Solar Dryer Design For Biomass

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Abstract - This study explores the design and performance of a mixed-mode solar dryer for drying biomass to improve the efficiency of co-firing in a power plant. The dryer combines passive and active solar drying methods to effectively operate in various weather conditions. By analyzing the thermodynamics and heat transfer processes within the system, the research evaluates the dryer's impact on biomass quality, particularly its calorific value. A mathematical model is used to predict drying times and optimize design parameters like solar collector size and airflow. The study investigates the relationship between heat requirements, drying efficiency, and biomass quality. Results indicate that the mixed-mode solar dryer effectively dries biomass while preserving its calorific value, offering a promising solution for sustainable and cost-effective biomass drying in power plants.

Keywords: *solar dryer, mixed-mode, co-firing, biomass, calorific value*

Nomenclature

α	Absorptivity
α	Thermal diffusivity (m²/s)
$\alpha\ w$	Water activity
β	Surface tilt angle (°)
$\beta\ f$	Air volume expansion coefficient (K^{-1})
ΔT	Temperature difference (°C)
Δt	Time interval for finite difference scheme solution (s)
Δx or Δy	Spatial interval for finite difference scheme solution (m)
δ	Solar declination angle (°)
η	Efficiency (%)
γ	Azimuth angle (°)
λ	Longitude (°)

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λmer	Standard meridian for time zone (°)
μ	Dynamic viscosity (Pa·s)
ν	Kinematic viscosity (m^2/s)
ω	Hour angle (°)
ω	Humidity ratio (kg_{moisture}/kg_{air})
Φ	Sphericity
φ	Latitude (°)
ρ	Density (kg/m^3)
ρ	Reflectivity
ρgr	Bulk density of the product in a wet basis (kg/m^3)
τ	Transmissivity
θ	Angle of incident radiation on a surface (°)
θz	Zenith angle (°)
ε	Emissivity

Global warming is a pressing issue, and one major culprit is carbon emissions from fossil fuel power plants. PLN Indonesia Power is tackling this challenge with an innovative approach: cofiring biomass at their Labuan power plant. This involves replacing a portion of the coal used with biomass like sawdust and rice husks, significantly reducing carbon emissions and paving the way for greener energy production in Indonesia.

However, cofiring comes with its own set of hurdles. Biomass availability and maintaining its quality, especially its calorific value (which determines its energy content), are critical. Improper storage can degrade biomass, making it less effective as fuel. This is where the concept of a solar dryer comes in. By utilizing the power of the sun, a solar dryer can efficiently dry biomass, ensuring optimal quality and maximizing its energy potential.

This research delves into designing an effective solar dryer for PLTU Labuan. It explores the potential of this technology to address the challenges of biomass cofiring, ultimately contributing to Indonesia's green energy goals. By optimizing the drying process and ensuring high-quality biomass, this initiative aims to boost the efficiency and sustainability of cofiring, making a significant impact on reducing carbon emissions in the power sector.

1 Introduction

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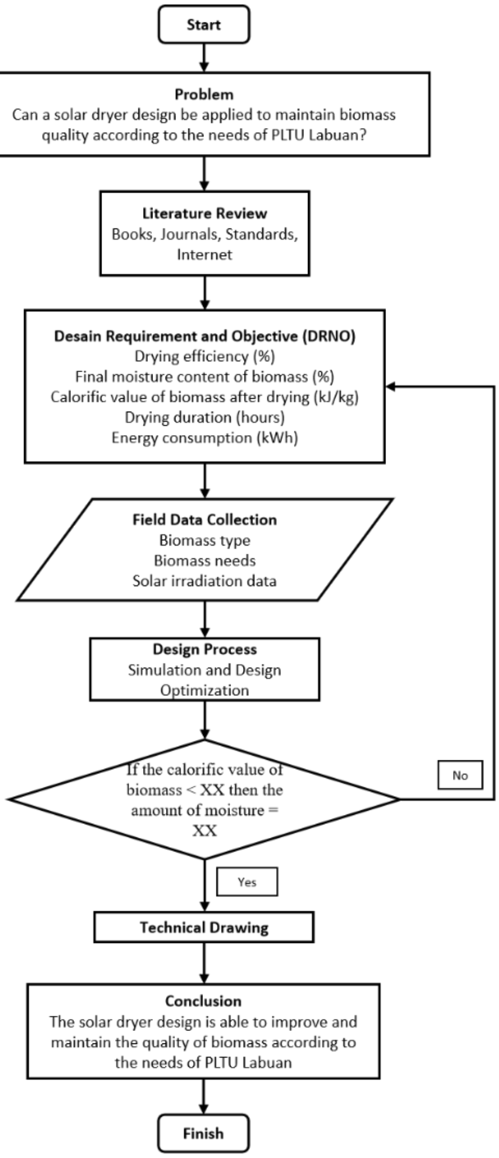
2 Methodology

