Design and Thermal Analysis of an Energy Efficient Solid Biomass Stove

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***Abstract*-An energy efficient solid biomass stove is design to eliminate incomplete combustion that will generate toxic gas-carbon II oxide (CO), accelerate heating with provision convergent-divergent (C-D) channel to reduce and build up pressure at the base of the cooking pot. The aeration from the natural draft favoures complete combustion at the charcoal bed and a provision of adjustment of the perforated burner with dilution, primary and secondary holes radially helps to varying the burning rate to compensate the mass of food on the stove. Besides, other parametric factors that will promote the thermal efficiency and performance of the solid biomass stove were investigated.**

Index terms: C-D Channel, toxic emission free, burning rate adjuster, energy efficient charcoal stove.

INTRODUCTION

Predominantly, in developing countries and areas liable to and where there are natural disasters like floods, earthquakes, etc. and terrorism attacks have refugees camps are prone like rural dwellers to use wood charcoal as sources of energy for cooking, heating and lighting that are already familiar to them and readily available in the areas where they are temporarily settled.

Over the years, development organizations, research institutes and hundreds of volunteers and specialists have been engaged in the development, testing and dissemination of improved cook stoves throughout the developing world of Asia, Africa and Latin America. Conceived as a major way to combat deforestation, increased efficiency of domestic cooking stoves was the major focus of researchers, but this has posed threat to the forest. Unfortunately, not all programs lived up to the expectations raised, a major reason being the lack of adequate attention to social, economic and institutional issues related to introducing improved cook stoves

A vast amount of literature has appeared in the last 25 to 30 years, covering almost all aspects of stove development, especially in the areas of hardware development and technologies (e.g. design, testing, stove material, stove production techniques, etc.). Unfortunately, much of it is widely scattered and it is difficult to get a good overview of the status of technological advancement in the stove field. This has led to duplication of efforts and lack of coverage for certain subjects. In some cases, stove technology has become an academic and highly technical subject, far beyond the understanding of the common research worker

BRIEF HISTORY

Evidence, found from archaeological excavations at Chou Kutien in China, indicated that the Peking man (Homo erectus pekingnensis), who lived in caves some 400,000 years ago during the first ice age, knew how to use fire (Bronowski 1973). At that time, fire was presumably used mainly for warmth rather than for cooking. The application of fire to cook food became apparent some 100,000 years ago, in the early part of the Upper Palaeolithic Period. During that period, the aim of cooking perhaps was to render food into a more digestible form. The making and use of refined stone implements and the mastery of fire can be considered important steps towards human civilization which took off only about 12,000 years ago, when man had begun domestication of some animals and cultivation of plants [1]. With the passage of time, human tastes gradually developed and later became sophisticated with many gastronomic innovations, the use of a wide range of food materials as well as cooking techniques. During the earlier ages, cooking was presumably done over an open-fire with fuel arranged in a pyramid configuration. This mode of cooking, primarily for roasting meat, had major drawbacks: dispersion of the flames and heat during windy conditions, a lack of proper control over the fire, exposure to heat and smoke as well as fire hazards. However, at the same time, heat and smoke had also certain benefits such as food preservation and/or protection against large animals, insects/rodents and providing warmth during the cold seasons. A major step towards the evolution of other cook stoves was the development of pots of various shapes and sizes. This necessitated the modification of the open-fire to create shielded-fires in order to balance the pot over the fire. The solid biomass fuel burning system in which heat is produced, by combustion, for immediate use in domestic cooking, Biomass fuel denotes solid biomass either in a raw or processed form. This includes fuel-wood, charcoal, agro-residues, briquettes, etc. While fuel-wood is generally preferred in domestic cooking, residue fuels in sticks, leaves, straw and granular forms are also increasingly used due to fuel-wood scarcity

COMBUSTION

Combustion defines the process through which the fuel and air chemically interact at sustainable elevated temperatures. The combustion process is dependent on the physico-chemical properties of the fuel, quantity and mode of air supply, and the conditions of the surroundings. Heat transfer is the process by which the heat generated from combustion is transferred (or purposefully targeted) at a heat absorbing surface. However, a part of the heat released on combustion to the food in the cooking vessel, while the rest is dissipated to the surroundings by different mechanisms of heat transfer, namely: conduction, convection, and radiation. Fluid flow is the movement mechanism of fluid, like air, gases and vapours, through a medium under normal or artificial pressure. Knowledge of fluid flow principles is essential for understanding the flow of air and flue gases through the stove, flow passages, and chimney. The application of fluid flow principles are required to understand the combustion process, convective heat transfer and the chimney draft mechanism.

