Burning of the Biomass in the Furnace using a Stirling Engine

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Abstract. *Today, advances in technology for combustion and to control emissions resulted in programs of research and development. Within these technologies used for generation of electricity from biomass has been the Stirling engine combustion which can be directly attached to a cycle of steam and gasification. The Stirling engine technology gained strength because of its great advantages you can use any source of heat, including solar. It is worth mentioning that the use of biomass as fuel in applied technology, energy conversion as a Stirling engine favors the generation of electricity distributed low-power, very viable in isolated communities, because of its low cost of acquisition and maintenance for synchronous generators. This paper aims to use the heat released during the burning of biomass (eucalyptus) to drive a Stirling engine.*

Keywords: *Biomass, Stirling Engine, Furnace, Combustion, Energy*

1. INTRODUCTION

Biomass is originated in municipal solid waste, animals, plants, industrial and forestry, and focused on energy purposes covers the use of various waste for the generation of alternative sources of energy. She also has capacity to generate jobs in rural areas and close to zero balance between the release and absorption of carbon into the atmosphere, which means that their use is both an array of social inclusion as a convenient tool to meet the requirements, always increasing, and environmental legislation. Moreover, biomass has a space in the relevant market for carbon sequestration, as its final use is for energy purposes. The technology of biomass in use worldwide have two key problems: the cost of biomass and energy efficiency of their production chain (Paul et al, 2004).

2. CHARACTERIZATION OF BIOMASS

Biomass fuels represent already today a big share of the Renewable Energy Sources used in the world. Biomass fuels generally contains a high percentage of volatiles (>70% mass) and the devolatilization phase, thus, plays a major role in the whole process of combustion/gasification in terms of conversion, yields and stability of the flame. So the need for characterization of the behaviour of these fuels in thermochemical conversion is evident and fundamental in order to provide the market with sustainable, reliable, efficient and cost-competitive technologies. The process of characterization of biomass is to define the object physical, chemical and energy to evaluate the behavior and possible lines of use. The determinations are made by chemical analysis of (carbon, volatile and ash) and elemental analyses (C, H, O, N, S) (Affonso et al, 2000). The content of moisture reduces the potential heat of the fuel for two reasons:

- The power Calorific Superior decreases to have a certain volume occupied by water that is unable to produce heat.
- The efficiency of burning down due to the heat being absorbed in the evaporation of water. For values less than 30% moisture, you can get a good income in combustion. For percentages above 60%, the combustion becomes unstable and above 85% there is no production of usable heat.

The higher the moisture content of greater the amount of air needed for combustion. As if producing greater quantity of gas, greater quantity of soot and unburnt

3. STIRLING ENGINE

The Stirling engine is an external combustion engine, invented in 1816 by Robert Stirling. Stirling engines feature a completely closed system in which the working gas (usually air but sometimes helium or hydrogen) is alternately heated and cooled by shifting the gas to different temperature locations within the system. Stirling engines feature a completely closed system in which the working gas (usually air but sometimes helium or hydrogen) is alternately heated and cooled by shifting the gas to different temperature locations within the system. The Stirling engine works with a thermodynamic cycle composed of 4 stages and performed in two pistons: isothermal compression (constant temperature), heating isometric (in volume), isothermal expansion and cooling isometric (Cinar C et al, 2002). In the two-cylinder Stirling, one cylinder is kept hot by burning fuel while the other is kept cool by an air cooled heat sink. The Stirling cycle may be thought of as four different phases: expansion, transfer, contraction, and transfer. Unlike internal combustion engines, the fluid of work never leaves the interior of the engine; it is therefore a closed-loop machine. Theoretically, the Stirling engine is the most efficient thermal machine possible. Some prototypes built by the Dutch company Philips in the years 50 and 60 came to rates of 45%, easily surpassing the engines on petrol, diesel and steam machines efficiency between 20% and 30% (Rizzo.J.G, 1995). The Figure 1 shows a stirling engine type Alpha.

