ENERGY AND EXERGY ANALYSES OF A MICROALGAE SOLAR DRYER FOR BIODIESEL PRODUCTION

Eunice A. Doblada[1a], Aristotle T. Ubando[1b,2], Alvin B. Culaba[1c,2]
[1]Mechanical Engineering Department, DLSU-Manila
[2]Center for Engineering and Sustainable Development Research (CESDR), DLSU-Manila
[a]eundoblada@gmail.com
[b]aristotle.ubando@dlsu.edu.ph
[c]alvin.culaba@dlsu.edu.ph

Abstract: Biodiesel from microalgae is garnering immense attention from different sectors worldwide due to the high oil yield per unit area produced compared to other conventional biomass feedstock. However, one of the challenges in commercialization of biodiesel from microalgae is the high energy requirement of the drying process which constitutes to about 59.3% of the total energy consumption of the whole production of biodiesel. In order to reduce the energy consumption, solar energy can be utilized to dry the microalgae into its required moisture content thru the use of solar dryers. Solar dryers are enclosed systems that are usually composed of a solar heater, drying chamber and an airflow system. To date, only a small number of studies focused on solar dryers for microalgae. However, the resulting drying efficiencies are low, but managed to achieve the required moisture content of less than 10% within 5 hours. To evaluate and optimize the performance of solar dryers, this paper presents energy and exergy analyses of a microalgae solar dryer. Using an experimental study, the results showed low energy and exergy efficiencies for the solar dryer with maximum values of 1.5% and 28%, respectively, which could be attributed to the small sampling size used in the experiment, high inlet temperature of the drying air and high humidity ratio of air inside the drying chamber.

Key Words: Microalgae; Solar Dryer; Exergy Analysis; Energy Analysis;

1. INTRODUCTION

Microalgae are single-cell photosynthetic microorganisms, with size ranges from from 1 to 20 microns (Lam and Lee, 2012). They contain high amount of lipids that are used for biodiesel production. Seventy percent (70 %) of the lipids consists of triglyceride (TAG); the oil that is essential for transesterification. In comparison, high amount of biodiesel can be generated from microalgae per annum than from any other plant feedstock (Lam and Lee, 2012).

The production of biodiesel from microalgae consists of several processes, namely cultivation, harvesting, dewatering, drying, lipid extraction and transesterification. In the cultivation process, CO_2, light and nutrients are applied on the system for the microalgae to grow until such time that they have reached the stationary growth phase and ready for harvesting. These harvested microalgae will be dewatered to about 12-35% dry basis at which point, the microalgae will no longer behave as liquid and then can be easily handled either manually or mechanically. Then, the microalgal biomass will be dried to the recommended moisture content of less than 10% to improve the lipid extraction efficiency and prevent the formation of water-oil emulsions during oil extraction process (Becker, 1994).

Based on Yanfen's et al. (2012) life cycle assessment (LCA) of microalgal biodiesel, the drying process for the recovery of microalgal biomass constituted 59.3% of the total energy input in the biofuel production, which led to negative energy balance in the whole production process. To reduce the required energy input for the production of biodiesel for its viability, solar drying is proposed.

Solar dryers are composed of 3 components, as shown in Figure 1: (1) the drying chamber where the product is dried; (2) the solar collector which heats the air; and (3) type of air flow system, either natural or forced convection. They can be classified according to the way they absorb energy from the sun – either direct, indirect or mixed-mode.

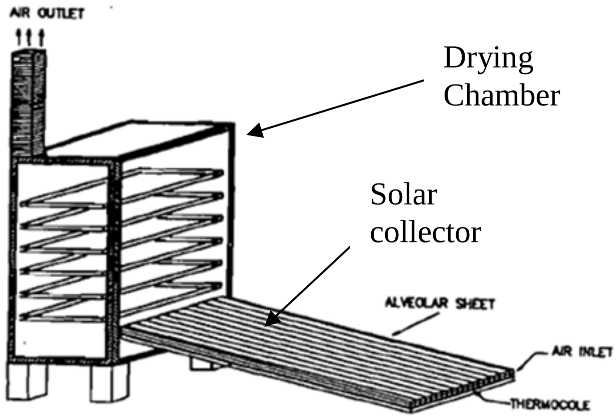

Figure 1. Solar Dryer for Microalgae (Prakash et al., 1997)