DESIGN

The design of the solid biomass stove is simplified using the tree diagram in fig 1.

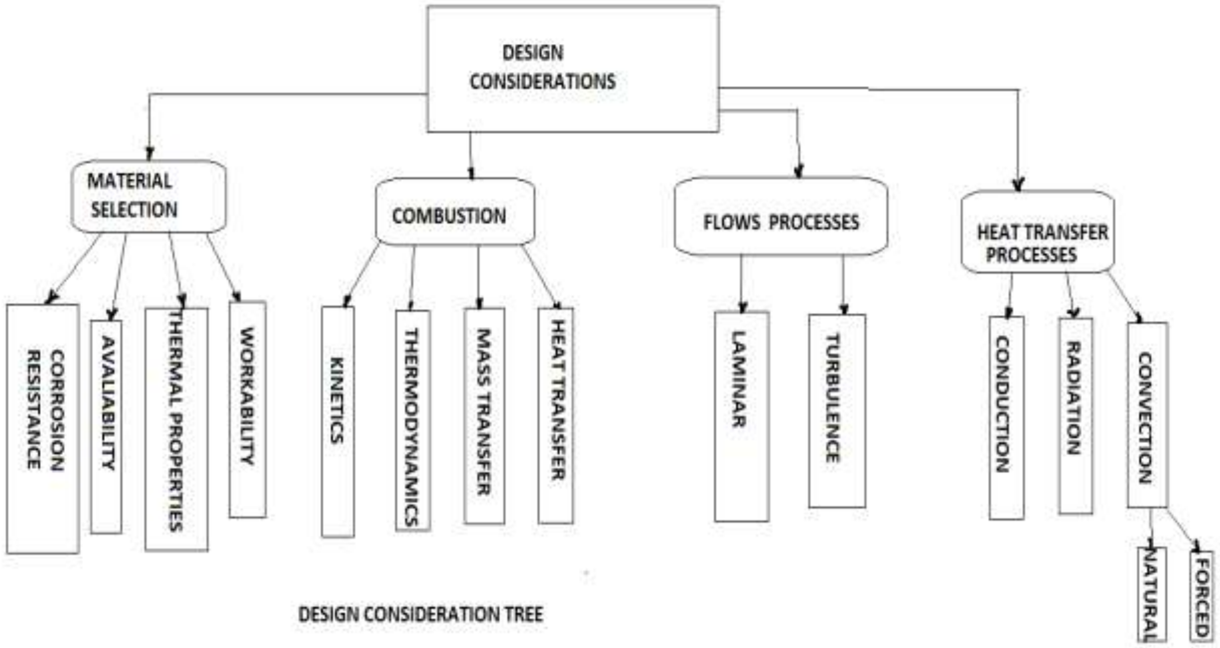


Fig.1. design tree diagram for the solid biomass stove

MATERIAL

Materials are metals –mild steel and stainless steel, and clay, but, more than one material is used for different important components. Classification of materials helps in selecting an appropriate design on the basis of locally available raw materials, skills for fabrication and necessary production facilities

PORTABILITY

It is Portable and collapsible

FUEL TYPE

The performance of different biomas stove, having the same function and constructed with the same materials, will ultimately depend on the type of fuel used. They are design based on fuel type and nature i.e granular.stick-form, pulverized form, briqueett form, caked form .An efficient charcoal biomass stove may perform very poorly with fuel wood or agri-residues. See fig 2.

