

## Energy Analysis of Microalgae Gasification

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### Abstract

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**M**icroalgae biotechnology has the potential of producing biofuel that can reduce over dependency on fossil fuel resources. The recent biodiversity of alternative fuel resources has identified microalgae biomass as viable resource for bio-gas production through thermochemical gasification process. The study identified dewatering process as the most energy intensive process; with increase in energy demand at higher water levels. Thermo-chemical processes of pyrolysis and gasification have energy demand of 1.4MJ/kg and 10.1MJ/kg of dry algae respectively. These energy demands are supplied from the combustion of microalgae biomass which produces 14.1MJ/kg of heat energy making the energy conversion entirely on renewable resource. The produced bio-gas has high and low heating values of 22.6MJ/kg and 21.2MJ/kg with exit temperature of 1171 °C. This study evaluates the energy analysis between 10–50 % humidity level.

**Keywords:** *Microalgae, Energy, Gasification, Dehumification*

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## **Background to the Study**

Algae are carbonaceous plants with promising prospect as feedstock for energy production; its ubiquity in nature, CO<sub>2</sub> sequestration, rapid growth rate (can double their biomass in 24 hrs) (Chisti, 2007), excellent CO<sub>2</sub> capture capabilities, high solar energy to chemical energy conversion rates and offers less competition to food security amongst other factors make algae biomass viable source for energy generation (Pengmei, 2007; Singh, et al., 2017; Asadian et al., 2018).

Currently microalgae are gaining high research interest as feedstock for liquid fuels and synthetic gas production (Alam, et al., 2015). Various technologies have been utilized in the past to produce biofuel from algae biomass including solvent extraction, gasification, anaerobic digestion and pyrolysis producing biofuel, synthesis gases, biogas respectively – (Brennan & Owende, 2010; Chen, et al., 2011; Speight, 2010). Thermochemical processes such as gasification, thermal liquefaction, to rrefaction, carbonization and pyrolysis have widely been studied to produce bio-oil from algae and other biomasses (Naik, 2010). Some of the studies conducted were reviewed by Verma et al. (2011) with the results indicating the need of upgrading the extracted bio-oil produced prior to biofuel production. With respect to other thermochemical processes, gasification process is relatively newer from commercial stand point view; however, it is lately gaining attention due to the biofuel produced by it needs no modification and the technology can produce bio-oil and bio-gas from diverse feedstocks; increasing the prospects of high process control and development of innovative conversion framework (Sikarwar, Vineet Singh, 2017). Additionally, due to high water content in algae biomass, gasification and liquefaction offer a fast tract conversion pathway to others technologies (Duman, et al., 2014). According to a study conducted by Yeh et al. (2012), it revealed gasification and liquefaction as useful routes in bio-oil and biogas (CH<sub>4</sub> and H<sub>2</sub>) productions; although the energy requirement for gasification is higher than liquefaction process. However in both processes, the high salt contents in algae biomass lead to corrosion and blockage.

Gasification converts solids biomass into high calorific values products, it is the partial burning of feedstock to in air or steam to produce synthetic gas (CO, H<sub>2</sub>, CO<sub>2</sub> and CH<sub>4</sub>) at high temperature (1100 – 1300 K)---(Higman, 2003; Speight, 2010; Sikarwar, 2017). The synthetic gas is colourless, odourless and can be used in gas engines due to its low calorific value (4-6 MJm<sup>-3</sup>) (Speight, 2010). The biomass undergo two distinct transformations: at temperature range of 300 – 500 K the biomass becomes dried, at 600 K thermal cracking occurs with the release of volatiles matters called char, this transformation is termed pyrolysis and gasification occurs at 1000 -1600 K where charcoal residue reacts with steam or air to produce syngas gas (Mermoud et al., 2018).

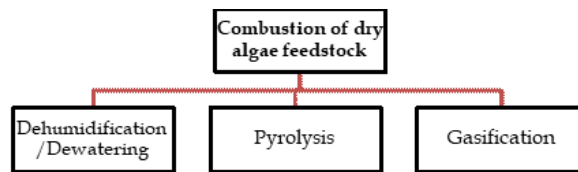
## **Materials and Method**

### **Materials**

The research used numerical simulations utilizing: Matlab, Microsoft excel and Solid Works programs to explore numerical values gotten from mathematical computations.

## Method

The method examined gasification through an indirectly heated gasifier (where heat is externally generated and delivered through a heat transfer media) as illustrated in Figure 1. The heat generated is from the thermal combustion of dry microalgae feedstock rather than fossil fuel thus making the research solely on renewable energy infrastructure. The energy conversion undergoes three main endothermic stages namely: dehumidification, pyrolysis and gasification as illustrated in Figure 1 with computational analysis performed between moisture contents of 10 to 50%.

