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Hybrid solar–biomass power plant without energy storage

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ABSTRACT

Non uniformity and high initial investment are the problems associated in solar energy technologies. Biomass power plant demands a huge amount of fuel feed which may not be available readily in all the places and times. A feed control in biomass fuel with variable solar radiation avoids the need of solar energy storage and saves the storage cost. In this work, solar parabolic collectors and biomass combustion have been arranged in parallel to produce steam for power generation. Solar energy is limited to a maximum share of 50% to avoid the operation of biomass combustion at low fuel feed rate in daytime. The performance characteristics of hybrid power plant have been developed with turbine inlet condition (pressure and temperature) and variation in solar energy sharing. The focused results are cycle thermal efficiency, hybrid plant thermal efficiency, plant fuel efficiency and specific power. The mass, energy and performance variations are studied under variable solar radiation. A case study has been carried out to validate the thermodynamic cycle results. The results show that the plant fuel energy efficiency increases from 16% to 29% with an increase in solar participation from 10% to 50% at the boiler pressure of 20 bar.

1. Introduction

The potential for biomass boilers in India is vast with over 370 million tons of biomass being produced every year. Biomass is available from agricultural wastes, direct harvesting and as a by-product from industries such as rice mills, sugar mills and saw mills. However, due to problems with infrastructure and the seasonal variability of biomass in India, consumers are struggling to obtain a consistent fuel supply. Furthermore, while biomass is still competitive, prices have increased considerably in recent years [1]. The solar energy is an intermittent nature of source. Integration of single source plants like combined cycle plants improve the overall energy conversion efficiency but it would not address the scarcity of fuel especially for seasonal available fuels [2,3]. Similarly the maximum limit for performance of solar thermal based power plant also limited to some extent [4]. Hybridization of solar thermal with biomass combustion complements each other, both seasonally and diurnally, to overcome their individual drawbacks and results continuous and uniform supply [5]. The sun's rays can be harnessed by solar collectors and biomass feedstock can be burnt as a supplementary fuel to achieve constant base load operation.

Hybrid power system has a great future due to its more flexibility in operation. Research and development efforts in solar, wind, and other renewable energy technologies are required to continue for, improving their performance, establishing techniques for accurately predicting their output and reliably integrating them with other conventional

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Nomenclature

h	specific enthalpy, kJ/kg
HHV	higher heating value, kJ/kg
m	mass flow, kg/s
I	solar radiation, W/m^2
q	heat, kJ
SESR	solar energy sharing ratio
w	work, kJ
η	efficiency

Subscripts

a	ambient
b	beam
c	collector
eg	electrical generator
g	global
p	pump
t	turbine

Abbreviations and acronyms

APH	air preheater
CPH	condensate preheater
ECO	economizer
ESP	electrostatic precipitator
EVA	evaporator
SH	superheater

generating sources [6]. Hybrid power systems can also be designed for power, heat and hydrogen generation [7]. Hybrid plants will become an increasingly attractive option as the cost of solar thermal falls and feedstock, fossil fuel and land prices continue to rise. Reichling and Kulacki [8] solved the economic factors for wind–solar hybrid power plant and showed the cost effectiveness of the total plant. Perez-Navarro et al. [9] proposed a hybrid system, combining a biomass gasification and a wind generation plants to compensate the deviations in the wind generation to 24 h. Astolfi et al. [10] evaluated the potential of a hybrid solar–geothermal plant based on an organic Rankine cycle (ORC). Nixon et al. [11] compared to biomass only, hybrid operation and showed a 29% of biomass savings. Michael Hart et al. [12] studied about the hybrid biomass–solar thermal system for heating and domestic hot water preparation for small residential applications. The literature survey shows that not much focus has been given in the area of hybridization of solar and biomass energies. The flow variations with variable solar participation have a key role on operation. The main objective of current work is the study of performance levels of biomass–solar hybrid plant under variable solar radiation and plant conditions. The flow rates, energy levels and performance variations are studied from sunrise to sunset time to understand the minimum and maximum levels.

2. Methodology

Fig. 1 shows the schematic layout for the hybrid power plant with water/steam, air and gas circuits. It is operated on a simple regenerative steam Rankine cycle. The heat source is separated and arranged in parallel for solar and biomass systems. The steam is generated from two sources in day time. In night time, steam can be generated only from biomass energy source without stopping. Biomass and preheated air are supplied to combustion chamber for complete combustion.

