 30 minute

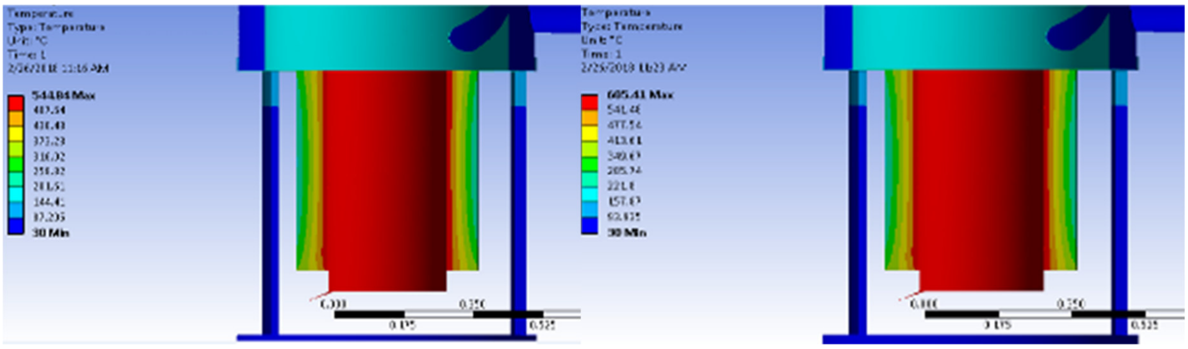

Figure 3.2: Temperature distribution at 45minute and 60 minute

Syngas was started to come out from the pyrolysis chamber through the exhaust outlet start at 10 minutes of pyrolysis. Pressurized gasses come out at this time; it was started burn in combustion chamber. It was because, the wood-chip was not completely dried and the gases have water vapor condense in pyrolysis chamber. After 60 minutes the pressurized combustible gasses (Syngas) was started to stop and gives low combustion.

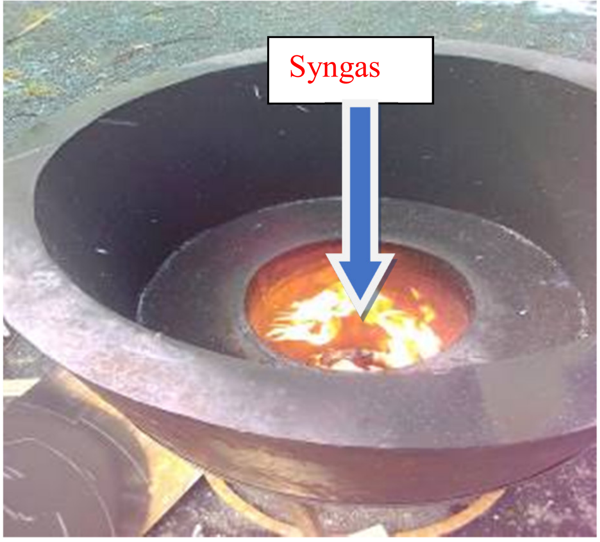

Figure 3.3: Syngas flow from Pyrolysis chamber

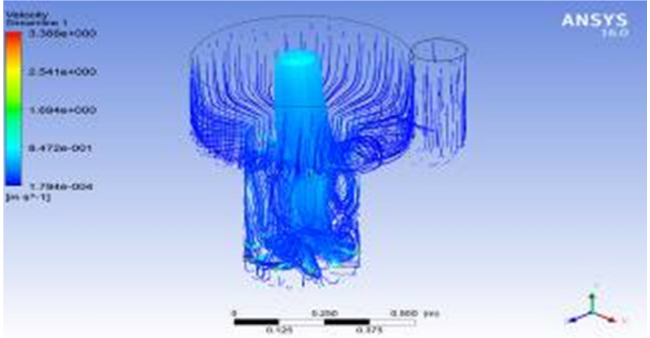

Figure 3.4: Velocity streamline

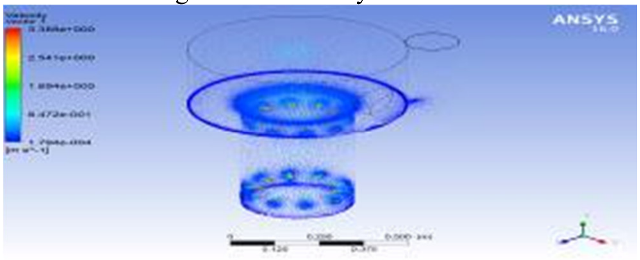

Figure 2.5: Velocity vector

Table 4.1: simulated temperature result

Location	**Simulation(K)**
Vessel bottom	873
Chimney exit	458

Maximum temperature reached when fuel was burning at a steady rate and there were also heat losses difference to the surrounding when using woodchip and without woodchip in pyrolysis chamber of the stove. Usually adiabatic temperatures are not obtained in practice due to heat losses (heat lost in flue gases, heat lost in evaporation of moisture, radiation losses from the surface of combustor, heat lost in excessive air) or due to incomplete combustion resulting from inadequate air supply

4. Summary and Conclusion

Basic principles in the design of bio char rocket stove of both direct combustion type and indirect type have been identified and a design methodology has been developed from the hybrid principles. The stove designed as per these procedures are found to work well. Several considerations have been taken from the more detailed study of the technology used for biomass burning, and characteristics of cooking stove.

The bio-char rocket stove has gas exhausting hole which takes the combustible gasses (produced during the pyrolysis reaction of the woodchips) directly to the combustion chamber. Taking these combustible syngas to the combustion chamber increases the rate of pyrolysis of wood chips by additional energy. It was seen as the installation of a chimney is of main importance. First to bring outdoor the combustion smoke and soot and as second aspect ensure a better draw.

5. Acknowledgements

The authors thank Jimma University and Oromia Agricultural research Institute, Jimma Agricultural Engineering Research Center (JAERC) as well as Asella Agricultural Engineering Research Center (AAERC), for their financial, instrument and raw material support.

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