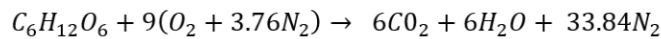


**Figure 1:** Three main Energy Pathway

## Microalgae Combustion

Combustion and gasification are two closely related thermochemical processes with little differences. Combustion converts feeds into gases, but these gases ( $\text{CO}_2$ ,  $\text{H}_2\text{O}$ ) cannot be further burned to generate energy while the latter gases can be further burned to produce energy ( $\text{CO}$  and  $\text{H}_2$ ) (Worley et al., 2012).

## Microalgae Stoichiometric Reaction



Where:

$\text{C}_6\text{H}_{12}\text{O}_6$  is the generic molecular formula of microalgae  
 $9(\text{O}_2 + 3.72\text{N}_2)$  is stoichiometric air composition

From reaction 1 above, one mole of biomass (fuel) takes 9 moles of oxidizer to completely burn all the carbon and hydrogen in a mole of dry feedstock to produce carbon dioxide and steam respectively assuming complete combustion.

**Enthalpy of Reaction and Heat of Combustion(2)** At standard state temperature and pressure conditions ( $25^\circ\text{C}$ , 1 atm), the amount of heat generated per mole of dry feedstock was calculated using steady flow equation as seen in equation 2

$$\Delta H_R = H_{\text{product}} - H_{\text{reactant}}$$

$$H_{\text{product}} = \sum N_i h_i \quad \text{also} \quad H_{\text{reactant}} = \sum N_i h_i \quad (2)$$

Combustion of a kilogram of dry algae feedstock yields  $\Delta H = -14.1$  MJ/kg. The negative sign indicates the reaction is exothermic (heat is released).

### High and Low Heating Value of Algae Feedstock

The heating values (HHV and LHV) are important indicators used to know the quality of the fuel (feedstock) when deciding on what type of gasifier to use---(Higman, 2003).

*High Heating Value (HHV)*

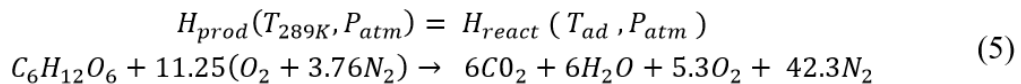
$$\Delta H_{C_{waterL}} = HHV = 1\bar{h}_{f_{C_6H_{12}O_6}} - [6\bar{h}_{f_{CO_2}} + 6\bar{h}_{f_{H_2O L}}] \quad (3)$$

*Lower Heating Value (LHV)*

$$LHV = 1\bar{h}_{f_{C_6H_{12}O_6}} - [6\bar{h}_{f_{CO_2}} + 6\bar{h}_{f_{H_2O g}}] \quad (4)$$

### Adiabatic Flame Temperature

Adiabatic flame temperature is the temperature at which product gas exits the combustor at standard temperature and pressure with 25% excess air.



### Dehumidification/Dewatering

Microalgae biomass is made up of large quantity of water which needs to be evaporated prior to thermal conversion. Dewatering analysis done at temperature range of 25°C - 200°C using equations 6-9.

*Phase 1*

Heating water from 25 to 100°C

$$Q_1 = M\bar{C}_p\Delta T \quad (6)$$

Where

$$\bar{C}_p = \frac{C_{p_{water}} \times M_2 + C_{p_{dryfeedstock}} \times M_1}{M_1 + M_2}$$

*Phase 2*

Boling of water at constant temperature

$$Q_2 = M_{water} \times h_{fg} \quad (7)$$

*Phase 3*

Heating of wet feedstock and steam from 100 °C to 200°C,

$$Q_3 = M\bar{C}_p\Delta T \quad (KJ/Kg) \quad (8)$$

Average specific heat value ( $C_p$ ) involved steam and wet feedstock.