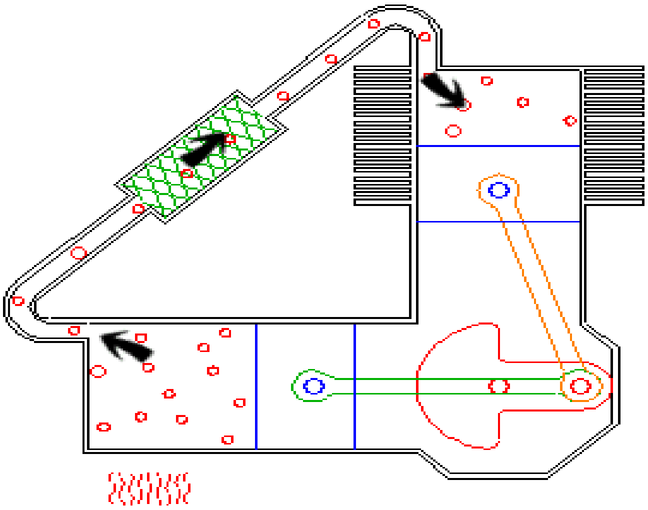

Figure 1: Stirling Engine type Alfa

The Stirling engine has many advantages: it is clean because the combustion is continuing and not intermittent as the Otto cycle engines and Diesel cycle, allowing a more complete and efficient combustion of fuel. It is multi-fuel; you can use virtually any energy source: gasoline, ethanol, methanol, natural gas, oleo diesel, biogas, GLP, solar, geothermal heat and others. Just generate a significant difference in temperature between the hot and cold chamber to produce work (the greater the difference in temperature, the greater the efficiency of the process and the more compact engine). His biggest drawback is the difficulty of giving departure and vary its speed of rotation quickly, and complicated its use in vehicles such as cars and trucks, while models of hybrid propulsion (electric motor and heat) can be viable. Furthermore, being a little known technology, the stirling engines are more expensive, both in the acquisition as the maintenance (Gingery. V et al, 1996). Due to high efficiency, low emission of pollutants, flexibility of fuels and their long life, the use of the Stirling engine has been cute in the world.

4. COMBUSTION OF BIOMASS

The External combustion of the Stirling engine makes it very attractive for small-scale Combined Heat and Power (CHP) plants using bio-fuels. Especially wood chips are an attractive fuel because of the high melting point and the low content of ash. Unfortunately, it is more complicated than expected to use bio-fuels for a Stirling engine. The high temperature in the hot heat exchanger transferring heat from the combustion to the Stirling engine combined with the low heating value of the fuel reduce the obtainable efficiency of the plant. The limitations of the combustion temperature in order to avoid melted ash in the combustion chamber decrease the obtainable efficiency even further. The problem for utilization of bio-fuels in Stirling engines is that the combustion of bio-fuels and transfer of the heat from the combustion gases to the Stirling engine need much more space than for natural gas as fuel (Carlsen H, 2005).

Table 1: Fraction of Molar Fuel 1

Composition	mf_i (kg)	MW_i(kg/kmol)	Mf_i/MW_i	$\overline{x}_i$ (Kmol)	$\overline{x}_i$ (Kmol/s)
C	0,3925	12	0,03289	0,4850	0,00156
H_2	0,047	2	0,02365	0,3493	0,00112
O_2	0,3522	32	0,01107	0,1635	0,00052
N_2	0, 0025	28	$8{,}93.\ 10^{-5}$	0, 00132	$4{,}2.\ 10^{-6}$
S	0, 0001	32	$3{,}1.\ 10^{-6}$	0, 00005	$1{,}6.\ 10^{-7}$
Total	1		0,0677024		

4.1 Calculus of the number of moles for the equation of combustion of biomass

$$n_{,i} = \frac{Y_{,i}\ mC}{M,i} \tag{1}$$

4.2 Stequiometric Equation

$$\left[xC + yH_2 + zO_2 + tN_2 + \gamma S\right]_{Comb} + \alpha\left[O_2 + 3{,}76N_2\right]_{Ar} \Rightarrow n_{CO_2}CO_2 + n_{H_2O}H_2O + n_{SO_2}SO_2 + n_{N_2}N_2 \tag{2}$$

$$0{,}485 + 0{,}3493H_2 + 0{,}1635O_2 + 0{,}00132N_2 + 0{,}00005 + \alpha\left[O_2 + 3{,}76N_2\right] \rightarrow n_1CO_2 + n_2H_2O + n_3SO_2 + n_4N_2$$