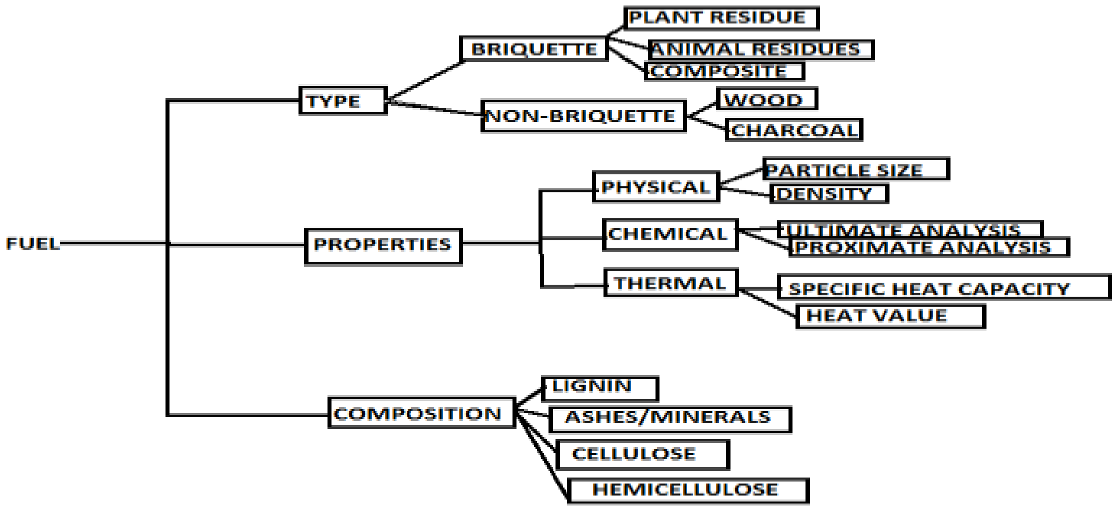
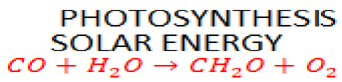


Fig.2 fuel analysis and classification

Fuels release heat energy during combustion this heat energy has heat value or calorific value ,the released heat during combustion is the energy trapped from the solar energy during photosynthesis



$CO + H_2O \rightarrow CH_2O + O_2$ photosynthetic process

$$(CH_2O)_n + nO_2 \rightarrow nCO_2(g) + {}^{2n}/_{2}\, H_2O(g) + \Delta H\ energy$$ unbalanced combustion equation

There is a self-sustaining effect during combustion among air, fuel and heat generation. Char, which is a solid carbon residue left after the release of volatile matter, burns with a glowing flame. When the combustion takes place at the surface, carbon dioxide is formed with the liberation of heat. Charcoals that are produced have tiny pore hence they are hydroscopic and they can dissolve gases for this reason when kept in an open space they absorb moisture. The stove efficiency is greatly dependent on the moisture content of the wood charcoal. Hence, The effect of moisture on the heat value of wood charcoal is given by

$$\Delta H = \frac{\Delta H_0}{1+M_C} - M_C * C_P \mathrm{T+L} \qquad \text{(i)}$$

where M_C is the moisture content, L is the latent heat of evaporation, ΔH is the heat of combustion of wood charcoal as fired, and ΔH_0 the lower heat of combustion of oven dried wood charcoal , C_P specific heat capacity of charcoal,T is the firing temperature

COMBUSTION CONTROLLING FACTORS

The factors which influence combustion are Physio-chemical properties of the fuel used and are given;

I. Fuel/air ratio;
II. Temperature of the flame/envelope;
III. Mode of fuel supply;
IV. Primary and secondary air supplies.

CHARCOAL

Charcoal is produced by heating wood in the absence of oxygen until many of its organic components gasify, leaving behind a black porous high carbon residue. The charcoal has a calorific value of 31-35 MJ/kg, depending on its remaining volatile content, compared to 18-19 MJ/kg for oven-dry wood. But the locally carbonized coal may have more of volatile constituents and will have high calorific value.