There were several studies that discussed solar dryers used for microalgae drying. For instance, Becker (1994) studied a design of a solar dryer used for *Spirulina sp*. which consisted of inner and outer boxes, separated by an insulation. Vent holes were drilled on the box to induce air flow and stretch-on-top 2-layered polythene film was placed as cover. However, the performance of the dryer was not disclosed. Prakash et al. (1997), on the other hand, used a mixed-mode, double pass, cabinet-type solar dryer to study the drying of microalgae *Scenedesmus* and *Spirulina*. Lopez (2011) based the design of his solar dryer on Prakash et al. (1997) to dry microalgae *Tetraselmis sp.* Even though, he used a single-pass solar heater instead of double-pass one (Prakash et al., 1997), the time it took for the microalgae to dry within the recommended 10% moisture content or less were both achieved within 5 hours. Lopez (2011) noted that the evaporative capacity of his solar dryer was 49% while its energy efficiency was 2.5%.

In evaluating the performance of a solar dryer, several studies gave emphasis on the importance of exergy and energy analyses as means of optimization. These analyses are governed by the 1st and 2nd laws of Thermodynamics. The 1st law deals with the quantity of energy on the system (how much is available and used) and constitute the energy analysis portion. On the other hand, the 2nd law, which comprises the exergy portion, deals with the quality of energy within the system and concerns with degradation of energy during a process, the entropy generation, and the lost opportunities to do work (Cengel and Boles, 2006). Dincer (2011) defined exergy as a measure of potential of a flow to cause change, as a consequence of not being in complete equilibrium relative to the reference environment. Exergy analysis is used to assess the efficient usage of solar energy.

This study focuses in the energy and exergy analyses of a mixed-mode solar dryer for microalgae biomass production. The next section discusses the governing equation of the energy and exergy analysis for this study.

2. ENERGY AND EXERGY ANALYSES

This section consists of the governing equations involve in doing energy and exergy analyses of a solar dryer.The energy analysis determines the how much of the energy absorb by the solar heater is actually used in drying, by calculating the energy gained by the air in the collector and comparing it to the energy lost by the air in the drying chamber. The exergy analysis determines how much of the energy from the solar heater is actually available for useful work and how much is wasted by computing the exergy at the inlet and oultlet of the drying chamber using the ambient conditions as reference. The lower the exergy difference between these values indicates higher exergy efficiency.

2.1 Energy Analysis: 1st and 2nd Laws of Thermodynamics

Solar drying is assumed as a steady-state process and the useful energy received by the solar collector can be determined through the relationship:

$$q_{col} = c_{p_{da}} (T_{da} - T_{ambient}) \qquad (Eq. 1)$$

where:

q_{col} = energy received by the solar collector, kJ/kg dry air
c_{pda} = specific heat of air, kJ/kg-K
T_{da} = temperature of drying air at the exit of the solar collector, ^{O}K

The energy utilization of the drying chamber (dc) is calculated by:

$$q_{dc} = h_{in} - h_{out} \qquad (Eq. 2)$$

where:

q_{dc} = energy utilization in the drying chamber, kJ/kg dry air
h_{in} = specific enthalpy of air entering the drying chamber, kJ/kg dry air
h_{out} = specific enthalpy of air leaving the drying chamber, kJ/kg dry air

Therefore, the energy utilization ratio (EUR) can be taken as:

$$EUR = \frac{q_{dc}}{q_{col}} \qquad (Eq. 3)$$

2.2 Exergy Analysis: 2nd Law of Thermodynamics

Exergy analysis is a tool to assess the efficient usage of solar energy as it enables to determine the location, types and magnitudes of waste emissions and internal losses. It indicates whether or not and by how much it is possible to design more efficient thermal systems by reducing inefficiencies (Dincer, 2011).

