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Application of Waste Heat Recovery Systems for Evaluating the Effectiveness and Electrical Energy Consumption Seaweed Convective Dryer

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Abstract

The research has practical implications for the design and operation of seaweed convective dryers, particularly in the context of energy conservation. Implementing a Waste Heat Recovery System (WHRS) to utilize waste heat from convective dryers that have been wasted into the environment is a promising development. This research aims to obtain the effective air velocity at which the effectiveness of the seaweed convective dryer is at its maximum and obtain drying time and minimum electrical energy consumption for operating conditions with and without the application of WHRS. The experimental method was carried out by varying the air velocity value from 1 to 5 m/s at certain temperatures, heat input, and humidity. Capturing and recording measured data after reaching steady conditions. The experimental results show that effectiveness decreases as air velocity increases, where the maximum effectiveness at minimum air velocity is 46.83% and 46.61% for operating conditions with and without WHRS implementation, where the average deviation value is 1.38%. On the other hand, drying time and minimum electrical energy consumption are at a maximum air velocity of 20.97 hr and 21.25 hr, respectively, and 19 kWh and 19.45 kWh for operating conditions with and without WHRS application, where the deviation of the average value in electrical energy consumption is 1.98%. It was concluded that the maximum air velocity can be used for convective drying of seaweed by applying WHRS, presenting a new and exciting approach to seaweed drying with significant potential benefits for energy conservation.

Keywords*:* *waste heat recovery system; convective dryer; seaweed; effectiveness; electrical energy consumption*

1. Introduction

A worldwide energy crisis caused by an increase in the need for energy consumption by industry and the general public (Mahmoudi et al., 2018). In addition, the ongoing conflict between Russia and Ukraine has caused an energy crisis that has a direct impact on energy costs (Johannesson & Clowes, 2022). Energy is required for several practical functions, including transportation (Cullen et al., 2021; García-Olivares et al., 2018; Gielen et al., 2019), mobility (Griffiths et al., 2021), food preparation (Chan et al., 2022), water purification (Alkhadra et al., 2022), communication (Krishnamoorthy et al., 2022) and others (Kalt et al., 2019).

The energy consumed currently is dominated by fossil energy at 66.4%, with details of the percentage of petroleum consumption at 40.8%, natural gas at 15.5%, and coal at 10.1% (Bimanatya & Widodo, 2018), where energy sources from fossil fuels are burned, producing waste heat that will have an impact on greenhouse gas emissions, which result in environmental problems such as global warming, climate change, acid rain, and ozone damage in the stratosphere (Moreira et al., 2016; Stramarkou et al., 2017; Uribe et al., 2020; Zamroni & Yamao, 2011).

Waste heat is energy produced by burning fuel or chemical reactions that are no longer utilized effectively (Abraham et al., 2020; Lion et al., 2017; Masud et al., 2017). The waste heat recovery approach can be converted into other proper forms of energy without additional electrical energy (Hoang, 2018) and is considered an effective measure for a sustainable, environmentally friendly development mode in various industries (Wang et al., 2018). Facts show that more than 50% of the energy used is wasted as waste heat that can be used as an energy source (Joardder & Masud, 2019; Mahmoudi et al., 2018). One energy conversion technology for waste heat recovery uses a heat exchanger (Abraham et al., 2020). Waste heat is categorized as quality heat: high with a temperature above 650 °C, medium with a temperature of 230 °C to 650 °C, and low with a temperature below 230 °C, where around 60% of waste heat is in the low-temperature range (Arsenyeva et al., 2021). Convective dryers are one of the waste heat producers in the low-temperature category, where the temperature of waste heat from convective dryers is usually < 55 °C (El et al., 2022).

Generally, the type of red algae seaweed, namely *Eucheuma cottonii*, is cultivated in Maluku province using the longline method (Maryunus et al., 2018; Talakua, 2017) and is a potential export commodity in improving the welfare of coastal communities (Suwati et al., 2021). Dried seaweed production in Maluku in 2022 will increase by 24.5% from the previous year (BPS Provinsi Maluku, 2022), where demand for seaweed increases by 5-10% every year to meet the needs of the domestic and export seaweed industry (Subaryono et al., 2021). The high water content of wet seaweed ranges from 75-93% (Fithriani et al., 2017; Neoh et al., 2016; Putri et al., 2018; Uribe et al., 2019), while the water content of dry seaweed is standardized by a maximum SNI of 30% for *Eucheuma cottonii* (BSN, 2015).

Seaweed drying is the most critical post-harvest processing process before it can be used in the processing industry (Gupta et al., 2011), where this process involves the simultaneous introduction of heat and mass to remove water molecules from the drying product (Joardder & Masud, 2019). However, removing water molecules during drying requires a large amount of high latent heat energy (Masud et al., 2020). In addition, convective dryers have advantages such as fast drying rates, low capital and maintenance costs, flexibility in operation, and water activity reduced to a level that inhibits the growth of microorganisms and affects process variables (temperature, air velocity, and humidity) (Inyang et al., 2017). However, convective dryers have disadvantages, such as long processing times and high energy costs. This is related to energy losses wasted as waste heat (Oğulata, 2004; Singh et al., 2020).