This study uses a quantitative approach to investigate the effectiveness of a biomass solar dryer system. By employing modeling and simulation techniques, the research aims to predict the system's performance under different operating conditions and environments. Furthermore, it will analyze the impact of various design parameters on the system's overall efficiency.



3 General Description of Solar Dryer

Solar dryer system performance and cost are affected by various components. Understanding these components is crucial for optimal design selection in specific applications. The drying chamber, where the product is placed, can be made of various materials like wood, plywood, or aluminum, with transparent covers like polyethylene or glass. Material selection should consider durability and hygiene. Different solar dryer designs, such as box, cabinet, tunnel, and greenhouse types, exist, with structure selection depending on the implementation scale.

To maximize performance and cost-efficiency, careful consideration of the solar dryer's components is essential. The drying chamber, constructed from materials like wood or aluminum with a transparent cover, houses the material being dried. Different dryer designs, such as box or greenhouse types, are chosen based on the project scale. Solar collectors capture the sun's energy, and auxiliary systems like fossil fuels or photovoltaics can be integrated to enhance drying efficiency, particularly during periods of low sunlight.

4 Design Considerations

- The minimum temperature used in the biomass drying process is 50°C - 70°C.
- The solar dryer is designed for optimal temperature, where T0 is 70°C while the ambient temperature is 33°C.
- The design of this solar dryer emphasizes good air circulation and a spacious drying chamber. Therefore, the dimensions of the drying chamber are 50 cm x 47 cm x 45 cm, while the air outlet duct measures 50 cm x 5 cm

5 Design Calculation

a) Solar Radiation Intensity and Other Measured Parameter Data

Based on the field measurement data using a solar power meter, the average total solar radiation obtained is 722.407 W/m². This value can be assumed as the solar radiation (S) that will hit the absorber plate. Several data required in the calculation process are as follows:

- Ambient Temperature (Ta): 33 °C = 306 K
- Glass Cover Temperature (Tc): 55 °C = 328 K (assumed)
- Plate Absorber Temperature (Tp): 60 °C = 333 K (assumed)
- Inlet Temperature (Tf, in): 31 °C = 304 K (assumed)
- Outlet Temperature (Tf, out): 45 °C = 318 K (assumed)
- Collector Area (Ac): 3.38 m²
- Insulation Thickness (sawdust): 0.05 m
- Insulation Thermal Conductivity (k): 0.15 W/m.K
- Acceleration Due to Gravity: 9.81 m/s²
- Plate Absorber Emissivity (εp): 0.94
- Plate Absorber Absorptivity (αp): 0.97
- Glass Cover Emissivity (εc): 0.96

- Glass Cover Transmissivity (ηc): 0.79
- Stefan-Boltzmann Constant (σ): 5.67 x 10^{-8} W/m².K
- Fluid Specific Heat (Cp): 1020 kJ/kg.K

b) Convection Coefficient of Plate Absorber and Glass Cover Using the hermophysical Properties of Gases at Atmospheric Pressure table, the following values are obtained:

v = 18.96 x 10^{-6} m²/s
α = 27.01 x 10^{-6} m²/s
k = 28.56 x 10^{-3} W/m.K

Calculate the value of β:

$$\beta' = \frac{1}{T_{film,p-c}} = \frac{1}{330{,}5} = 0{,}00303K^{-1}$$

Calculate the Rayleigh Number:

$$Ra = \frac{g.\beta'.\Delta T.L^3}{v.\alpha} = \frac{9{,}81 \,.\, 0{,}00303 \,.\, (333-328).\, 0{,}05^3}{19{,}54 \text{ x } 10^{-6} \;.\; 26{,}89 \text{ x } 10^{-6}} = 36225{,}52$$

