Energy and exergy evaluation of an onshore solar dryer for seaweeds

A Culaba*, A H Atienza¹, A Ubando¹, A Mayol¹ and J Cuello²

¹ Mechanical Engineering Department, De La Salle University Manila, Philippines
² Department of Agricultural and Biosystems Engineering, University of Arizona

*alvin.culaba@dlsu.edu.ph

Abstract. The possible sources of the energy losses in the drying systems can occur in the drying chamber and solar collector. The energy from these parts were not properly utilized so it is evident to further search for improvements. Energy and exergy analyses were being used to identify the possible source of inefficiencies quantitatively and qualitatively in the drying system and aid in recommendation for its improvement. This study aimed to evaluate the performance of an onshore drying system for seaweeds by conducting energy and exergy analyses. It has shown that the dryer efficiency was 33.58% and its solar collector efficiency was 68%. The exergy efficiency was obtained as 41.38% relates to an exergy improvement potential of 256.30 W. It is recommended to perform partial to full exhaust air recirculation and provide thermal storage may boost the exergy efficiency hence minimizing energy losses in the drying system.

1. Introduction

A solar dryer is composed of two major parts namely the solar collector and the drying chamber. The solar collector gathers energy from the sun in the form of solar radiation. This energy is used in heating the moist air that enters the pipes of the solar collector. The air comes from a fan or air blower to force in air into the solar collector. Heated air exits the solar collector and eventually enters the drying chamber. However, energy losses occur due to convection and evaporation inside the drying chamber [1]. In the case of the solar collector, the incident solar radiation strikes the surface of the glass cover of the collector. Around 10% of the radiation is reflected, 5% absorbed the glass cover and 85% transmitted to the piping. Approximately 5% of the reflected radiation is still present in the pipings and 80% of the heat is collected by the absorber plate. Heat loss on the absorber plate is estimated to be 35%. The collector only utilizes 45% of the incident solar radiation [2]. Due to the losses from the drying chamber and solar collector it is necessary to improve the drying system. One of the important concepts that must be focused to lessen energy losses is analyzing exergy. Exergy is a property that measures the potential for use of energy. It is considered as the maximum theoretical work of the system in equilibrium with the environment and is destroyed in the process due certain irreversibilities [3]. Conducting an exergy analysis on the drying system can help pinpoint sources of inefficiencies and can provide possible improvement in the system [4]. Few literatures discuss exergy and energy analyses in seaweed drying. The study of [5] focuses mainly on energy and exergy analysis of a forced convection indirect type drying system for red seaweeds. The study has shown that the average solar, dryer and exergy efficiencies are 35%, 27% and 30%, respectively. A 247 W average exergy improvement potential was
obtained. For this study, a forced convection indirect type dryer will also be employed, however the air distribution system has different configuration. This study also mainly focuses on the exergy and energy analyses of the onshore solar dryer for Eucheuma cottonii seaweeds. From the data obtained from the analyses, this also highlights the possible improvements that can be implemented to increase productivity and efficiency of the onshore solar dryer.

2. Materials and Methods

2.1. Onshore solar dryer

The onshore solar dryer as seen in Figure 1 consists of a solar collector and drying chamber. The drying chamber is 1.20m x 0.92m x 0.62m length, width, and height, respectively. Its body frame is composed of 1.5mm thick 1” x 1” square tube. The trays made up of stainless-steel expanded sheets with 1” x 1” x 1/8” angle bars serve as support. The materials for the walls of the drying chamber are galvanized steel gauge 20 for the inner and outer walls, and polyurethane insulation aluminized in between. The trays made up of stainless-steel expanded sheets with 1” x 1” x 1/8” angle bars serve as support. The air distribution system in the dryer is modified. It consists of a ¾” copper pipe works as a main pipe connected to ½” copper distribution pipes. The main pipe is connected to the solar collector. The solar collector has serpentine piping configuration made up of ¾” copper tube with aperture area of the solar is 0.43m². The absorber plate is made up of matte black aluminum and the insulation is composed of polyurethane foam aluminized. The cover of the solar collector is acrylic glass.

![Figure 1. The onshore solar dryer](image)

2.1.1. Operation of the Onshore Solar Dryer

The dryer can be classified as an indirect solar forced convection type where it consists of a solar collector that heats up incoming air going to the drying chamber. The air is brought in by the forced circulation of the blower. The air then circulates into the main pipe branching to the distribution pipes that delivers the flow to the tray locations until it goes out of the exhaust pipes.