Various experimental and numerical studies have been conducted to optimize seaweed convective dryers with various dryer operational parameters to increase the thermal performance of convective dryers to obtain better quality dried seaweed (Hakim et al., 2020; M. Masud et al., 2019; Moreira et al., 2016; Orilda & Ibrahim, 2021; Uribe et al., 2017). Comparative study of drying methods (sunlight and oven) for seaweed to obtain the appropriate drying treatment to preserve bioactive compounds (Kadam et al., 2015). In a study of different drying methods (oven, freeze, and microwave) on certain essential nutrients of seaweed, it turns out that drying at low temperatures, such as freeze drying and oven drying at 40 °C, produces higher concentrations of essential chemicals (Badmus et al., 2019). In the study of the physicochemical and bioactive composition of red seaweed, which is influenced by different drying methods (freeze, vacuum, solar, and convective), it turns out that solar and convective drying produce dry samples with the highest retention of polyunsaturated fatty acids and, in general, freeze drying produces dry samples with high quality best overall (Uribe et al., 2020). Study of the mathematical model of drying kinetics that is most suitable for describing the characteristics of the drying rate of seaweed using the greenhouse effect solar drying method, it turns out that a relatively short time is obtained, the Midilli model is the best with an effective moisture diffusivity of 2.54×10^{-8} m^2/s (Rauf, 2021).

The study predicted the mathematical model of seaweed drying kinetics using microwave drying. It turned out that the modified Page model was the best, with an accuracy of 99.98% and the highest performance index of 453.1967 (Culaba et al., 2021). In a study of drying nori made from brown seaweed using a mechanical dryer with the addition of seaweed powder as an alginate-based bio-filter with different concentrations, it turns out that the addition of the bio-filter does not have a positive effect on the mechanical properties of the alginate, but the barrier and antioxidant properties increase (Dysjaland et al., 2022). The study of hot water blanching pre-treatment was done to increase the drying rate, whereas blanching uses a temperature of 88 C at different times (5, 15, and 30 seconds). The drying methods (solar and mechanical) are different, with a final moisture content of 14-15%; it turns out that blanching 5 and 15 seconds is 8 hours faster with the mechanical drying method, while with the solar drying method blanching 5 s is faster drying for 32.67 hours. Pre-treatment does not significantly affect ash and protein content, and pre-treatment and drying methods do not affect texture and ash preferences (Rosario & Mateo, 2019).

Although there has been much research on drying seaweed using various operational parameters that influence thermal performance to obtain the quality of dried seaweed and comparing several drying methods to get the proper drying treatment to preserve bioactive compounds, there is not much information regarding the application of Waste Heat Recovery Systems (WHRS) to evaluate the effectiveness and electrical power consumption of seaweed convective dryers, where waste heat (exhaust gas) from the convective dryer is used as a hot fluid to preheat cold fluid from the surrounding air. The innovation carried out in this research is the introduction of a bare staggered bank tube heat exchanger as a heat recovery system (WHRS) in a seaweed convective dryer.

Therefore, the main focus of this research is to examine the application of waste heat recovery systems (WHRS) to evaluate the effectiveness and electrical power consumption of seaweed convective dryers. If you vary the air velocity at a drying temperature of 50 °C (Arufe et al., 2018; Arufe et al., 2018) and particular heat input of 400 W (Kermite et al., 2023). The indication of temperature distribution and flow in the convective dryer will be that the more it is accelerated, the more it will impact the combined convection coefficient and cause the effectiveness of the convective dryer, thereby shortening the drying time. This research was also carried out for convective dryer operating conditions with and without a waste heat recovery system (WHRS). Suppose the surrounding air is a cold fluid with a specific temperature preheated with waste heat from the convective dryer and used as a hot fluid in the waste heat recovery system. In this case, the temperature of the cold fluid will increase to a specific limit before being heated by the heater until it reaches a drying temperature of 50 °C, resulting in a gradient in electrical energy consumption in the convective seaweed dryer. Next, the experimental measurement data will be studied theoretically to obtain the heat transfer mechanism. They will produce calculations of the effectiveness of convective dryers and electrical power consumption. The forced convection coefficient is considered the boundary condition of the inner surface of the convective dryer. In contrast, natural convection is regarded as the boundary condition of the outer surface of the convective dryer.

This research aims to obtain the effective air velocity at which the effectiveness of the seaweed convective dryer is maximum and obtain drying time and minimum electrical energy consumption for operating conditions with and without the application of a waste heat recovery system (WHRS).

2. Materials and Methods

2.1 Experimental equipment and setup

The bare staggered tube bank heat exchanger is a WHRS used to preheat the air in a seaweed convective dryer. It consists of two parts: the shell and the staggered bare tube bank, the manufacture of which is presented in Figure 1. This research has designed a bare staggered tube bank heat exchanger as an initial air heater for seaweed convective drying by considering simulation results using Ansys software.

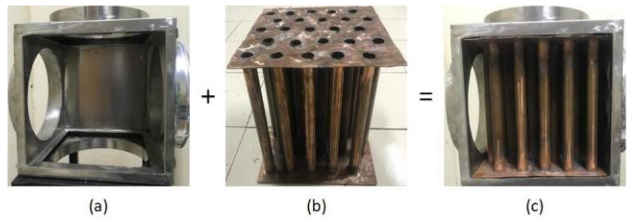

Figure 1. Fabrication steps for a bare staggered tube bank heat exchanger as a waste heat recovery system: (a) shell tube bank, (b) bare staggered tube bank, (c) bare tube bank staggered.

Heat transfer to or from banks (or bundles) of tubes in crossflow is relevant for various industrial applications. Figure 2 schematically shows its geometric arrangement. Typically, cold fluid moves through the tube while hot fluid of different temperatures passes through it. In this section, a convection heat transfer mechanism related to crossflow through the pipe occurs.

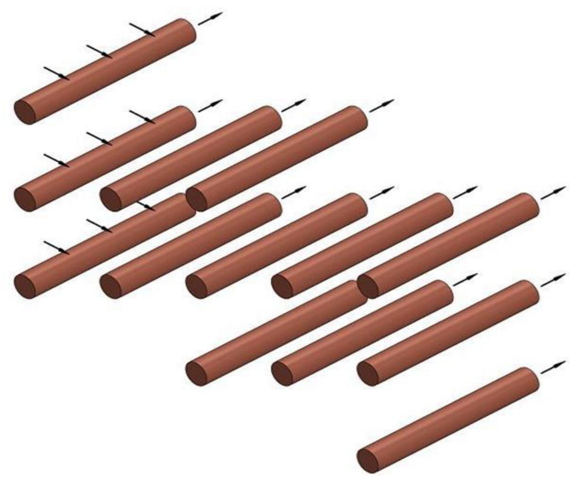

Figure 2. Schematic of a tube bank in cross-flow

Geometric parameters of a bare staggered bank tube heat exchanger as a waste heat recovery system for application in seaweed convective dryers. Overall, the geometric characteristics of bare staggered tube bank heat exchangers are presented in Table 1.

