Modelling and performance analysis of a combined solar-biomass assisted grain drying and power generation system

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Abstract. In this paper, a novel scheme of a solar-biomass integrated Fluidized Bed Drying (FBD) system has been proposed for drying of agricultural food-grains. During the hours of sunshine, ambient air passes through a solar air-heater and gets heated to the required drying temperature. When solar heating becomes inadequate or unavailable such as during cloudy days or at night, a biomass furnace assisted backup heat exchanger is used for heating the incoming air. This ensures continuous operation of the drying system all through the day and night (24h). Surplus heat from the biomass furnace after meeting the in-house requirements is utilized in an Organic Rankine Cycle (ORC) to generate electricity. A thermal model has been developed for the proposed system for drying of paddy grains. The performance of the system has been analyzed for representative days of January, May and September for the city Kolkata (22°34ʹN 88°22ʹE), located in the plains of India. The study reinforces the viability of development of a solar-biomass powered FBD for drying of grains of paddy in rural areas of the country and at the same time has potential for power generation that can meet the utility requirements of rural population.

1. Introduction
The primary energy requirements of mankind are met through burning of fossil fuels. However a series of serious problems have occurred due to over utilization of fossil fuels, such as climate change, CO₂ emission and ecological unbalance. Therefore, research and development activities are being actively undertaken worldwide on renewable energy sources. There are numerous applications of renewable energy sources such as space heating, space cooling and refrigeration, water heating, distillation, drying, etc. The main renewable energy sources which are used nowadays are solar, wind, biomass, geothermal and hydel. However, most of them have certain limitations in terms of consistency in availability, cost of harnessing, sustainability, etc. In India though wind energy is available in plenty, the pattern of wind changes in a particular place over a period of time. Thus, among the various options available, solar and biomass energy in combination has been identified as a viable option. Major part of Indian sub-continent receives abundant insolation for a considerable part of a year. Also, being predominantly an agricultural economy India has huge quantity of biomass available in the form of husk, straw, jute, cotton, shells of coconuts, wild bushes etc. Biomass fuels used in India account for about one third of the total fuel used in the country, being
the most important fuel used in over 90% of the rural households and about 15% of the urban households [1].

Drying is an important operation in the chemical, food, metallurgical, pharmaceutical and other industries. Fluidized bed drying (FBD) is considered to be one of the most successful drying techniques. The advantages of fluidized bed drying can be summarized as follows [2]:

- High heat and mass transfer rates, because of good contact between the particles and the drying gas.
- Uniform temperature and bulk moisture content of particles due to intensive particle mixing in the bed.
- Excellent temperature control and operation up to the highest temperature.
- High drying capacity due to high ratio of mass of air to mass of product.

Paddy is one of the food grains that is required to be dried after harvesting. Paddy is usually harvested at moisture content between 24 and 26% (wet basis). Any delays in drying, incomplete drying, or uneven drying will result in qualitative and quantitative losses. Drying process is energy intensive and the energy can be harnessed from solar biomass integrated system. Excess energy after meeting the in-house requirement of drying can be supplied to run an Organic Rankine Cycle (ORC). An ORC is a Rankine power cycle that uses an organic working fluid such as toluene, butane, isobutane, pentane, alkanes, fluorinated alkanes, ethers, fluorinated ethers etc. ORC technology has great potential in low and medium grade heat sources, especially in fields as waste heat recovery, biomass combustion, geothermal energy and solar thermal power [3]. ORC systems are also effectively applied in relatively small scale biomass power plants. Further benefits include low maintenance, favourable operating pressures and possibility of operation in a standalone mode.

2. System description

The working of the proposed solar-biomass integrated Fluidized Bed Dryer (FBD) for drying of paddy grains associated with Organic Rankine Cycle (ORC) power generation is shown in Fig.1. There are two separate air heating units that is solar air heater and biomass furnace assisted backup Heat Exchanger (HX). A conventional solar air heater typically consists of a transparent glass cover, finned absorber plate coated with lamp black and an outside insulation. Inside the biomass furnace there is a combustion chamber where biomass fuel (rice husk, coconut shell charcoal, wood chips, straw etc.) is charged at a required quantity, while ambient air is supplied at a required rate using a blower.