2.2. Experimental Procedure

The seaweed drying experiment set-up involves the installation of instrumentations, fine tuning and testing proper. Load cell-based weighing scales, Arduino Uno Software, temperature sensors, pyranometer and digital anemometer were used for data gathering. For the first phase of the seaweed drying experiment, the initial moisture content of the seaweeds is to be determined. Placing 100 grams of seaweeds in aluminum foils and brought into the microwave oven with temperature setting at 105°C based. The aluminum foil is pulled every 10 minutes to observe and record the mass reduction of the
seaweeds. Three same successive mass readings can safely assume that the seaweeds are totally dried. The initial moisture content of the seaweeds is obtained using the formula below:

\[ \text{Initial Moisture Content} = \frac{m_i - m_f}{m_i} \times 100\% \]  

(1)

The experiment started from 8am-5pm but to provide accurate reading the 800 W blower was turned on 30 minutes prior to data gathering for forced air circulation into the drying chamber. One kilogram of *Eucheuma cottonii* seaweeds was placed per tray location. The moisture content reduction of seaweeds per tray location was monitored and the target final moisture content is 40% [6]. The temperatures for the drying system and solar irradiance were monitored.

2.3. **Energy Analysis**

The collector efficiency \( \eta_{SC} \) is described as the ratio of the useful heat transfer \( Q_u \) of the collector and the incident solar energy over a time. The incident solar energy is the product of solar irradiance \( S \) and solar collector area \( A_{SC} \)

\[ \eta_{SC} = \frac{Q_u}{S A_{SC}} \]  

(1)

Since the useful heat transfer \( Q_u = \dot{m} C_p (T_{outlet} - T_{inlet}) \), the solar collector efficiency formula in (1) can be modified with equation in (2) resulting to

\[ \eta_{SC} = \frac{\dot{m} C_p (T_{outlet} - T_{inlet})}{S A_{SC}} \]  

(2)

\( \dot{m} \) is the air mass flow rate, \( C_p \) is the specific heat at constant pressure of air while \( T_{outlet} \) and \( T_{inlet} \) are the outlet and inlet solar collector temperatures, respectively. This study will use (2) based on the study of [5].

Below are the set of equations that will serve as performance parameters in the dryer energy analysis used by [5].

The dryer efficiency is described by the formula

Dryer efficiency

\[ \eta_{dryer} = \frac{M L}{(A_S + P_{blower}) t} \]  

(3)

Mass of water evaporated, \( M \) in kg:

\[ M = m (M_o - M_f) \frac{100}{100 - M_f} \]  

(4)

\( m \) is the mass of the seaweeds, \( M_o = \) initial moisture content of the seaweeds, \( M_f = \) final moisture content of the seaweeds, \( L \) is the latent heat of vaporization of water at an exit air temperature in J/kg, \( P_{blower} \) is the power input of the blower in W and \( t \) = time in seconds

2.4 **Exergy Analysis**

The exergy analysis under steady state of the dryer from the study of [5] is composed of the exergy inflow, outflow, and losses from the drying chamber and described by the following formulas.

For exergy inflow in the dryer,

\[ E_{x dryer, i} = \dot{m} C_p \left[ T_{i, dryer} - T_{amb} - T_{amb} \ln \frac{T_{i, dryer}}{T_{amb}} \right] \]  

(5)

For exergy outflow in the dryer,

\[ E_{x dryer, o} = \dot{m} C_p \left[ T_{o, dryer} - T_{amb} - T_{amb} \ln \frac{T_{o, dryer}}{T_{amb}} \right] \]  

(6)

\( \dot{m} \) is the mass flow rate of air, \( C_p \) is the specific heat at constant pressure, \( T_{i, dryer} \) and \( T_{o, dryer} \) are the inlet temperature and outlet temperatures of the dryer, respectively, finally \( T_{amb} \) is the ambient temperature.