The heat exchanger shell component is made of G.304 stainless steel and has a heat conductivity value of 14.9 W/m.K. The heat exchanger shell wall consists of an adiabatic wall and an isothermal wall. The adiabatic walls are covered with asbestos tape insulation 0.17 m thick between the inner and outer stainless steel.

The tube bank heat exchanger component is pure copper with a heat conductivity value of 401 W/m.K.

Table 1. Geometric characteristics of the staggered bare tube heat exchanger as waste heat recovery system

Parameters	Value (m)
Longitudinal pitch distance (S_L)	0.051
Transverse pitch distance (S_T)	0.051
Diagonal pitch distance (S_D)	0.057
Tube diameter (D_T)	0.0254
Tube length (L_T)	0.030
Tube bank width (W)	0.030
Channel diameter (D_{ch})	0.0282
Inner shell height ($H_{sh,i}$)	0.035
Outer shell height ($H_{sh,o}$)	0.038
Gap distance (G_s)	0.0023
Inner shell width ($B_{sh,i}$)	0.035
Outer shell width ($B_{sh,o}$)	0.038

2.2 Experimental procedure

The research procedure diagram is presented in Figure 3. The research begins by setting the dryer temperature (T_{mp}) to 50 °C, heat input (Q*) to 400 W, and air velocity to 1 m/s in the control box, while humidity (RH) is 30% in the sensor box.

While waiting for the dryer temperature to reach stable operating conditions, seaweed slices will be prepared per rack with a capacity of 1 kg for the three convective drying racks. After the drying temperature is reached, the seaweed product is put into the drying chamber, and the data collection process begins, where all the measured parameters will automatically be read on a desktop PC.

Measured data in the form of temperature, speed, humidity, heat input, drying time, and weight of seaweed products will be appropriately recorded in the Excel file. The experiment will be completed if the weight of the seaweed product has reached 20% of the initial weight, and all systems will automatically be disconnected from electricity. They are measuring the weight of seaweed products using a loadcell sensor and humidity using an SHT11 sensor connected to a sensor box. Next, the research will be based on Table 2—convective dryer operational parameter ranges.

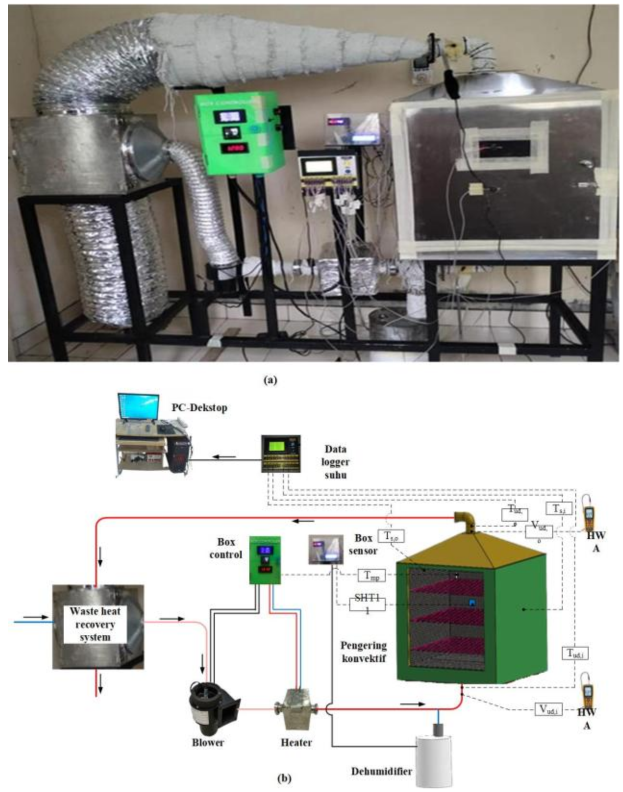

Figure 3. (a) Convective dryer with WHRS, (b) Schematic diagram of the research procedure.

Table 2. Operational parameter ranges of seaweed convective dryers

No	Parameter	Range
1	Air velocity (v), m/s	1, 2, 3, 4, 5
2	Air humidity (RH), %	30
3	Dryer temperature (Tmp), °C	50
4	Heat input ((Q*), W	300

2.3 Data Reduction

2.3.1 Energy balance of convective dryers

The energy balance of the control volume of a convective drying system with steady operating conditions describes the amount of energy entering the system equal to the energy leaving the system expressed in equation (1), which is quoted from (Titahelu, 2021):

$$E_i - E_o = \frac{dE}{dt} \Rightarrow E_i - E_o = 0 \quad \Rightarrow \quad E_i = E_o \qquad (1)$$

Equation (1), in the form of a heat balance, describes the amount of heat entering the system equal to the amount of heat leaving the system expressed in equation (2), which is quoted from (Kermite et al., 2023):

$$Q_h = Q_x + Q_c + Q_r + Q_{eva} \qquad (2)$$

with Q_x = conduction heat transfer, Q_c = convection heat transfer, Q_r = radiation heat transfer and Q_{eva} = evaporation heat transfer.

If the convective dryer during the process ignores the radiation transfer mechanism, then equation (3) can be written as:

$$Q_h = Q_x + Q_c + Q_{eva} \quad (3)$$

Figure 4 shows heat loss in a convective dryer, which occurs through air heat transfer, combined heat transfer, and evaporation heat transfer.