The balance of elements is

$$\begin{array}{ll} C & \rightarrow\ x = n_{CO_2} = 1{,}374.10^{-4} \\ H_2 & \rightarrow\ y = n_{H_2O} = 9{,}87.10^{-5} \\ O_{2,Ar} & \rightarrow\ \alpha = n_{CO_2} + \dfrac{n_{H_2O}}{2} + n_{SO_2} - z = 1{,}405.10^{-4} \\ N_{2,Ar} & \rightarrow\ t = n_{N_2} - 3{,}76\alpha = 5{,}287.10^{-4} \\ S & \rightarrow\ \gamma = n_{SO_2} = 1{,}313.10^{-8} \end{array} \tag{3}$$

4.3 The Coeficient of free Oxygen in the Product of Combustion

$$\%O_2 livre = \frac{W}{\sum + 4{,}76.W} \tag{4}$$

With the excess air the equation is:

$$\left(xC + yH_2 + zO_2 + tN_2 + \gamma S\right) + \alpha\mu\left(O_2 + 3{,}76N_2\right) \Rightarrow n_1CO_2 + n_2H_2O + n_3O_2 + n_4N_2 + n_5SO_2$$

$$\sum{}_{(1)} = x + y + n_4 = 6{,}67.10^{-4} \tag{5}$$

The balance of elements is

$$\begin{array}{ll} C & \rightarrow\ x = n_1 = 1{,}374.10^{-4} \\ H_2 & \rightarrow\ y = n_2 = 9{,}87.10^{-5} \\ O_{2,Ar} & \rightarrow\ \lambda = \dfrac{n_1}{\alpha} + \dfrac{n_2}{2.\alpha} + \dfrac{n_3}{\alpha} + \dfrac{n_5}{\alpha} - \dfrac{z}{\alpha} = 3{,}139.10^{-4} \\ N_{2,Ar} & \rightarrow\ t = n_4 - (3{,}76)\alpha\mu = 1{,}007.10^{-3} \\ S & \rightarrow\ \gamma = n_5 = 1{,}313.10^{-8} \\ W & \rightarrow W = n_3 = 1{,}271.10^{-4} \end{array} \tag{6}$$

4.4 Adiabatic Temperature

$$\begin{aligned}\Delta HR = {} & [(0.3925.4.1868\cdot 7819) + (0.047\cdot 4.1868\cdot 28642) + (0.0001\cdot 4.1868\cdot 2210)\cdot mC] + ..\\ & O2\cdot\left[0 + \left(7.10\cdot Ta + 0.0040\cdot Ta^{2} + 5000\cdot Ta^{-1} - 2313\right)\cdot 4.1868\right] + ...\\ & N2\cdot\left[\left[0 + \left(6.72\cdot Ta + 0.0042\cdot Ta^{2} + 1100\cdot Ta^{-1} - 2106\right)\cdot 4.1868\right]\right]\end{aligned}$$

$$\Delta H = 89{,}192\ [KJ/kg] \tag{7}$$

$$\begin{aligned}T_{Adiabatic} = \Delta HR = {} & x\cdot\left[\left(10.6\cdot T + 0.011\cdot T^{2} + 2050\cdot T^{-1} - 3926\right)\cdot 4.1868\right] \ldots\\ & + \left[y\cdot\left[\left(7.20\cdot T + 0.0113\cdot T^{2} + 0\cdot T^{-1} - 2276\right)\cdot 4.1868\right] \ldots\right.\\ & \quad + \left[\gamma\cdot\left[\left(11.02\cdot T + 0.0093\cdot T^{2} + 1830\cdot T^{-1} - 3990\right)\cdot 4.1868\right] \ldots\right.\\ & \quad\quad + \left[W\cdot\left[0 + \left(7.1\cdot T + 0.0040\cdot T^{2} + 5000\cdot T^{-1} - 2313\right)\cdot 4.1868\right] \ldots\right.\\ & \quad\quad\quad \left.\left.\left. + n_{4}\cdot\left[0 + \left(6.72\cdot T + 0.0042\cdot T^{2} + 1100\cdot T^{-1} - 2106\right)\cdot 4.1868\right]\right]\right]\right]\end{aligned}$$