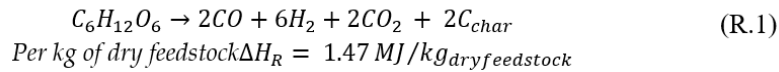
$$\bar{C}_p = \frac{C_{p_{steam}} \times M_2 + C_{p_{dryfeedstock}} \times M_1}{M_1 + M_2}$$

$$Q_{Dewat.} = Q_1 + Q_2 + Q_3$$

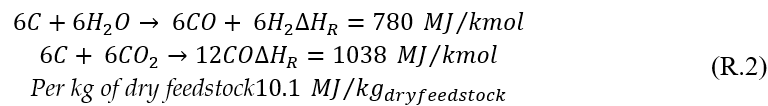
Where  $C_{p_{steam}} = 2.02 \text{ KJ/kg.K}$ ,  $M_1 = \text{mass of dry feedstock (kg)}$ ,  $M_2 = \text{mass of water (kg)}$   $C_{p_{water}} = 4.02 \text{ KJ/kg.K}$ ,  $C_{p_{dryfeedstock}} = 0.6$  (9)

$$h_{fg} = 2258 \text{ KJ/kg (latent heat of vap at 1 atm)}$$

**Pyrolysis of Algae Biomass(R.1)** Pyrolysis of algae is an endothermic process with heat supplied from an energy source. The energy requirement for this process to drive through is explained in reaction (R1).



**Microalgae Gasification(R.2)** This is an endothermic process. Thermal conversion of algae biomass through gasification process is governed by two key reactions and the energy required is 10.1 MJ/kg



## Results and Discussion

### Combustion Values

Values from the combustion of microalgae fuel when compared with a conventional fossil fuel (methane) are presented in Table 1. It was observed that due to the presence of oxygen in algae feedstock its combustion value is higher than that of methane (fossil fuel), additionally, the complex molecular structure of algae biomass also account for the high intake of intake of oxygen in the stoichiometric process (equation1). Also, nitrogen formed in the combustion of algae is higher than that formed in the combustion of methane fuel. This increase is due to high oxygen intake by algae biomass during combustion.

**Table 1:** Heat of Reaction and Nitrogen formed at STP

Formula	Fuel	Heat of reaction (exothermic) (MJ/Kmol)	Amount of ( $N_2$ ) formed (mole)
$C_6H_{12}O_6$	Algae	2540	33.84
$CH_4$ (Fossil fuel)	Methane	802	8

### Heating Values and Flame Temperature

The high and low heating values of algae with generic structure of carbon, hydrogen and oxygen were compared against methane fuel with result presented in Table 2. The values of higher heating value (HHV) and lower heating value (LHV) of methane were observed to be about three (3) times higher that of microalgae. These values suggest that microalgae biomass can suitably be used as fuel source in algae gasification.

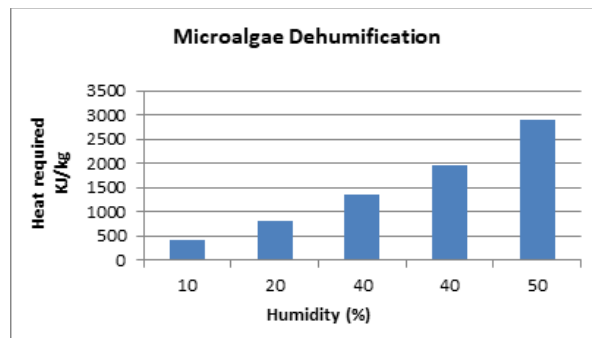
**Table 2. High and Low Heating Values**

Fuel	Molecular Weight (kg/kmol)	HHV (KJ/kg)	LHV (KJ/kg)	Flame Temperature (K)
Microalgae	180.1	22,640	21,161	2458 (at stoichiometry) 1444 (25% excess air)
Methane	16.043	55,528	50,016	2226

Also, as seen in Table 2, at stoichiometric conditions, the adiabatic temperature (exist temperature) of microalgae is 10.4% higher than methane fuel. This rise in flame temperature is due to insufficient nitrogen content in the combustion product which acts as a heat absorber to reduce the flame temperature and lowers NO<sub>x</sub> formation. With 25% increase in oxidizer (air) the flame temperature reduced to 1444K. This reduction is due to increase in oxygen which produces more nitrogen and oxygen in the product to sufficiently absorb heat and lower the flame temperature.

**Dehumidification**

Wet microalgae feedstock was analyzed between 10 to 50 % moisture content and heat required for drying at each moisture level is illustrated in Figure 2.