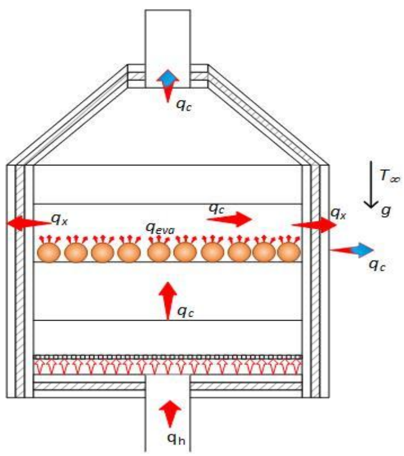

Figure 4. Convective dryer slice heat balance scheme

Combined heat loss is through two heat transfer mechanisms: conduction and convection. This heat loss occurs through forced convection heat transfer from the drying medium (air) to the inner walls. Heat transfer occurs from the inner walls to the outer walls through a conduction heat transfer mechanism, and then natural convection heat transfer occurs from the outer walls into the surrounding air. Heat is also lost through the evaporation mechanism, namely the heat needed to evaporate water vapor from seaweed products. Thus, equation (3) can be described in equation (4), which is quoted from (Kermite et al., 2023):

$$Q_h = Q_{ud} + \left(Q_{c,f} + Q_{x,w} + Q_{c,n}\right) + Q_{eva} \quad (4)$$

2.3.2 Heater heat transfer

The heat input from the heater is the amount of electrical power consumption expressed in equation (5), which is quoted from (Nada et al., 2015; Syatauw et al., 2023):

$$Q_h = V \cdot I \quad (5)$$

with V = electric voltage (Voltage) and I = electric current (Ampere).

2.3.3 Air heat transfer

Air heat transfer is heat loss through the drying medium (air) that leaves the convective drying chamber expressed in equation (6), which is quoted from (Titahelu, 2011; Zakeralhoseini et al., 2020):

$$Q_{ud} = \dot{m}_{ud} \cdot c_{p,ud} \left(T_{ud,i} - T_{ud,o}\right) \quad (6)$$

with $c_{p,ud}$ = specific heat (J/kg.K), $\dot{m}_{ud}$ = mass flow rate (kg/s), $T_{ud,i}$ dan $T_{ud,o}$ = dryer inlet and outlet air temperature (K).

2.3.4 Combined heat transfer

Combined heat transfer is the sum of forced convection heat transfer, conduction heat transfer, and natural convection heat transfer analyzed based on Figure 5, which is related to the temperature distribution in series composite walls and the concept of thermal resistance.

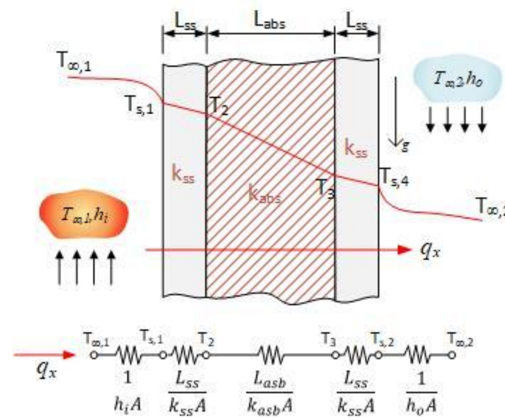

Figure 5. Temperature distribution scheme and thermal resistance of convective drying composite walls

A. Forced convection heat transfer

Thermo-physical properties of matter (Bergman et al., 2011) Among others, kinematic viscosity (ν), Prandtl number (Pr), and thermal conductivity (κ) were evaluated using film temperature (T_f) (El-Samadony et al., 2015). Which occurs between the drying medium at temperature ($T_{\infty,1}$) and the inner wall at temperature ($T_{s,i}$).

The mass flow rate of the drying medium (air) is expressed in equation (7), which is quoted from (Fouda et al., 2018; Jadar et al., 2019; Titahelu et al., 2023):

$$\dot{m} = \rho \cdot v \cdot A \quad (7)$$

with ρ = density (kg/m^3), v = air velocity (m/s), A = cross-sectional area (m^2).

During the process, the drying air is circulated by the blower so that forced convection heat transfer occurs in the convective dryer, so it is necessary to resolve the forced convection coefficient in the dryer. Thus, the Reynolds number due to the circulation of the drying air is expressed in equation (8), which is quoted from (Alnaimat & Ziauddin, 2021; Hatumessen et al., 2021; Titahelu, 2010):

$$\mathrm{Re}_D = \frac{4\dot{m}}{\pi \cdot D_h \cdot \mu} \tag{8}$$

with D_h = hydraulic diameter of the convective dryer expressed in equation (9), which is quoted from (Bhandari & Prajapati, 2021; Huang et al., 2016):

$$D_h = \frac{4AC}{P} = \frac{4ab}{2(a+b)} = \frac{2ab}{(a+b)} \tag{9}$$

with a and b = length of the convective dryer's rectangular cross-section (m).

The Nusselt number is a function of the flow field, namely the flow parameters, namely the Reynolds number (Re_D) (González et al., 2019) and the fluid parameter is the Prandtl number (Pr) (Mangrulkar et al., 2020). The relationship between these three variables depends on the flow pattern and trajectory so that the Nusselt number of the drying media is expressed in equation (10), which is quoted from (Promvonge et al., 2020):

$$Nu_D = 0.023 \cdot (\mathrm{Re}_D)^{4/5} \cdot (\mathrm{Pr})^n \tag{10}$$

with n = 0,4 if $T_s > T_f$.

The forced convection coefficient of the drying medium (air) in the convective drying chamber is expressed in equation (11), which is quoted from (Titahelu et al., 2021; Titahelu & Litiloly, 2018):

$$h_{i,f} = \frac{Nu_D \cdot \kappa}{D_h} \tag{11}$$

with κ = heat conductivity of drying air (W/m.K).