ANALYSIS

COMBUSTION PROCESS

Combustion of the products of pyrolysis of biomass, in particular, char and volatiles, takes placein two modes, flaming combustion of the volatiles and glowing combustion of the char.The combustion process is dependent on the physico-chemical properties of the fuel (size, shape,density, moisture content, fixed carbon content, volatile matter, etc.), quantity and mode of air supply (primary and secondary air) and the conditions of the surroundings (temperature, wind,humidity, etc.).The composition of the volatiles is variable and depends on the temperature of pyrolysis and the length of time that these volatiles are subjected to an elevated temperature. Thus, the combustion of volatiles is a complex process. The higher the temperature of the pyrolytic zone, the more severe is the cracking of the higher molecules into smaller ones, which in turn burn more readily. charcoal fires generally produce a diffusion flame. This consists of a jet of flammable gas with a combustion reaction taking place at the air-gas interface, resulting in the formation of hot gaseous combustion products and heating the remainder of the gas to some extent. The products of combustion are lighter due to their high temperature resulting in a vertical rise-up. During the ascent, these products also entrain some surrounding air.

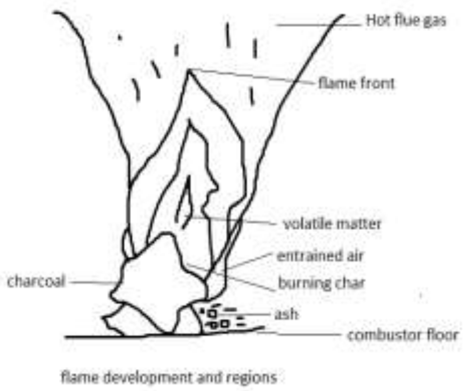


Fig.3 charcoal fire flame

The rate of heat output from a fire in an enclosure is assumed to be composed of two components:heat released from charcoal and heat released from the combustion of volatile matter if any. Based on various assumptions the design power has been defined (Bussman et al 1983) as:

$$P_{design} = 0.7 * (P_C + P_{V.max}) \qquad (1)$$

where $P_{V.max}$ is proportional to: the fire penetration rate, volatile fraction, charge weight, heat of combustion of volatiles, and the area to volume ratio of the wood pieces. The rate of heat output is controlled by the volumetric flux of air and depends upon the size of the opening of the fire-box and grate hole openings

The engineering design of the fire-box is very important in order to ensure Complete combustion and the efficient delivery of this heat to the cooking pot. The design of the fire box is based on the average power output P av of the cookstove in kW, which is defined as

$$P_{AV} = \frac{\sum m_f * H_C}{t_T} \qquad (2)$$

where $\sum m_f$ is the sum of the individual Charcoal charges during the experiment, Hc is the net calorificvalue of the fuel and t_T is the total burning time. Equation 3 .can also be written as shownin equation where Br_{av} equals the average burning rate:

$$Br_{av} = P_{av} * H_C^{-1} \qquad (3)$$

Through substitution, equation 4 can also be written as follows

$$Br_{av} = \frac{V}{V_{th}} \qquad (4)$$

where V is the volumetric flow rate of primary air and Vth is the theoretical amount of air required for combustion.

The design of the combustion chamber must take into account the effect of some of the Competing factors such as heat transfer and combustion quality.

$$H_{CC} = \frac{\sum M_f}{X * \rho_f * Acc} \qquad (5)$$

where$\sum M_f$ denotes the fuel charged (kg), x is the packing density, pf is the density of the fuel, A

cc is the cross-sectional area of charcoal bed and Hcc equals the height of the charcoal bed.

$$A_{CC} = \frac{P_{design}[Kg]}{P_{density}[Kg/m^2]} \qquad (6)$$

Where $P_{design}[Kg]$ is the design power and $P_{density}[Kg/m^2]$ as power density