Soon

$$T_{adiabatic} = 2180\ K \tag{8}$$

4.5 Calculus of the Entropy and Enthalpy of reaction_1

$$CO_2 \text{ ---------------> } CO + 1/2\ O_2 \tag{9}$$

R = 8.314 $J.mol^{-1}.\ K^{-1}$

$$\Delta H_{(CO_2)} := \int_{298}^{T_f}\left[\frac{-3.7357 + \left[30.529\left(\frac{T}{100}\right)^{0.5}\right] - \left[(4.1034)\left(\frac{T}{100}\right) + (0.024198)\cdot\left(\frac{T}{100}\right)^{2}\right]}{T}\right] dT$$

$$\Delta H_{CO2} = 9,\ 795.\ 10^{-4}\ [kJ/kmol] \tag{10}$$

$$\Delta H_{C0} = \int_{298}^{T} 69.145 + \left[-0.70463\left(\frac{T}{100}\right)^{0.75}\right] + \left[-200.77\cdot\left(\frac{T}{100}\right)^{-0.5}\right] + 176.76\left(\frac{T}{100}\right)^{-0.75} dT$$

$$\Delta H_{CO} = 6{,}064.\ 10^{4}\ [kJ/kmol] \tag{11}$$

$$\Delta H_{O2} = \int_{298}^{T} 37.432 + \left[0.020102\left(\frac{T}{100}\right)^{1.5}\right] - \left[178.57\cdot\left(\frac{T}{100}\right)^{-1.5}\right] + 236.88\left(\frac{T}{100}\right)^{-2} dT$$

$$\Delta H_{O2} = 6{,}33.\ 10^{4}\ [kJ/kmol] \tag{12}$$

$$\Delta S_{(CO_2)} := \int_{298}^{T_f} \left[\frac{-3.7357 + \left[30.529\left(\frac{T}{100}\right)^{0.5}\right] - \left[(4.1034)\left(\frac{T}{100}\right) + (0.024198).\left(\frac{T}{100}\right)^{2}\right]}{T} \right] dT$$

$$\Delta S_{CO2} = 98,628 \text{ [kJ/kmolK]} \tag{13}$$

$$\Delta S_{CO} = \int_{298}^{T} \frac{69.145 - \left[0.70463\left(\frac{T}{100}\right)^{0.75}\right] - \left[200.77\left(\frac{T}{100}\right)^{-0.5}\right] + \left[176.76\left(\frac{T}{100}\right)^{-0.75}\right]}{T} dT$$

$$\Delta S_{CO} = 62{,}972 \text{ [kJ/kmolK]} \tag{14}$$

$$\Delta S_{O2} = \int_{298}^{T} \frac{37.432 + \left[0.020102\left(\frac{T}{100}\right)^{1.5}\right] - \left[178.57\left(\frac{T}{100}\right)^{-1.5}\right] + \left[236.88\left(\frac{T}{100}\right)^{-2}\right]}{T} dT$$

$$\Delta S_{O2} = 65{,}623 \text{ [kJ/kmolK]} \tag{15}$$

4.6 Calculus of the Gibbs Energy of reaction

$$\begin{aligned}\Delta G = &\left(Hf_{CO} + 0.5\cdot Hf_{O2} - Hf_{CO2}\right) \cdots \\ &+ \left(\Delta H_{CO} + 0.5\cdot\Delta H_{O2} - \Delta H_{CO2}\right) - T\cdot\left[\left(Sf_{CO} + \Delta S_{CO}\right) + 0.5\cdot\left(Sf_{O2} + \Delta S_{O2}\right) - \left(Sf_{CO2} + \Delta S_{CO2}\right)\right]\end{aligned}$$

$$\Delta G\_1 = 1.012.10^{5} \text{ [KJ/Kmol]} \tag{16}$$

4.7 Calculus of the Constant of Equilibrium K_{eq_1}

$$K_{eq\_1} = \exp\left(\frac{-\Delta G\_1}{RT}\right) \Rightarrow K_1 = 3{,}102.10^{-3} \tag{17}$$