Exergy can be determined through the formula (Midilli and Kucuk, 2003):

$$Exergy_n = \bar{c}_p \left[(T_n - T_0) - T_0 \ln\left(\frac{T_n}{T_0}\right) \right] \qquad (Eq. 4)$$

where:

$\bar{c}_p$	=	average specific heat of drying air, kJ/kg-K
T_0	=	ambient temperature. ^{O}K
T_n	=	temperature at *n* location, ^{O}K

To determine the inflow and outflow exergy in the drying chamber, use the formula as specified above *(Eq. 4)*. The exergy loss can be calculated using *Eq. 5* below:

$$Exergy_{loss} = Exergy_{inflow} - Exergy_{outflow} \qquad (Eq. 5)$$

Now, the exergetic efficiency can be computed as (Cengel and Boles, 2006):

$$\eta_{ex} = \frac{Exergy\ outflow}{Exergy\ inflow} = 1 - \frac{Exergy\ Loss}{Exergy\ inflow} \qquad (Eq. 6)$$

3. RESULTS AND DISCUSSION

In drying the microalgae, Prakash et al. (1997) and Lopez (2011) used a mixed-mode, cabinet-type dryer as shown in Figures 1 and 2, which had both successfully reduced the water content of microalgae to 5% or less after 5 hours.

For the evaluation of the solar dryer for microalgae, the experimental results of Lopez (2011) was used in the equations shown in Section 2. The enthalpies corresponding to the dry-bulb and wet-bulb temperatures at specified locations were computed using thermodynamic formulas associated in air-conditioning.

Figure 2. Solar Dryer for Microalgae (Lopez, 2011)

In the energy analysis, it could be seen that values of Energy Utilization Ratio (EUR) range from 0.35% to 1.50% which were near with the computed value of 2.5% energy efficiency by Lopez (2011). These values indicated that large amount of energy was still available from the exit air as seen in Figure 3 and had not been used in the drying process. One reason for this unused energy could be attributed to the smaller sampling size of microalgae used during experiment than what the dryer was designed for, which now affected the amount of heat that was given off by the air during drying. Utilization of this energy must be considered when redesigning solar dryer for microalgae.

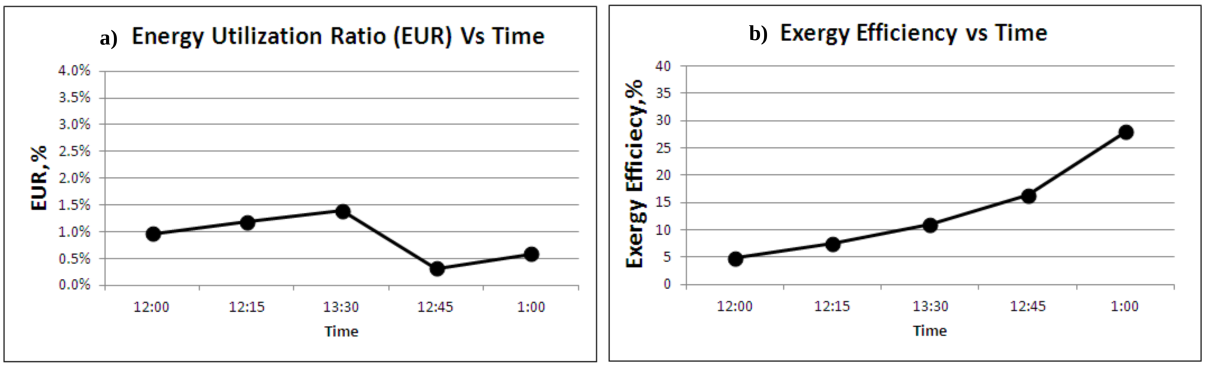

Figure 3. Calculated a) EUR vs Time and b) Exergy Efficiency vs Time (data taken from Lopez, 2011).

In the exergy analysis, the values ranged from 5% to 28%. This means that more than 70% of the work potential was wasted. Low exergy efficiencies are attributed to the small sampling size of microalgae, high inlet temperature of drying air, high velocity for inlet air, high humidity ratio of drying air and low initial moisture content of product (Dincer, 2011). As mentioned, the sampling size used in the experiment, which was smaller than the required size based on the design of the dryer, contributed to the low exergy efficiency. The effect of high inlet temperature for the drying air was evident from the graph shown in Figure 3.b wherein the lowest exergy efficiency could be found at noon when the ambient temperature was at its highest.