In the case of a Biomass cooking stove with a grate, the power density depends on the type of grate. The diameter, calculated by the use of equation (5.7) gives a smaller diameter of the fire-box in relation to that of the pan, which results in a lower efficiency. From his studies on open fires, Prasad (1981b) concluded that the heat output from the combustion system increased with the increase Of the fuel bed diameter and its thickness. However, a large fuel bed thickness hampers the efficient combustion. The diameter of the user's pot and the quantity of the food cooked should also be taken into consideration in deciding the fuel bed diameter.Based on the experimental studies on flame heights in open fires, Herwijn (1984) concluded that the flame height of an open-fire can be expressed by

$$H_{f1} = C_2 * P^{2/5} \qquad (7)$$

The design power should be based on the time required for cooking

$$t_b = 550 * M_f^{0.38} \qquad (8)$$

where t_b is the time for cooking and M_f the mass of the food to be cooked. Based on this, the maximum power can be defined from equation .9

$$\eta = \frac{M_f * C_P(T_b - T_i)}{P_{max} * t_b} \qquad (9)$$

where η is the efficiency, Pmax the maximum power, Cp the specific heat of food, Tb the temperature of boiling and Ti the initial temperature.

$$V = 29.7 * A * h^{1/2}(1 - T_a/T_i)^{1/2} \qquad (10)$$

where Ta and Ti are the temperatures of ambient air and the average temperature of the bed, A is the area of the side air entrance, and h is the height of the air entrance.

The volumetric flux of air required to generate a specified power is a function of $Av \times h^{1/2}$

The stove performance can also be expressed in terms of specific consumption (SC) which Measures the fuel charcoal required to produce a unit output for cooking, this can be expressed by the equation

$$SC = \frac{mass\ of\ charcoal\ consumed\ (kg)}{mass\ of\ food\ cooked(kg)} \qquad (11)$$

There is a relationship between SC and the cooking efficiency, η_c which can be expressed as shown in the following equation:

$$\eta_c = \frac{1}{SC} * \frac{C_{Pf}.T}{H_C} \qquad (12)$$

Where C_{Pf} is heat capacity of specific food and Hc is the calorific value.

The emission of the pollutants is inversely proportional to the combustion efficiency and the overall efficiency is inversely proportional to the amount of fuel used.A number of operational parameters, such as size and shape of fuel, burning rate, moisture contents,excess air factor etc. are also critica

HEAT TRANSFER

Heat energy generated in the combustion chamber of the stove has a part of it useful during cooking,this useful part is transfer to the cooking pot and the food, but other part are loss heat via heat transfer mechanisms. In order to minimize the losses to the surroundings and maximize the transfer of heat to the food in the pot a thorough knowledge of heat transfer mechanisms and their underlying principles is required to determine the reasons for the losses, how these losses can be reduced through modifications of the design of the cook stove, etc.

CONDUCTION

Heat loss by conduction via the metallic parts of the stove, however this could be inevitable but can be minimize through insulation especially at the upper part of the stove where the heat generated interact with the pot. Clay serve better insulation but cannot adopted in the combustion chamber as much heat will be absorb by the insulating material. The transfer of heat through conduction can be calculated using the following equation (Fourier conduction law).

$$q = -\frac{k.A(\Delta T)}{\Delta x} \qquad (13)$$

where q is the rate of heat transfer, k ,the thermal conductivity, A the area, Δx the thickness of the surface wall through which the heat is conducted and ΔT being the difference in the temperatures between the sides of the wall.

The thermal resistance.

$$R_{th} = \frac{\Delta x}{kA} \qquad (14)$$

For part of only metal wall ,this equation determines the heat transfered

$$q = \frac{A \times \Delta T}{\frac{1}{h_1} + \frac{\Delta x}{k} + \frac{1}{h_2}} \qquad (15)$$

where $1/h_1$ and $1/h_2$ are the inner and outer surface resistances and $h_1$and h_2 are convective heat transfer coefficients respectively. The ability of a material to store heat is another important factor in conductive heat transfer. This is measured by its specific heat, which is the energy required to raise the temperature of 1 kg of its mass by 1^0C

$$\Delta Q = m \times C_P \times \Delta T \qquad (16)$$

ΔQ is the energy absorbed by the stove insulating material, $C_{P,}$ specific heat capacity of the material. ΔT is temperature difference

The thermal inertia of the stove is a direct function of the specific heat and mass, while the rate of heat transfer is a function of thermal conductivity.Thus, in order to increase the rate of heat transfer to the pot material, a high thermal conductivity of the pot material is preferred. In other words, an aluminum pot will help in faster cooking as compared to fired clay pots. Similarly, in order to reduce losses from the walls, materials having a low thermal conductivity such as mud or clay are better.