B. Natural convection heat transfer

The thermophysical properties of the material between the outer wall of the convective dryer at temperature ($T_{s,o}$) and the surrounding fluid at temperature ($T_{\infty,o}$) are evaluated using the film temperature (T_f) (Ononogbo et al., 2022).

The transition from natural convection heat transfer in the vertical boundary layer depends on the attractive relativity forces of buoyancy and fluid viscosity forces, where these parameters are the Rayleigh number (Ra_L) expressed in equation (12), which is quoted from (Kogawa et al., 2021; Kumar et al., 2020; Titahelu, 2002; Titahelu et al., 2023):

$$Ra_L = \frac{g \cdot \beta (T_{s,o} - T_{\infty,o}) L^3}{\nu \cdot \alpha} \tag{12}$$

with g = gravitational acceleration (m/s^2), β = volumetric thermal expansion coefficient (K^{-1}), L = characteristic length of the vertical wall (m) dan α = heat diffusivity (m^2/s).

The Nusselt number is a comparison between the convection coefficient and the conduction coefficient of the drying medium (air) expressed in equation (13), which is quoted from (Jobair, 2017):

$$Nu_L = 0.68 + \frac{0.67 (Ra_L)^{1/4}}{\left[1 + (0.492/\mathrm{Pr})^{9/16}\right]^{4/9}} \tag{13}$$

The natural convection coefficient on the outside of the convective dryer is expressed in equation (14), which is quoted from (Rao et al., 2016; Titahelu & Tupamahu, 2019):

$$h_{o,n} = \frac{Nu_L \cdot \kappa}{L} \tag{14}$$

C. Total heat resistance

The total heat resistance is the sum of the forced convection heat resistance, conduction heat resistance, and natural convection thermal resistance due to the combined heat transfer that occurs in the convective dryer to the surrounding air, expressed in equation (15), which is quoted from (Ahmed et al., 2018; Pietrak & Wiśniewski, 2015):

$$R_{tot} = \frac{1}{h_{i,f} A} + \frac{L_{ss}}{\kappa_{ss} A} + \frac{L_{abs}}{\kappa_{abs} A} + \frac{L_{ss}}{\kappa_{ss} A} + \frac{1}{h_{o,n} A} \tag{15}$$

with L = wall thickness (m), κ = wall thermal conductivity (W/m.K), subscript ss and abs = stainless steel and asbestos materials.

D. Heat transfer flux

The heat transfer rate per unit area or heat transfer flux is expressed as a ratio between the fluid temperature gradient and the total heat resistance expressed in equation (16), which is quoted from (Kermite et al., 2023; Ononogbo, 2020):

$$q''_{mix} = \frac{\left(T_{\infty,i} - T_{\infty,o}\right)}{R_{tot}} \tag{16}$$

with $T_{\infty,i}$ = drying air temperature in the convective dryer (K), $T_{\infty,o}$ = surrounding fluid temperature (K).

Thus, the combined heat transfer is obtained from the product of the heat transfer flux and the heat transfer surface area of the convective dryer, which is expressed in equation (17), which is quoted from (Kothandaraman, 2006):

$$Q_{mix} = q''_{mix} \cdot A_{cd} \tag{17}$$

with A_{cd} = heat transfer surface area of a convective dryer (m^2).

2.3.5 *Evaporative heat transfer*

Evaporative heat transfer is the heat needed to dissipate the water contained in seaweed products so that they become dry products with a certain water content. Evaporative heat transfer is obtained from the amount of heat entering the convective drying system minus the amount of heat leaving the convective drying system expressed in equation (18), which is quoted from (Deshpande et al., 2021; Kermite et al., 2023):

$$Q_{eva} = Q_h - \left(Q_{ud} - Q_{mix}\right) \tag{18}$$

2.3.6 *Effectiveness of convective dryers*

The effectiveness of a convective dryer is the ratio of actual heat transfer (evaporation) to maximum heat transfer (heater), which is expressed in equations (19a) and (19b), which are quoted from (Said et al., 2021; Şevik et al., 2019):

$$\varepsilon = \frac{Q_{act}}{Q_{\max}} \times 100\% \tag{19a}$$

or

$$\varepsilon = \frac{Q_{eva}}{Q_h} \times 100\% \tag{19b}$$

2.4 *Seaweed water content*

The water content of seaweed products during the drying process is expressed in equation (20), which is quoted from (Zohrabi et al., 2020):

$$M_t = \frac{W_t - W_d}{W_d} \tag{20}$$

where M_t = water content of seaweed (g water/g dry matter), W_t = weight of seaweed product (g) at time t, and W_d = weight of dry seaweed product (g).

2.5. *Convective dryer electrical energy consumption*

The total electrical energy consumed during the drying process is obtained as the product of the total dryer electrical energy output and the total drying time expressed in equation (21) quoted from (Chibuike et al., 2021):

$$P_t = P_{outd} \cdot d_t \tag{21}$$

with

$$P_{outd} = V \cdot I$$

where d_t = total drying time (hours), P_{outd} = total electrical power of convective dryer (kW).

3. Results and Discussion

The experimental results of a seaweed convective dryer integrated with a bare staggered bank tube heat exchanger as a waste heat recovery system were carried out based on research procedures and Table 2 of operational parameter ranges, so the measurement results were obtained in the form of temperature data, drying air velocity, humidity, heat input, electrical voltage, electric current, drying time, wet weight and dry weight of seaweed, which are presented in Table 3 and Table 4.

Analysis of the effectiveness of the seaweed waste heat convective dryer is based on energy balance, which consists of input energy, namely heater heat transfer, and output energy, namely air heat transfer, combined heat transfer, and evaporation heat transfer. The entire analysis will boil down to analyzing the effectiveness of waste heat convective dryers and electrical power consumption.