Calculate the Nusselt Number:

$$Nu = 1 + 1{,}44\left[1 - \frac{1708(sin1{,}8\beta)^{1{,}6}}{Ra\cos\beta}\right]\left[1 - \frac{1708}{Ra\cos\beta}\right] + \left[\left(\frac{Ra\cos\beta}{5830}\right)^{\frac{1}{3}} - 1\right]$$

$$Nu = 1 + 1{,}44\left[1 - \frac{1708(sin1{,}8.0)^{1{,}6}}{35307{,}11\cos 0}\right]\left[1 - \frac{1708}{35307{,}11\cos 0}\right] + \left[\left(\frac{35307{,}11\cos 0}{5830}\right)^{\frac{1}{3}} - 1\right]$$

$$Nu = 3{,}2105$$

Convection Coefficient of Plate Absorber and Glass Cover (hcv,p-c):

$$h_{cv,p-c} = \frac{Nu\,.\,k}{L} = \frac{3{,}19311 \,.\; 28{,}31 \text{ x } 10-3}{0{,}05} = \mathbf{1{,}8}339\,\frac{\boldsymbol{W}}{\boldsymbol{m^2}}.\boldsymbol{K}$$

c) Radiation Coefficient of Plate Absorber and Glass Cover

$$h_{r,p-c} = \frac{\sigma(T_p^2 + T_c^2)(T_{p+}T_c)}{{}^1/_{\varepsilon_p} + {}^1/_{\varepsilon_c} - 1} = \frac{5{,}67.10^{-8}(333^2 + 328^2)(333 + 328)}{{}^1/_{0{,}94} + {}^1/_{0{,}96} - 1} = \mathbf{7,7385}\ \frac{\boldsymbol{W}}{\boldsymbol{m^2}}.\boldsymbol{K}$$

d) Convection Coefficient of Glass Cover and Ambient

$$T_{film,p-c} = \frac{(T_c + T_a)}{2} = \frac{(328 + 306)}{2} = 317\ K$$

Using the Thermophysical Properties of Gases at Atmospheric Pressure table, the following values are obtained:

v = 17.60 x 10^{-6} m^2/s
α = 25.07 x 10^{-6} m^2/s
k = 27.56 x 10^{-3} W/m.K

Calculate the characteristic length (L), which is 4 times the area of the absorber plate divided by the perimeter of the absorber plate:

$$L = \frac{4\,.A_c}{P} = \frac{4\,.\ 3{,}38}{6} = 2{,}25\ m$$

Calculate the Reynolds Number:

$$Re = \frac{V\,.\ L}{v} = \frac{0{,}4\,.2{,}25}{17{,}60 \text{ x } 10^{-6}} = 51212{,}12$$

Calculate the Grashof Number:

$$\beta' = \frac{1}{T_{film,p-c}} = \frac{1}{317} = 0{,}00315K^{-1}$$

$$G_r = \frac{g\beta'(T_c - T_a)L}{v^2} = \frac{9{,}81\,.0{,}00315\ (328 - 306).\,2{,}25}{(17{,}60 \text{ x } 10^{-6})^2}$$

$$G_r = 4952591769$$

Since the value of Gr/Re > 1, it falls into the free convection category.

Calculate the Rayleigh Number:

$$Ra = \frac{g\,.\,\beta'.\,\Delta T\,.\,L^3}{v\,.\,\alpha} = \frac{9{,}81\,.\,0{,}00315\,.\,(328 - 306).\,2{,}25^3}{(17{,}60 \text{ x } 10^{-6}).\,(25{,}07 \text{ x } 10^{-6})}$$

$Ra =$ **17653944132**

Calculate the Nusselt Number:

$$Nu = 1 + 1{,}44\left[1 - \frac{1708(sin1{,}8\beta)^{1{,}6}}{Ra\cos\beta}\right]\left[1 - \frac{1708}{Ra\cos\beta}\right] + \left[\left(\frac{Ra\cos\beta}{5830}\right)^{\frac{1}{3}} - 1\right]$$

$$Nu = 1 + 1{,}44\left[1 - \frac{1708(sin1{,}8.0)^{1{,}6}}{17653944132\cos 0}\right]\left[1 - \frac{1708}{17653944132\cos 0}\right] + \left[\left(\frac{17653944132\cos 0}{5830}\right)^{\frac{1}{3}} - 1\right]$$