**Figure2:** Microalgae Dehumidification at Varying Humidity

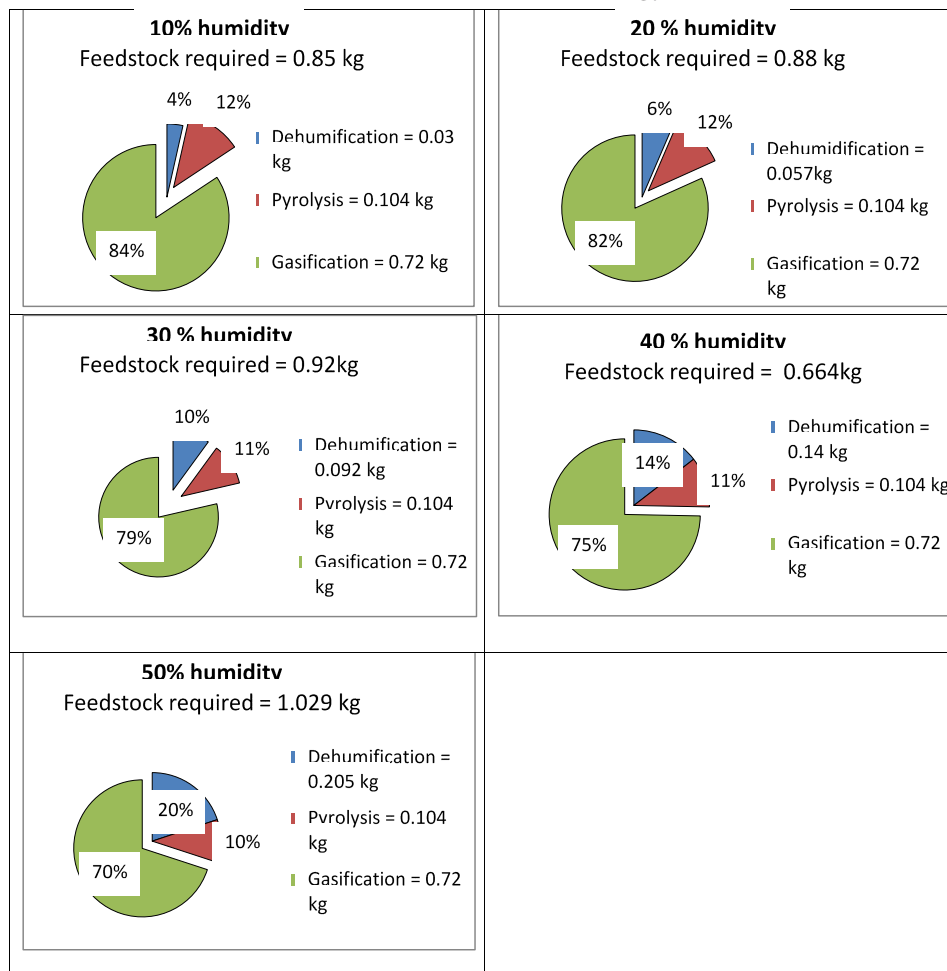
As expected, the amount of heat required to dry wet feedstock containing water increases with increase in water content. The increasing heat demand which makes the drying process capital intensive, according to research by Speight, (2014) it stated that for optimum gasification moisture contents should be between 12 and 15%. Gasification using dried feedstock increases operation efficiency reduces costs of maintenance and improves the quality of product gas. However, this practice comes with an increase in expenditures due to pre-processing of feedstock prior to pyrolysis and gasification

**Amount of Algae Feedstock Required To Produce Heat**

The quantity of microalgae required to produce heat for microalgae gasification at 10 -50 % humidity is shown in figure 3. Results of calculations carried out from thermodynamic view point to estimate just how much dry feedstock is required to be burned (combustion)

to produce sufficient heat energy needed for three main processes (drying, pyrolysis, gasification) are illustrated in figure 3. From figure 3, gasification and pyrolysis have fixed demands values (because these stages contain no water moisture in them) while dehumidification values increase. As expected, the amount of feedstock for dehumidification increases as the water content increases with an average of 4% rise between 10, 20, 30, 40 and 50% humidity levels.