RADIATION

The ability of an object to emit and absorb radiation is given by its emissivity and absorptivity, which are usually functions of the wavelength of the radiation. The emissivity and absorptivity of a black material are equal. Heat radiation is absorbed,reflected, and transmitted when these come in contact with any solid body. The radiation is emitted over a range of wavelengths. The emitted radiation has a maximum intensity at the wavelength given by Wien's law with T being the absolute temperature.

$$\lambda_{Max} = \frac{2897.8}{T} microns \qquad (17)$$

λ_{Max} maximum wavelength ,T is the absolute temperature of the medium

Areas liable to radiation are

I. Radiation emitted by the flame;
II. Radiation exchange between the inner walls, pot and the wood;
III. Radiation loss to the atmosphere from the wall, pot, and the opening of the fire box.

The rate of heat transfer by radiation, which is one of the most important modes of heat transfer in the combustion chamber is given by the Stefan-Boltzman law for black bodies.

$$q = \sigma \times A \times T^4 \quad (18)$$

Where σ is the Stefan-Boltzman constant, which is equal to 5.6697 * 10^{-8}W/m^2K^4, A is the emitting area of the object in square meters, and Tis its temperature in K.

A mordified Stefan-Boltzman law suggests

$$q = E_m \times \sigma \times A \times T^4 \qquad (19)$$

where E_m is the emissivity of the material

Radiative heat transfer from the fire bed in a cook stove can be increased, either by increasing the fire bed temperature (by controlling the air supply to the fire bed) or by increasing the View Factor.VF. The View Factor can be increased by either decreasing the distance between the pot and the fire bed or by increasing the diameter of the pot. The ratio of pot radius r_{pot} and the charcoal bed radius,

r_{fbed} as well as height of the pot above firebed h_{fbed} to pot radius, r_{pot} ,r_{pot}/ r_{fbed} and h_{fbed}/ r_{pot} respectively are use to determine VF and whether there will be incomplete combustion.

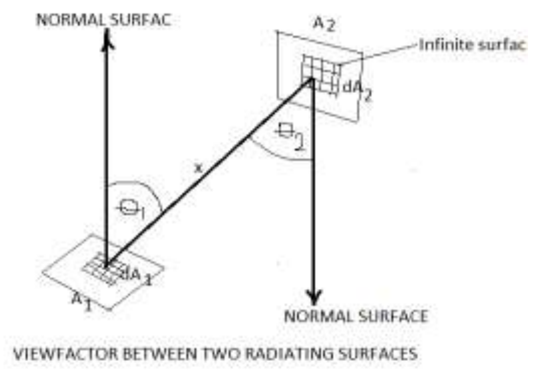


Fig4.viewfactor determination on radiate surfaces

However, too small a distance between the pot and the fire bed will result in quenching of the fire resulting in incomplete combustion and increased emission of CO and hydrocarbons due to poor air supply. This distance should be more than the combined height of the fuel bed and the flame length.Flame length is dependent on the type of fuel. The fuels with high volatile matter will produce longer flames. The length of the flame can be reduced by generating turbulence through design innovations.

$$F_{1,2} = \frac{1}{A_1}\int_{A_1}\frac{1}{\pi}\int_{A_2}\frac{\cos\theta_1\cos\theta_2}{x^2}dA_1dA_2 \qquad (20)$$

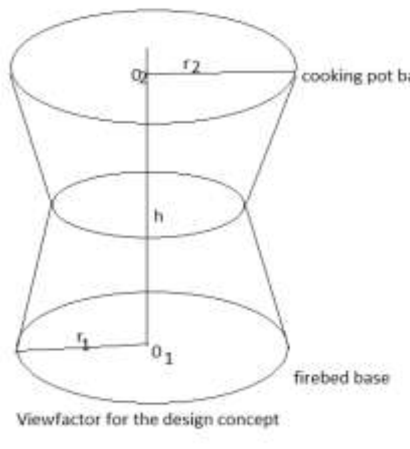


Fig5. Viewfactor of the concept under design

$$F_{1,2} = \frac{1}{2}\left[\frac{\left[\frac{h}{r_2}\right]^2+1}{\left[\frac{r_1}{r_2}\right]^2} + 1 - \left[\left[\frac{\left[\frac{h}{r_2}\right]^2+1}{\left[\frac{r_1}{r_2}\right]^2} + 1\right]^2 - \frac{4}{\left[\frac{r_1}{r_2}\right]^2}\right]^{1/2}\right] \qquad (21)$$