During a sunny day when adequate solar insolation is available, ambient air is to be inducted through a solar air heater. The incoming air gets heated and its temperature rises. A thermocouple temperature sensor measures the exit air temperature from the solar air heater and generates an equivalent electrical voltage. A Programmable Logic Controller (PLC) unit senses the electrical signal and generates an output signal. A programming unit controls the function of PLC. A limiting minimum threshold air temperature is reached for drying operation in a FBD as there is a risk of condensation of the outgoing air from FBD if the temperature of air further drops. Depending upon thermocouple temperature, PLC gives output signal to an actuator unit which in turn operates the flow control valves (valve 1 and valve 2). If the required temperature is gained by the solar air heater, then the hot air bypasses directly to the FBD using valve 2. Accordingly, valve 1 bypasses the hot flue-gas from biomass furnace to the Heat Recovery Steam Generator (HRSG). If the exit air temperature from solar air heater is less than the required drying temperature, then again the air is passed through a backup heat exchanger for further heating. Accordingly, hot flue-gas from biomass furnace first passes through the HX and then to the HRSG by means of valve 1. However, during cloudy days or at night when solar heating is unavailable, solar air heater is cut-off and ambient air enters the backup HX directly by means of valve 2. Accordingly, hot flue-gas from biomass furnace pass through the HX followed by the HRSG. Therefore, the system operates in following three different modes:

a. Solar only (during the hours of peak sunshine),
b. Solar-biomass (when solar heating is inadequate) and
c. Biomass only (During cloudy days or at night when solar heating is unavailable).
Figure 1. Proposed schematic of the solar-biomass integrated drying and power generation system
2.1 Drying
Hot air from the outlet of solar air heater or backup HX goes to a FBD. A blower is incorporated to pressurize the hot incoming air to generate the required air flow inside the dryer. In the FBD, hot air is passed at high pressure through a perforated bottom (air distributor) of the container containing grains to be dried. The grains are suspended in the stream of air and are lifted from the bottom. This condition is called fluidized state. The hot air surrounds every grains to completely dry them. Thus, all grains are dried uniformly. Then air along with some amount of dried grains pass through the cyclone separator. Through vortex separation remaining amount of dried grains are collected at bottom of the cyclone and air is discharged into the atmosphere by means of a blower.

2.2 Power generation
Hot flue-gas from the biomass furnace or backup HX is utilized in a HRSG to run ORC. HRSG typically consists of two units i.e. economiser and evaporator. Economiser is a heat exchanger intended to reduce energy consumption by performing useful function such as preheating the organic working fluid. It heats up the working fluid up to a temperature where it does not get converted into vapour. Thus it recovers residual heat from the flue-gas before releasing the same to atmosphere through the stack. In the evaporator, the working fluid is heated to saturated or superheated vapour. Next, the working fluid expands through an expander and produces mechanical work. A generator converts the mechanical work into electricity. A portion of this electricity generated is used to drive the blowers and the other in-house accessories, while the surplus electricity is supplied to the power grid. To re-use the heat after the expander for preheating the working fluid, a recuperator is used, which essentially increases the thermal efficiency. Thus a high power output can be maintained for a low heat input to the ORC. In order to use a recuperator, a superheated state is necessary after the expander [4]. Next, the working fluid is condensed to saturated liquid in the condenser. Then the pump pressurizes the working fluid and transports it to the economiser thereby completing the cycle.

3. Thermal modelling
The energy incident on the plane of the solar collector can be calculated as:

\[ E_s = I A_c \]  

(1)

where, \( A_c \) is the area of collector and \( I \) is the solar radiation incident on the collector. Useful heat gain rate from the solar air heater:

\[ Q_u = \dot{m}_a C_{pa}(T_{co} - T_{ci}) \]  

(2)

where, \( \dot{m}_a \) is the air mass flow rate, \( C_{pa} \) is the specific heat of air and \( T_{ci} \) and \( T_{co} \) are the inlet and outlet air temperatures of the solar air heater respectively. Outlet air temperature can be determined from instantaneous efficiency (\( \eta_i \)) of the solar air heater which can be given by:

\[ \eta_i = \frac{Q_u}{E_s} \]  

(3)

Well mixed continuous drying is considered for the Fluidized Bed Dryer (FBD) [5]. For the linear falling rate period residence time (\( t_k \)) can be determined from the equation:

\[ t_k = \frac{1}{k} \left( \frac{X_{in} - X_{eq}}{X_{in} - X_{eq} - 1} \right) \]  

(4)

In equation (4), \( X_{in} \) and \( X_{out} \) are the inlet and outlet moisture contents (db) of paddy grains respectively; \( X_{eq} \) is the equilibrium moisture content. \( k \) is the drying constant. Considering wet grain mass flow rate \( \dot{m} \), dry solid mass flow rate \( \dot{m}_g \) can be expressed as:

\[ \dot{m}_g = \frac{\dot{m}}{1 + X_m} \]  

(5)
Sizing of the bed is based on simple holdup mass balance. Cross-sectional area of the fluidized bed ($A_b$) can be determined from the following equation:

$$A_b = \frac{\dot{m}_g t_R}{\rho_a H_b}$$  \hspace{1cm} (6)

where, $\rho_a$ and $H_b$ are the bed density and bed height respectively. Operating air velocity ($u_a$) can be given by:

$$u_a = \frac{\dot{m}_a}{\rho_a A_b}$$  \hspace{1cm} (7)