For the exergy losses in the dryer, this would be the difference of exergy inflow and outflow

\[ E_{x losses} = E_{x dryer, i} - E_{x dryer, o} \]  

(7)

The exergy efficiency of the dryer is expressed as the ratio of the exergy outflow to inflow as expressed by [5, 7] below.
\[ \eta_{Ex} = \frac{E_{Ex, dryer,o}}{E_{Ex, dryer,i}} = 1 - \frac{E_{losses}}{E_{Ex, dryer,i}} \] (8)

It is highly necessary to include in the exergy analysis of a system the exergy improvement potential. The exergy improvement potential, EIP, of a system pertains to the maximum improvement on the exergy of the system and can be achieved if the exergy losses were reduced [5, 8]. The formula for exergy improvement potential is provided by the equation
\[ EIP = (1 - \eta_{Ex})E_{losses} \] (9)

3. Results and Discussion

3.1 Seaweeds
The initial moisture content was determined to be 89.8% in 5 hours and 19 minutes to reach 40% moisture content. The velocity of air into the drying chamber is about 12.5 m/s. It is found out that top tray has reduced the maximum moisture content of the seaweeds in a drying rate of 1.384 g/min while the lowest rate of 1.126 g/min was observed in the bottom tray as seen in Figure 2. The increase in the moisture reduction in the top tray is caused by the hot air flow circulation which is maintained at the top due to the chimney effect [9].

![Figure 2: Moisture Content per Tray locations](image-url)

3.2. Solar Collector
The trend in inlet and outlet temperatures have been monitored and shown in Figure 3. It can be observed that the peak solar inlet and outlet temperatures were 41.54°C and 51.30°C, respectively. These temperatures both occurred at 12nn with solar irradiance of 465W/m². The outer temperature is observed to be higher compared to the inlet due to heat transferred from the serpentine tubes into the air [10]. This result agrees with study of [11].
In reference to the time of day, the highest average efficiency went as high as 68% at a solar irradiance of 427.72 W/m² as seen in Figure 4. The average solar collector efficiency is 43.40% at an average solar irradiance of 351.20 W/m². The value of solar collector efficiency is higher compared to the results of [5] and [12] due to the turbulent flow provided by the serpentine configuration.

The outlet and inlet temperatures were monitored per time of day. It can be observed that the highest inlet temperature was 46.8°C at 12nn with 471.9 W/m² solar irradiance while the outlet temperature peaked to 51.3°C at 1pm corresponds to a solar irradiance of 473.3 W/m² as seen in Figure 5.

### 3.3. Dryer

The outlet and inlet temperatures were monitored per time of day. It can be observed that the highest inlet temperature was 46.8°C at 12nn with 471.9 W/m² solar irradiance while the outlet temperature peaked to 51.3°C at 1pm corresponds to a solar irradiance of 473.3 W/m² as seen in Figure 5.
The highest dryer efficiency was reached at 33.58% at 2pm. The lowest drying efficiency was observed as 27.08% at 9am 1 hour after the drying process started. The average dryer efficiency is 32.79% at an average solar irradiance of 351.20 W/m² shown in Figure 6. The value of the dryer efficiency is relatively high compared to the study of [5] and [12]. The sudden spike of the dryer efficiency from 9am to 10am is caused by less solar irradiance yielded since the experiment started thirty minutes before 8am, the heat is not that enough to increase its temperature.

3.4 Exergy Efficiency and Improvement Potential
Exergy analysis for the dryer has been carried out to determine the exergy inflow, out flow and losses. Figure 7 shows the exergy efficiency per time of day. The lowest observed value of 16.60% at 10am while the average exergy efficiency is 28.72%. The value of exergy efficiency is lower compared to 30% of Fudholi et al. (2014).
The improvement potential of the dryer as shown in Figure 8 has been obtained per time of day. The peak exergy improvement potential of 256.30W was observed at 10am. The lowest observed value of 225W was observed at 8am. The average exergy improvement potential is 350.03W. It is has higher exergy improvement potential compared to 247W of Fudholi et al. (2014). Introduction of partial to full recirculation of exhaust air can be implemented to increase the exergy efficiency and exergy potential of the solar dryer. This would increase the exergy efficiency by 33% to 58% as observed in the study of [13]. This is being supported by the study of [14] that states that energy savings can be increased up to 70% by recirculation of exhaust air. Also, providing thermal storage medium such as sodium sulfate decahydrate and sodium chloride will further increase the exergy efficiency by 29.3% [14,15].
4. Conclusion and Recommendation

The energy and exergy analyses were conducted in the onshore solar dryer. It is found out that the peak dryer efficiency was 33.58% and highest solar collector efficiency was 68%. The highest exergy efficiency was determined to be 41.38% that corresponds to an exergy improvement potential of 256.30 W. Future works would focus on further improvements that can be conducted in the onshore solar dryer such as partial to full exhaust air recirculation and provide thermal storage medium in the system.

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