Where $r_1$and $r_2$are radii for firebed and pot base respectively and $r_2 > r_1$

From the definition of the view factor as the fraction of the total energy radiated by surface 1 which is intercepted by surface 2, an enclosed surface i gives the identity,then it becomes

$$\sum_k F_{i,j} = 1 \qquad (22)$$

where the surfaces j are all the other surfaces which enclose surface i.

The net radiant heat lost or gained by surface i is the difference between the heat it radiates and that which it absorbs from other radiating surfaces. Thus, for blackbodies

$$Q_i = \sigma A_i T_i^4 - \sum_j \sigma A_j F_{j,i} T_j^4 \qquad (23)$$

Symmetrical surfaces have relationship like

$$A_i F_{i,j} = A_j F_{j,i} \qquad (24)$$

CONVECTIVE HEAT TRANSFER

Convective heat transfer involves the transfer of heat by the movement of fluid (liquid or gas), followed by conductive heat transfer between newly arrived hot fluid and the matter. Depending on the type of driving force involved in the movement of the fluid, heat transfer by convection takes place by two distinct mechanisms. When fluid's movement takes place as a result of the buoyancy force created by the temperature difference, the phenomenon is known as natural convection. On the other hand when the fluid is forced to flow by a blower or a fan or by windy conditions, the phenomenon is known as forced convection. Predominantly, Convective heat transfer becomes the frequent mode of heat transfer in cook stoves. The convective heat transfer is estimated using a general equation:

$$q = h \times A \times \Delta T \quad (25)$$

FLUID FLOW

heat transfer by natural convection, generally encountered in naturally vented cookstoves, the Nusselt number can be evaluated from the relation:

$$Nu = C \times (Gr \times Pr)^n \qquad (26)$$

In cook stoves the values of C and n are taken as 0.53 and 0.25 respectively. where Grand Prare the Grashoff and Prandtl numbers respectively which are defined as

$$Gr = \frac{g \times B \times T \times l^3}{U^2} \qquad (27)$$

$$Pr = \mu \times \frac{C_P}{k} \qquad (28)$$

where g is the acceleration due to gravity, B ,the volumetric expansion coefficient (approx.= 1/T), T is the temperature difference between the surface and the ambient, µ the viscosity of the fluid, k the thermal conductivity and U the kinematic viscosity. For flow over vertical cylindrical surfaces, the characteristic length l is equal to the height. The induction of air required for the combustion of fuel in the combustion chamber and the subsequent flow of the combustion products through various chambers and connecting tunnels is governed by the principles of fluid flow. The suction effect, responsible for the induction of air into the combustion chamber,

$$\rho_1 \times A_1 \times V_1 = \rho_2 \times A_2 \times V_2 \qquad (29)$$

where ρ is the density, A is the area and V is the velocity. This equation can be used to calculate the velocity of the flue gases and air at different locations in the stove. Density of air varies with temperature difference .Bernoulli's equation can be derived, based on the applications of conservation of energy to the flow of fluid

$$H_{Total} = H_{st} + H_{dy} + H_{Po} \qquad (30)$$

$$\Delta P_{stat} = h_{ch}(\rho_a - \rho_g) \qquad (31)$$

$$\Delta P_{dyn} = \frac{\rho_g \times V^2}{2g} \qquad (32)$$

where Hst is the static head, Hdy is the dynamic head, H po is the potential head and H_{Total} is the total frictional head. The head is expressed in meters and is equal to ΔP/ ρ where ΔP is the pressure loss and ρ is the density. The potential head or Hpo is equal to Hz where z is the elevation above any given level in meters .At choke or throat ,the friction lost is