Based on Table 3 and Table 4, an analytical study was carried out to obtain the effectiveness and electrical power consumption of seaweed convective dryers, which are described based on heat transfer characteristics for operating conditions before and after implementing waste heat recovery, which is described as follows:

Table 3. Measured data of drying air temperature and convective drying walls

Parameter	**Range**				
v, (m/s)	1.0	2.0	3.0	4.0	5.0
Without applying a WHRS					
Working fluid					
$T_{ud,i}$ (K)	325.3	324.0	323.5	322.2	322.9
$T_{ud,o}$ (K)	322.7	322.6	322.5	322.4	322.3
$T_{\infty,1}$ (K)	323.0	323.0	323.0	323.0	323.0
$T_{\infty,2}$ (K)	302.0	302.0	302.0	302.0	302.0
Internal walls					
$T_{ss,i1}$ (K)	326.4	326.0	325.6	325.2	324.8
$T_{k,i1}$ (K)	315.2	214.8	314.4	314.1	313.5
$T_{ss,i2}$ (K)	325.2	324.9	324.6	324.6	324.0
$T_{ss,i3}$ (K)	325.2	324.9	324.7	324.4	324.1
$T_{ss,i4}$ (K)	325.3	325.1	324.9	324.6	324.3
$T_{ss,i5}$ (K)	326.5	326.2	325.9	325.6	325.4
$T_{ss,i6}$ (K)	325.6	325.4	324.9	324.6	324.4
Outer walls					
$T_{ss,o1}$ (K)	305.9	305.7	305.5	305.3	305.1
$T_{k,o1}$ (K)	309.6	309.3	308.8	308.3	308.0
$T_{ss,o2}$ (K)	308.1	307.8	307.6	307.4	307.2
$T_{ss,o3}$ (K)	308.4	308.1	307.8	307.5	307.2
$T_{ss,o4}$ (K)	308.5	308.3	307.9	307.6	307.3
$T_{ss,o5}$ (K)	309.5	309.2	308.9	308.6	308.4
$T_{ss,o6}$ (K)	308.6	308.4	308.2	307.7	307.5
With applying a WHRS					
Working fluid					
$T_{ud,i}$ (K)	325.5	324.3	323.9	323.5	323.3
$T_{ud,o}$ (K)	322.9	322.8	322.8	322.7	322.6
$T_{\infty,1}$ (K)	323.0	323.0	323.0	323.0	323.0
$T_{\infty,2}$ (K)	302.0	302.0	302.0	302.0	302.0
Internal walls					
$T_{ss,i1}$ (K)	325.2	324.8	324.4	324.2	324.1
$T_{k,i1}$ (K)	316.1	315.7	315.4	315.1	314.9
$T_{ss,i2}$ (K)	326.1	325.7	325.6	325.3	325.2
$T_{ss,i3}$ (K)	326.1	325.8	325.6	325.4	325.3
$T_{ss,i4}$ (K)	326.2	326.1	325.8	325.6	325.5
$T_{ss,i5}$ (K)	327.4	327.1	326.7	326.6	326.5
$T_{ss,i6}$ (K)	326.4	326.3	325.7	325.6	325.5
Outer walls					
$T_{ss,o1}$ (K)	306.7	306.5	306.4	306.3	306.2
$T_{k,o1}$ (K)	308.4	308.1	307.8	307.3	307.2
$T_{ss,o2}$ (K)	307.0	306.7	306.5	306.4	306.3
$T_{ss,o3}$ (K)	307.3	307.0	306.7	306.5	306.4
$T_{ss,o4}$ (K)	307.4	307.1	306.8	306.6	306.5
$T_{ss,o5}$ (K)	307.2	307.1	306.9	306.6	306.5
$T_{ss,o6}$ (K)	307.4	307.3	307.2	306.7	306.6

Table 4. Measured data of other parameters of convective dryers

Parameter	Range				
v, (m/s)	1.0	2.0	3.0	4.0	5.0
	Without applying a WHRS				
V (Volt)	220	220	220	220	220
I (Amp)	3.92	3.99	4.06	4.13	4.16
T_d (hour)	50.25	42.23	34.97	26.07	21.25
M_b (kg wet)	2.790	2.790	2.790	2.790	2.790
M_t (kg dry)	0.9	0.9	0.9	0.9	0.9
	With applying a WHRS				
V (Volt)	220	220	220	220	220
I (Amp)	3.88	3.94	4.02	4.08	4.12
T_d (hour)	49.85	42.07	34.42	25.90	20.97
M_b (kg wet)	2.790	2.790	2.790	2.790	2.790
M_t (kg dry)	0.9	0.9	0.9	0.9	0.9

3.1 Heater heat transfer analysis

This section explains the behavior of the heater heat transfer curve for the two operating conditions of the waste heat convective dryer illustrated in Figure 6. The heater heat transfer increases as the air velocity (v) increases. This is caused by the increasing use of electric current, where the electric current is directly proportional to the heater's heat transfer. The maximum heat transfer is found at the maximum air velocities of 915.2 W and 906.4 W, respectively, for operating conditions with and without applying WHRS.

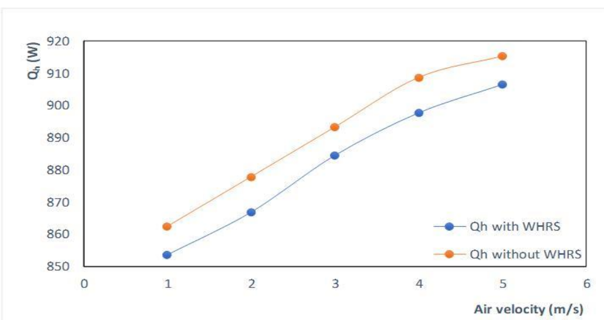

Figure 6. Heat transfer curve behavior of the heater

On the other hand, the minimum heater heat transfer is found at a minimum air velocity of 853.6 W and 862.4 W for each operating condition with and without applying a WHRS.