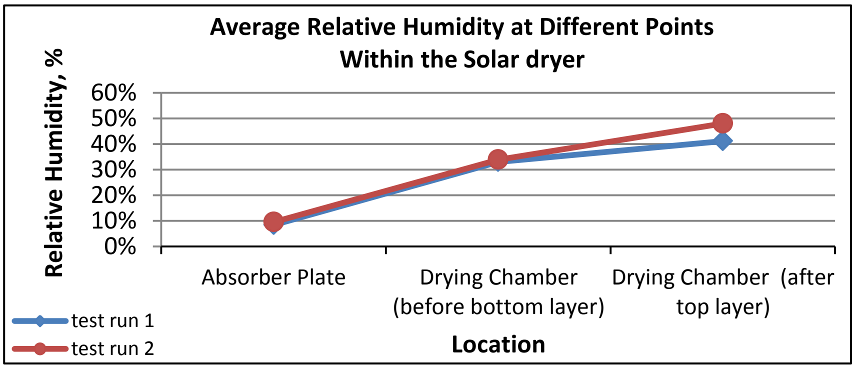

Figure 4. Average RH within the Dryer from Lopez's (2011) Data

Based on the temperature readings from the experimental results (Lopez, 2011), the designed solar heater was capable to decrease the relative humidity (RH) of air to below 10%. The relative humidity reflects the quantity of moisture that the air can absorb – the lower the value of RH, the higher the amount of moisture that it can take in. However, upon entering the drying chamber, there was an abrupt increase in values of RH as seen Figure 4, before it passed the microalgae at the bottom layer, from an average RH of 10% at the exit of solar heater to an average RH of 33% just beyond the inlet of the drying chamber, which lowered the amount of moisture the air could carry. Minimizing this surge in RH increases the exergy efficiency, as one of the reason for low exergy efficiency is the high humidity ratio or relative humidity of the drying air.

4. CONCLUSIONS

In conclusion, low values of energy and exergy efficiencies were observed in the solar dryer for microalgae drying. These values indicate that there is an available energy and work potential that can still be utilized in the system. Finding the sources of this irreversibility, and addressing them, can maximize the work potential of the dryer while minimizing the wasted heat. Sources of low exergy efficiencies of the considered solar dryer can be attributed to the low sampling size, high inlet temperature of drying air and high humidity ratio of air inside the chamber.

5. ACKNOWLEDGEMENT

The main author would like to express her gratitude to the ERDT Scholarship Program Committee for the opportunities and support to make this research paper possible.

6. REFERENCES

Becker, E. W. (1994). *Microalgae: Biotechnology and Microbiology*. In Carey NH, Higgins IJ, Potter WG (eds) Sir J Baddiley, Cambridge University Press: United Kingdom.

Cengel Y. A. & Boles M. A. (2006). *Thermodynamics: An engineering approach*, 5th ed. McGraw-Hill: New York.

Dincer, I. (2011). Exergy as a potential tool for sustainable drying systems. *Sustainable Cities and Society, 1*, pp. 91- 96.

Lam, M. K., & Lee, K. T. (2012). Microalgae biofuels: A critical review of issues, problems and the way forward. *Biotechnology Advances, 30*, pp. 673-690.

Lopez, N.S.A. (2011). *Energy modeling, fabrication and evaluation of a small-scale natural convection solar dryer for microalgae biofuel production*. M. Eng. thesis, De La Salle University, Manila, Philippines, December 2011.

Midilli A, Kucuk H., "Energy and exergy analyses of solar drying process of pistachio", *Energy, 28*, pp. 539-56, 2003.

Prakash, J., Pushparaj, B., Carlozzi, P., Torzillo, G., Montaini, E. and Materassi, R. (1997). Microalgal biomass drying by a simple solar device. *International Journal of Sustainable Energy*, *18*(4), pp. 303 - 311.

Yanfen, L., Zehao, H., & Xiaoqian, M. (2012). Energy analysis and environmental impacts of microalgal biodiesel in China. *Energy Policy*, *45*, pp. 142-151.