DIAGRAMMS

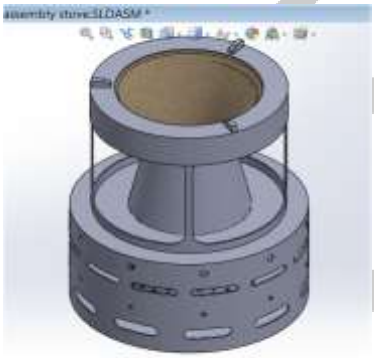


Fig6 .3-D isometric model of a charcoal stove

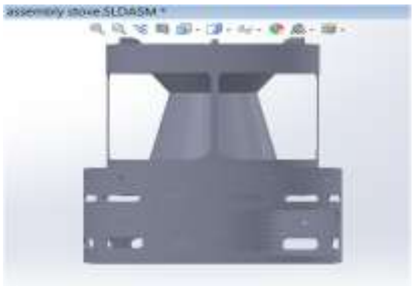


Fig7. view of the stove

$$H_{fr} = \frac{(V_1 - V_2)}{2g_c} \qquad (33)$$

The loss of pressure due to the friction encountered during the flow through passes which have different shapes in the cook stove known as friction pressure losses. From the fluid dynamic point of view, all these shapes can be grouped into different geometric shapes such as: (a) Straight channels of uniform cross section, (b) bends, (c) sudden expansion, and(d) sudden contraction. The pressure loss due to flow friction is given by the equation:

$$\Delta P_{fr} = \frac{f \times h_{ch} \times \rho_g \times V^2}{2g \times d_h} \qquad (34)$$

where;f is the friction factor, d_h is the hydraulic diameter, which is defined as ΔX the cross sectional area/wetted perimeter.The value of the friction factor depends on the flow regimes, which may be either laminar or turbulent, depending upon a dimensionless parameter known as Reynold's number. The Reynold's number is defined as:

$$\Delta R_e = \frac{d_h \times V \times \rho_g}{\mu} \qquad (35)$$

where μ is the dynamic viscosity.

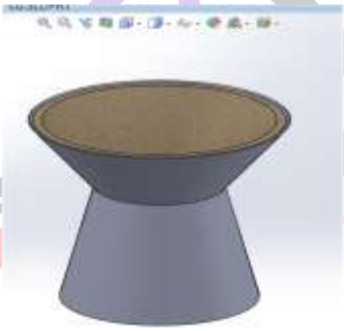


Fig8. 3-D View of CD –nozzle insulated with clay

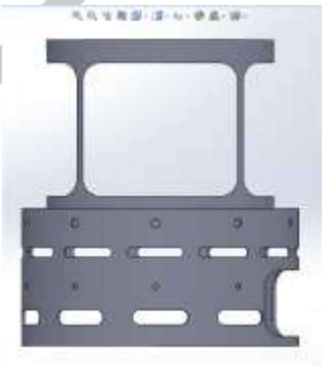


Fig9. 3-D View of the frame

Fig10. 3-D view of the charcoal bed/burner

Fig 11. 3-D view of the outer burner

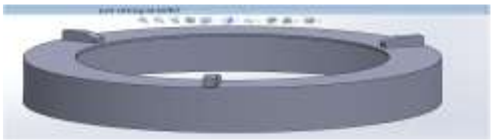


Fig12. 3-D view of pot sitting

Fig13. Major parts of the biomass stove

CONCLUSION

Poor combustion will negatively affect a stove's thermal performance; it is not as significant a factor as heat transfer efficiency. Energy losses due to inefficient or incomplete combustion typically account for less than 8% of total energy input [17]. However, the incomplete combustion of biomass fuels will produce harmful emissions. These include carbon monoxide (CO), unburned hydrocarbons (UHC), nitrogen oxides (NOx), smoke and soot, [18].Hence .dilution,primary and secondary holes as well as slots are provided in the burners and combustor chamber to allow enough air into the combustor for complet combustion. The charcoal stove designed and analysis mathematically by various relevant thermodynamics ideas and equations ,applying fluid flow to idealize the CD nozzle channel to maximize the heating capacity and minimize heat loss.it will be energy efficient.

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