3.2 Air heat transfer analysis

Figure 7 illustrates the behavior of the air heat transfer curve as air velocity increases for both operating conditions in the convective dryer. As the air velocity increases, the air heat transfer increases. This is caused by the increasing air mass flow rate, which is directly proportional to the air heat transfer.

The maximum air heat transfer is found at an air velocity of 5 m/s of 575,63 W and 584,91 W, respectively, for operating conditions with and without applying a waste heat recovery system. On the other hand, the minimum air heat transfer is found at an air velocity of 1 m/s of 444,93 W and 452,16 W for each operating condition with and without applying a WHRS.

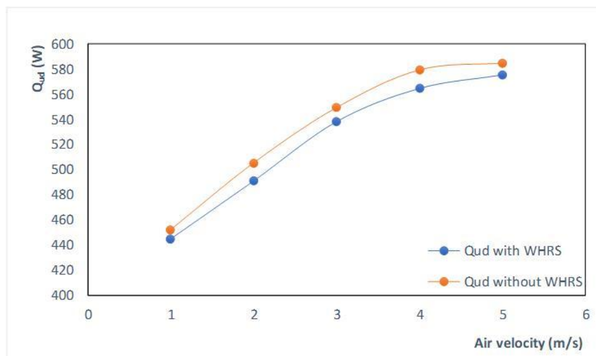

Figure 7. The air heat transfer curve's behavior

3.3 Combined heat transfer analysis

This section explains the behavior of the combined heat transfer curve for operating conditions with and without applying a WHRS, illustrated in Figure 8. It can be seen that as the air velocity (v) increases, the combined heat transfer increases. This is caused by the decreasing thermal resistance caused by the decreasing temperature gradient between the inner wall temperature and the hot fluid temperature, where the thermal resistance is directly proportional to the combined heat transfer.

The maximum combined heat transfer is found at an air velocity of 5 m/s of 8.602 W and 9.045 W, respectively, for operating conditions with and without applying a WHRS. In contrast, the minimum combined heat transfer found at an air velocity of 1 m/s is 8.28 W and 8.91 W for each operating condition before and after applying WHRS.

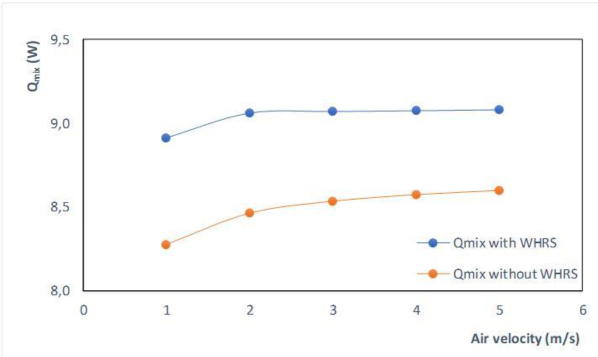

Figure 8. Combined heat transfer curve's behavior

3.4 Evaporative heat transfer analysis

This section explains the behavior of the evaporative heat transfer curve for operating conditions with and without applying a WHRS, illustrated in Figure 9. The evaporative heat transfer decreases as the air velocity (v) increases. This is caused by the increasing sum of air heat transfer and combined heat transfer caused by the rising air mass flow rate, where the sum of air heat transfer and combined heat transfer is directly proportional to evaporative heat transfer.

The maximum evaporative heat transfer is found at an air velocity of 1 m/s of 399,76 W and 401,97 W, respectively, for operating conditions with and without applying a WHRS. On the other hand, the minimum evaporative heat transfer is found at an air velocity of 1 m/s of 321.69 W and 321.68 W for each operating condition with and without implementing the WHRS.

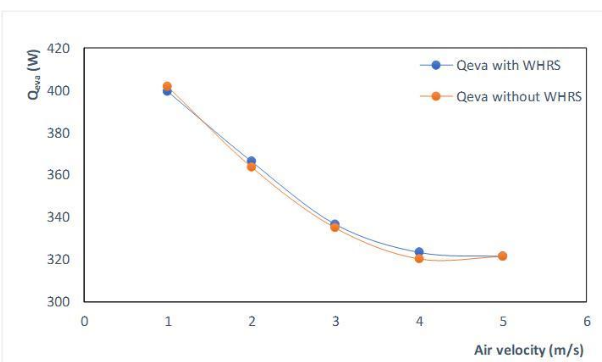

Figure 9. Evaporative heat transfer curve's behavior

3.5 Analysis of the effectiveness of convective dryers

This section explains the behavior of the effectiveness curve for operating conditions with and without implementing a WHRS, illustrated in Figure 10. It appears that as the air velocity (v) increases, the effectiveness of the seaweed dryer decreases. This is caused by increasing air heat transfer and combined heat transfer so that evaporation heat transfer decreases, where evaporation heat transfer is directly proportional to effectiveness.

The maximum effectiveness is found at an air velocity (v) of 1 m/s of 46.83% and 46.61%, respectively, for operating conditions with and without implementing a WHRS. On the other hand, the minimum effectiveness is found at an air velocity (v) of 5 m/s of 35.49% and 35.15%, respectively, for operating conditions with and without implementing a WHRS. It also appears that the effectiveness of a convective dryer without implementing a WHRS tends to be smaller than that of a convective dryer with a WHRS, where the effectiveness gradient for the two operating conditions has an average deviation value of 1.38%.