Table 2: The variation of the adiabatic temperature versus the constant of equilibrium

Temperature (K)	**Equilíbrio Constant K_{eq_1}**
298	0..00
573	5.98 10-10
873	8.82 10-7
1174	3.142 10-6
1273	7.044 10-5
1473	2.58 10-4
1573	4.362 10-4
1773	1.044 10-3
1873	1.503 10-3
2000	2.275 10-3
2173	3.693 10-3
2180	3.759 10-3

The figure 2 shows the temperature of the reaction versus the constant of equilibrium Keq_1

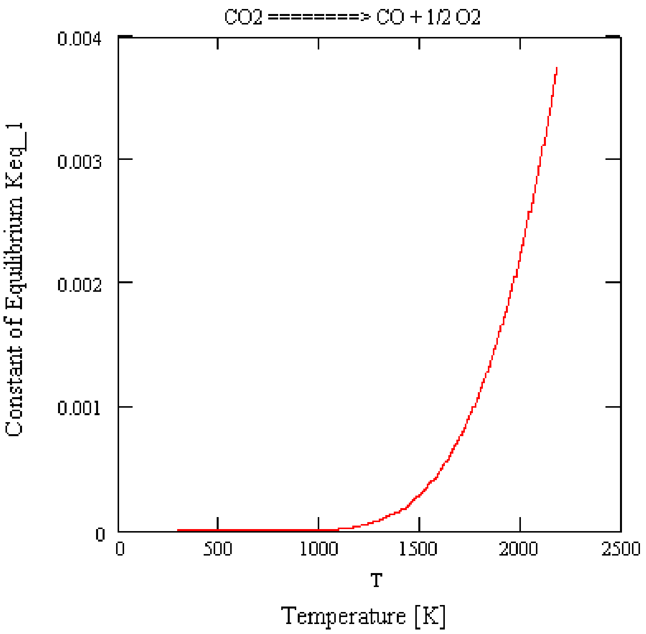

Figure 2: The variation of the Temperature of reaction versus the Constant of Equilibrium Keq_1

4.8 Calculus of the Entropy and Enthalpy of reaction_2

$$1/2O_2 + 1/2N_2 \text{ ======> } NO \tag{18}$$

$$\Delta H_{NO} = \int_{298}^{T} 59.283 - \left[1.7096\left(\frac{T}{100}\right)^{0.5}\right] - \left[70.613\left(\frac{T}{100}\right)^{-0.5}\right] + \left[74.889\left(\frac{T}{100}\right)^{-1.5}\right] dT$$

$$\Delta H_{NO} = 6{,}182.\ 10^{4}\ [kJ/kmol] \tag{19}$$

$$\Delta H_{N2} = \int_{298}^{T} 39.060 - \left[512.79\left(\frac{T}{100}\right)^{-1.5}\right] + \left[1072.7\left(\frac{T}{100}\right)^{-2}\right] - \left[820.40\left(\frac{T}{100}\right)^{-3}\right] dT$$

$$\Delta H_{N2} = 6{,}001.\ 10^{4}\ [kJ/kmol] \tag{20}$$

$$\Delta S_{NO} = \int_{298}^{T} \frac{59.283 - \left[1.7096\left(\frac{T}{100}\right)^{0.5}\right] - \left[70.613\left(\frac{T}{100}\right)^{-0.5}\right] + \left[74.889\left(\frac{T}{100}\right)^{-1.5}\right]}{T} dT$$