**Figure3:** Amount of Feedstock Required to Produce Energy

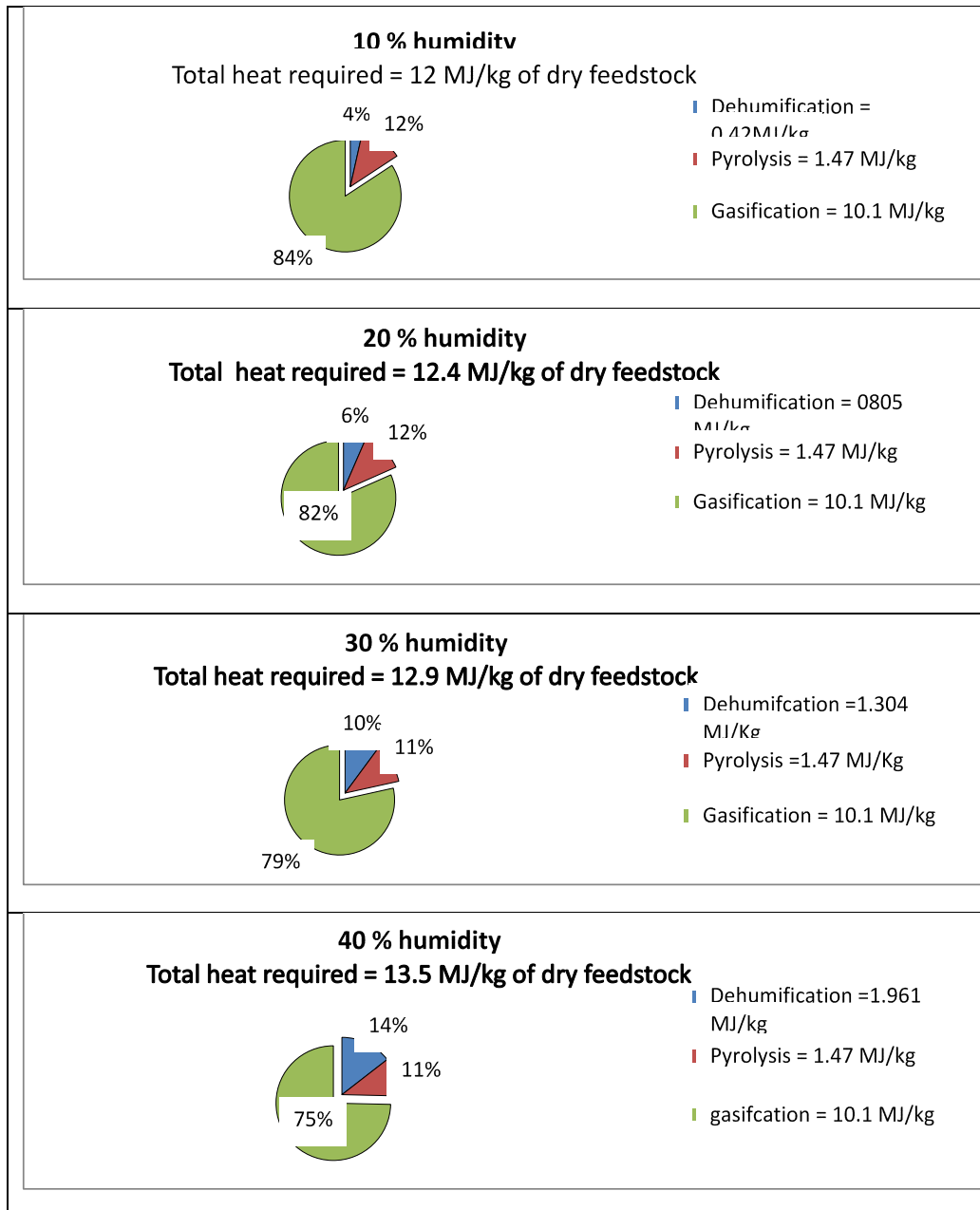


### Heat Distribution at Varying Humidity Levels

Expectedly, the heat generated by combusting a mole of dry feedstock (Eqn. 2) should be sufficient to provide energy demand to the three heat sinks (dehumidification, pyrolysis, gasification) processes (Figure 4). Heat required for gasification and pyrolysis are fixed at 14.1 MJ/kg and 10.1 MJ/kg respectively (R.1 and R.2) because at these stages no water is trapped. About 50% increase in energy demand was observed from 30 to 50 % humidity level. This indicated that the sensible enthalpy (latent heat) of steam was further used in boiling un-evaporated water. Additionally, a 21% heat increase was recorded between

the highest and lowest moisture contents. This increment signals increase in capital cost of energy generation for gasification with increase in complexity of design of gasifiers due to high energy demand.

**Figure 4:** Heat Distribution to Dehumidification, Gasification and Pyrolysis





## Conclusions

The energy analysis of microalgae combustion indicates that the process requires high amount of heat from energy source (combustion). Although, algae biomass retains considerable moisture content, the drying process is the most energy consuming process with considerably high energy demand at higher moisture levels. Despite having moisture, the lower values of HHV and LHV (22MJ/kg and 21MJ/kg) when compared to that of Fossil fuels (methane 55MJ/kg) suggests microalgae biomass to be a suitable fuel feedstock in synthetic gas production. Knowing the amount of fuel (feedstock) required to produce the needed energy provides a useful tool in towards increasing the conversion efficiency and provides a template towards understanding the energy demand profile in an algae gasification process.

## Recommendation

Research on the viability of integrating a solar dryer to the gasification process should be explored as solar drying can adequately dewater wet microalgae biomass and reduce the total energy demand.

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