In equation (7), $\rho_a$ is the density of air. Outlet air absolute humidity ($Y_{out}$) can be determined from the following mass balance equation:

$$\dot{m}_g (X_{in} - X_{out}) = \dot{m}_a (Y_{out} - Y_{in})$$  \hspace{1cm} (8)

where, $Y_{in}$ is the inlet air absolute humidity. Heat balance for the single-phase model gives the following energy balance:

$$\dot{m}_g h_{g,in} + \dot{m}_a h_{a,in} = \dot{m}_g h_{g,out} + \dot{m}_a h_{a,out} + Q_w$$  \hspace{1cm} (9)

In equation (9), $h$ denotes specific enthalpy and $Q_w$ is the rate of heat loss from wall of the dryer. As the bed of particles is perfectly mixed, the bed temperature is uniform and is equal to the product and exhaust air temperatures. The product and exhaust air temperature can be obtained from the heat balance equation (9). Specific enthalpy of grains at the inlet ($h_{g,in}$) and outlet ($h_{g,out}$) of the dryer can be obtained from the following equations:

$$h_{g,in} = (c_{pg} + X_{in} c_t) T_{g,in}$$  \hspace{1cm} (10)

$$h_{g,out} = (c_{pg} + X_{out} c_t) T_{g,out}$$  \hspace{1cm} (11)

where, $c_{pg}$ is the specific heat of dry grains, $c_t$ is the specific heat of water, $T_{g,in}$ and $T_{g,out}$ are the inlet and outlet temperatures of grains. Specific enthalpy of air at the inlet ($h_{a,in}$) and outlet ($h_{a,out}$) of the dryer can be obtained from the following equations:

$$h_{a,in} = (c_{pa} + Y_{in} c_t) T_{a,in} + Y_{in} \lambda$$  \hspace{1cm} (12)

$$h_{a,out} = (c_{pa} + Y_{out} c_t) T_{a,out} + Y_{out} \lambda$$  \hspace{1cm} (13)

where, $\lambda$ is the latent heat of vaporization of water, $T_{a,in}$ and $T_{a,out}$ are the air temperatures at inlet and outlet of the dryer respectively. From the psychrometric chart, relative humidity (RH) of outlet air can be determined from outlet air absolute humidity ($Y_{out}$) and outlet air temperature ($T_{a,out}$).

**Results and discussion**

Computer codes using Engineering Equation Solver (EES) have been developed based on the thermal model presented in the previous section to analyze the performance of the Fluidized Bed Dryer (FBD) for solar only condition (during the hours of sunshine) in Kolkata, India. The model considers various climatic and design parameters of the collector as well as the parameters related to the product to be dried (grains of paddy) as input and predicts the particle residence time, mass of water evaporated from the product per unit time, bed area as well as velocity, outlet temperature and absolute humidity of the air leaving the dryer. Also, the time required for drying of a given mass of wet product is estimated. Figure 2 shows the variation of grain moisture content at the outlet with drying time for various seasons of a climatic cycle (January, May and September). It is found that the moisture content reduces with the passage of time for all the months considered. However, it may be noted that the rate of decrease of moisture is maximum for a representative day in the month May followed with that of January and September respectively. The possible reason for this may be the fact that in the month of May both solar radiation intensity as well as ambient temperature are highest, while in the month of September ambient air relative humidity is the highest. Figure 3 shows the variation of dryer outlet air temperature and outlet grain moisture content with bed area keeping other parameters constant. It is found that air outlet temperature decreases with the increase in bed area. Also, the grain moisture content at the outlet also increases with the increase of the area of bed. The reason for this is the fact...
that with increase in area of the fluidized bed, mass flow rate of air increases, which in turn reduces the outlet air temperature from the dryer. But it may be noted that the decrease in air outlet temperature is highly non linear indicating that the reduction in air temperature is very high initially. Thus, from the design point of view, minimum bed area is desirable which will give minimum moisture content at the outlet of FBD and maximum grain/air temperature at the outlet.

4. Conclusion
In this paper, a novel scheme of a solar-biomass integrated Fluidized Bed Drying (FBD) system has been proposed for drying of agricultural food-grains like paddy. A thermal model for the proposed system has been developed. The performance of the system has been analysed for solar only condition for three months of a calendar year which represents three various seasons of the place considered. Following points are revealed from the analysis:

   a. For a given mass of paddy (60 kg) to be dried, the time required for removal of same quantity of moisture (25 to 15% db) is found to be minimum for a representative day in May (60 min) and the same is found to be maximum for a representative day in September (110 min).
   
   b. The bed area of FBD should be minimum to get best performance from the dryer in terms of more moisture removal and maximum grain/air outlet temperature.
   
   c. The study thus reinforces the viability of development of a solar energy based Fluidized Bed Dryer for drying of grains of paddy in rural areas of the country.

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