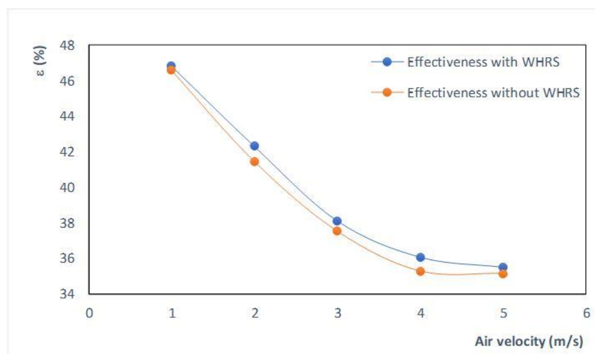

Figure 10. Convective dryer effectiveness curve's behavior

3.6 Analysis of seaweed water content

This section explains the behavior of the seaweed moisture content curve for operating conditions with and without applying WHRS, as illustrated in Figure 11 and 12. It can be seen that with the more significant air velocity (v), the drying time for the seaweed becomes minimal.

This is caused by the increasing mass flow rate of air entering the drying chamber, which increases the hot fluid convection coefficient, thereby speeding up the drying time of the seaweed.

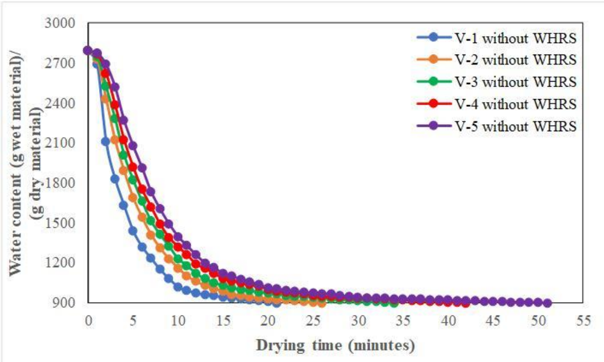

Figure 11. The behavior of seaweed moisture content curves for operating conditions without applying WHRS.

The maximum drying time at air velocity (v) 5 m/s is 20.97 hours and 21.25 hours, respectively, for operating conditions with and without implementing a WHRS (Figure 12). On the other hand, the minimum drying time at air velocity (v) 1 m/s is 49.85 hours and 50.25 hours, respectively, for operating conditions with and without implementing a WHRS. Respectively, 660 minutes and 570 minutes. This means that air velocity smaller than five m/s no longer significantly affects the drying time of seaweed.

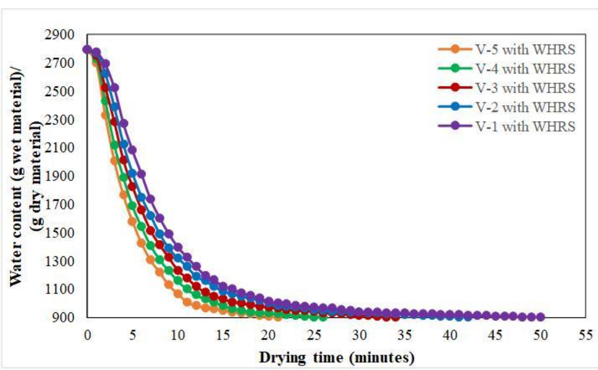

Figure 12. The behavior of seaweed moisture content curve for operating conditions with applying WHRS.

3.7 Convective dryer electrical energy consumption

This section explains the behavior of the electrical energy consumption curve for operating conditions with and without implementing WHRS, as illustrated in Figure 13. As the air velocity (v) increases, the electrical energy consumption decreases. This is caused by the dryer's increasing total electric energy output, which is caused by the increasing use of electric current. The total electric energy output of the dryer is directly proportional to the electric energy consumption.

The maximum electrical energy consumption at air velocity (v) 1 m/s is 42.55 kWh and 43.34 kWh, respectively, for operating conditions with and without implementing a WHRS. On the other hand, the minimum electrical energy consumption is found at an air velocity (v) of 5 m/s of 19 kWh and 19.45 kWh, respectively, for operating conditions with and without implementing a WHRS. It also appears that the electrical energy consumption of convective dryers using a WHRS tends to be smaller than that of convective dryers without a WHRS, where the gradient of electrical energy consumption for both operating conditions has an average deviation value of 1.98%.

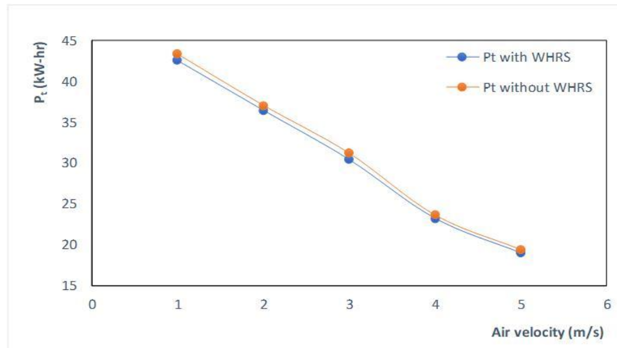

Figure 13. The behavior of the electric energy consumption curve of a convective dryer.

4. Conclusion

An experimental study of application with and without a WHRS was carried out to evaluate the effectiveness and electrical energy consumption of seaweed convective dryers by varying the drying air velocity from 1 to 5 m/s, concluded as follows:

1. The more air velocity increases, the less effective the convective dryer will be. Maximum effectiveness at an air velocity of 1 m/s is 46.83% and 46.61% for operating conditions with and without implementing a WHRS, which means that air velocity more incredible than one m/s does not have a significant effect on the effectiveness of convective dryer seaweed.
2. The minimum seaweed drying time at an air velocity of 5 m/s for operating conditions with and without implementing a WHRS is 20.97 and 21.25 hours, respectively.
3. The seaweed convective dryer's minimum electrical energy consumption at an air velocity of 5 m/s is 19 kWh and 19.45 kWh for operating conditions with and without a WHRS, with an average deviation value gradient of 1.98%.

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