$Nu = 146{,}1142$

Convection Coefficient between Glass Cover and Ambient:

$$h_{cv,c-a} = \frac{Nu\,.\,k}{L} = \frac{146{,}1142\,.\;27{,}56 \text{ x } 10^{-3}}{3{,}38} = \mathbf{1},7871\;\frac{\boldsymbol{W}}{\boldsymbol{m^2}}.\boldsymbol{K}$$

e) Radiation Coefficient of Glass Cover and Ambient

Calculate the value of Tsky:

$$T_{sky} = 0{,}0522T_a^{1{,}5} = 0{,}0522\,.\,306^{1{,}5} = 279{,}42K$$

Radiation Coefficient between Glass Cover and Ambient:

$$h_{r,c-a} = \varepsilon_c.\,\sigma\,(T_c^2 + T_s^2)(T_c + T_s)$$

$$h_{r,c-a} = 0{,}96\,.\,5{,}67x10^{-8}(328^2 + 279{,}42^2)(328 + 279{,}42) = \mathbf{6,1384}\;\frac{\boldsymbol{W}}{\boldsymbol{m^2}}.\boldsymbol{K}$$

f) Thermal Heat Loss

Top Part (Ut)

Calculate the Thermal Resistance between the Plate Absorber and Glass Cover:

$$R_1 = \frac{1}{h_{cv,p-c} + h_{r,p-c}} = \frac{1}{1{,}8339 + 7{,}7385} = 0{,}1045\ \frac{W}{m^2}.K$$

Calculate the Thermal Resistance between the Glass Cover and Ambient:

$$R_2 = \frac{1}{h_{cv,c-a} + h_{r,c-a}} = \frac{1}{1{,}7992 + 6{,}1384} = 0{,}1262\ \frac{W}{m^2}.K$$

Then the value of Ut:

$$U_t = \frac{1}{R_1 + R_2} = \frac{1}{0{,}1045 + 0{,}1262} = 4{,}3357\ \frac{W}{m^2}.K$$

Bottom Part (Ub)

Calculate the Thermal Resistance between the Plate Absorber and Insulation:

$$R_3 = \frac{L_{ins}}{k_{ins}} = \frac{0{,}05}{0{,}15} = 0{,}3333\frac{W}{m^2}.K$$

Then the value of Ub:

$$U_b = \frac{1}{R_3} = \frac{1}{0{,}3333} = 3\frac{W}{m^2}.K$$

Thus, the Total Thermal Heat Loss (UL):

$$U_L = U_t + U_b = 4{,}3357 + 3 = \mathbf{7{,}33}57\ \boldsymbol{\frac{W}{m^2}.K}$$

g) Mass Flow Rate (m)

$$\dot{m} = \frac{-U_L F' A_c}{C_p \ln\left(1 - \frac{U_L(T_o - T_i)}{S - U_L(T_i - T_a)}\right)} = \frac{-7{,}3393 \,.\, 0{,}1477 \,.\, 2}{1020 \ln\left(1 - \frac{7{,}3393\,(318 - 304)}{722{,}407 - 7{,}3393\,(304 - 306)}\right)}$$

$$\dot{m} = 0{,}0239\ kg/s$$

h) Heat Removal Factor (FR)

$$F_R = \frac{\dot{m}\,.\,C_p\,.\,(T_{f,out} - T_{f,in})}{A_c\left(S - U_L\left(T_{f,in} - T_a\right)\right)} = \frac{0{,}0142\,.\,1020\,.\,(318 - 304)}{2\left(722{,}407 - 7{,}3393\,(304 - 306)\right)} = 0{,}1372$$

10) Useful Energy Gain (Quseful)

Under steady-state conditions, the performance of the solar collector is an energy balance that shows the distribution of incoming solar energy into useful energy gain, heat loss, and optical loss. The solar radiation absorbed by the collector per unit absorber area S is equal to the difference between the incoming solar radiation and the optical loss.

$$Q_u = A_c F_R\left(S - U_L\left(T_{f,in} - T_a\right)\right)$$

$$Q_u = 3{,}38\,.\,0{,}1372\left(722{,}407 - 7{,}3357(304 - 306)\right)$$

$$Q_u = 341{,}93\ Watt$$

Furthermore, it can be calculated that the energy generated from the solar collector that can be utilized for drying biomass for 8 hours is:

$$QD = \frac{(341{,}93\,.\ 8\,.\ 3600)}{1000} = 9847{,}45\ Kilojoule$$

6 Conclusion

The designed mixed-mode solar dryer effectively dries sawdust biomass under various weather conditions, performing better in sunny weather due to higher solar radiation intensity. Drying duration and biomass calorific value are influenced by variations in heat requirements, highlighting the importance of optimizing the drying process to balance efficiency and preserve biomass quality.

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