$$\Delta S_{NO} = 64{,}328\ [kJ/kmolK] \tag{21}$$

$$\Delta S_{N2} = \int_{298}^{T} \frac{39.060 - \left[512.79\left(\frac{T}{100}\right)^{-1.5}\right] + \left[1072.7\left(\frac{T}{100}\right)^{-2}\right] - \left[820.40\left(\frac{T}{100}\right)^{-3}\right]}{T} dT$$

$$\Delta S_{N2} = 62,\ 384\ [kJ/kmolK] \tag{22}$$

$$\Delta G = \left[\left(Hf_{NO} - 0.5\cdot Hf_{O2} - 0.5\cdot Hf_{N2}\right) + \left(\Delta H_{NO} - 0.5\cdot \Delta H_{O2} - 0.5\cdot \Delta H_{N2}\right)\right] - ....$$

$$T\cdot\left[\left(Sf_{NO} + \Delta S_{NO}\right) - 0.5\cdot\left(Sf_{O2} + \Delta S_{O2}\right) - 0.5\cdot\left(Sf_{N2} + \Delta S_{N2}\right)\right]$$

$$\Delta G\_2 = 6.343.10^{5}\ [KJ/Kmol] \tag{23}$$

4.9 Calculus of the Constant of Equilibrium K_{eq_2}

$$K_{eq\_2} = \exp\left(\frac{-\Delta G\_2}{RT}\right) \Rightarrow K_{eq\_2} = 0.027 \tag{24}$$

Table 3: The variation of the adiabatic temperature versus the constant of equilibrium K_{eq_2}

Temperature (K)	**Equilíbrio Constant K_{eq_2}**
298	0..00
573	$2,653\ 10^{-8}$
873	$1,808\ 10^{-5}$
1174	$4,415\ 10^{-4}$
1273	$9,076\ 10^{-4}$
1473	$2.896\ 10^{-3}$
1573	$4.631\ 10^{-3}$
1773	0,01
1873	0,014
2000	0,02
2173	0,031
2180	0,032

The figure 3 shows the temperature of the reaction versus the constant of equilibrium Keq_2

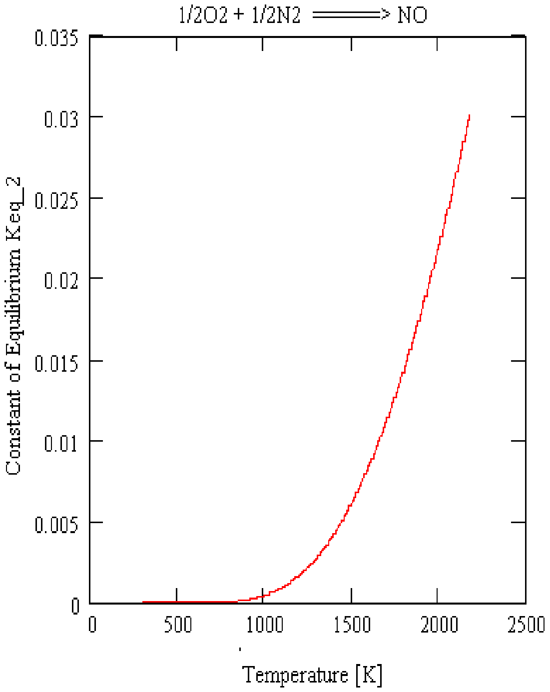

Figure 3: The variation of the Temperature of reaction versus the Constant of Equilibrium Keq_2

5. CONCLUSION

The Biomass can be transformed into energy through combustion, gasification, fermentation, or production of liquid substances. The energy originated from biomass is considered durable from the moment that where you can ensure proper management through its cycle. It is also renewable in the sense that all energy from biomass has biological processes. From an economic perspective, biomass is more interesting than other renewable sources of energy. The use of biomass to generate energy is going through several changes. It is believed that the future of coal plants begins to operate also with biomass, so that it can gradually replacing coal as the main product. The use of biomass as fuel in applied technology, energy conversion as a Stirling engine favors the generation of electricity distributed low-power, very viable in isolated communities, because of its low cost of acquisition and maintenance for synchronous generators.

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