The hot flue gasses coming from the furnace flows over water/steam coils to generate steam from the feed water. The heat exchangers in the direction of flue gas are superheater, evaporator, economizer, condensate preheater and air preheater

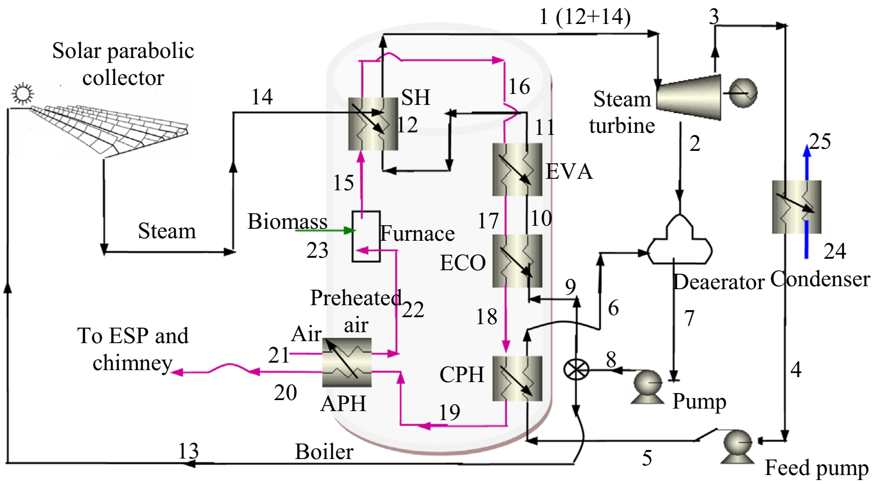

Fig. 1. Material flow diagram for hybrid solar–biomass power plant with solar collectors and biomass combustor.

and arranged to match the temperature glide. The biomass power plant is designed to operate from half load to full load condition. The condition of equal sharing occurs in day time at maximum available solar radiation in solar noon time. The full load condition for biomass plant will be reached in the night, sunrise and sunset timings. The biomass power plant will be operated at part load conditions from 50% to 100% load capacity between sunrise to noon and noon to sunset. An open feed water heater known as deaerator is located in between condenser pressure and boiler pressure. It is an inevitable component in a steam power plant [13]. Its location is defined in temperature ratio to analyze the deaerator pressure or temperature. The collector's efficiency decreases with an increase in working fluid temperature. Therefore, the steam temperature from collectors is limited to 350 °C to control the heat losses.

The following are the assumptions used in the proposed hybrid power plant. Atmospheric condition is taken as 1.01325 bar and 25 °C. The global solar radiation is considered as 960 W/m^2 with a beam component of 700 W/m^2. The solid fuel used in combustion is rice husk. For biomass combustion, the ultimate analysis of rice husk sample considered as C: 36.74%, H: 5.51%, O: 42.55%, N: 0.28%, S: 0.55 and ash 14.37% [4]. The moisture content in the rice husk is taken at 11.7%. The combustion chamber temperature is 850 °C which is maintained below the adiabatic flame temperature. The steam turbine inlet temperature and steam temperature in furnace is considered as 450 °C at 30 bar. The steam temperature from solar collectors is taken as 350 °C. Feed water heater is located in between the boiler saturation temperature and condenser temperature i.e. at 0.2 temperature ratio. The flue gas temperature at exit of economizer is 300 °C. The isentropic efficiency for the pump and turbine is taken at 75%. Electrical generator efficiency (η_{eg}) is taken as 98%. The mechanical efficiency for pump and turbine is considered as 96%. There are no heat losses in components and pipe lines.

The following are the formulae developed for thermodynamic evaluation of hybrid plant. The water supply to solar collectors depends on the instant value of solar radiation to generate the steam. The balanced steam can be generated using biomass from full combustion.

SESR (solar energy sharing ratio) is the ratio of solar energy usage to the total energy input to the hybrid plant to generate the steam.

$$\mathrm{SESR} = \frac{\text{Solar Energy Usage}}{\text{Solar Energy Usage} + \text{Biomass Energy Usage}} \tag{1}$$

$$\mathrm{SESR} = \frac{m_{13}(h_{14}-h_{13})}{[m_{13}(h_{14}-h_{13})]+[m_5(h_6-h_5)+(1-m_{13})(h_1-h_9)+m_{13}(h_1-h_{14})]} \tag{2}$$

The above equation can be simplified for m_{13} (steam generation from solar energy).

The water feed to solar collectors per unit mass of steam at turbine inlet,

$$m_{13} = \frac{\mathrm{SESR}(m_5(h_6-h_5)+(h_1-h_9))}{h_{14}-h_{13}+\mathrm{SESR}(h_{13}-h_9)} \tag{3}$$

SESR is kept constant at 0.5 for thermodynamic evaluation. It indicates that 50% of heat from solar collectors and the rest from biomass can be obtained at peak sun time. For biomass power plant, the rice husk is defined by a general formula as $C_{a_1}H_{a_2}O_{a_3}N_{a_4}$. For single carbon atom fuel, coefficient a_1 becomes one. The coefficients a_2, a_3 and a_4 are H/C, O/C and N/C mole ratios, respectively. The moisture content in the rice husk has been accounted in thermodynamic evaluation. The following is the chemical reaction in biomass combustion.

$$\begin{aligned}&(C_{a_1}H_{a_2}O_{a_3}N_{a_4})_{\text{biomass fuel}}+(a_5(O_2+3.76N_2))_{\text{air}}+(a_6H_2O(l))_{\textit{moisture content}}\\&\Rightarrow (b_1CO_2+b_2H_2O+b_3O_2+b_4N_2)_{\text{product gas}}\end{aligned} \tag{4}$$

The resulted chemical equation at the combustion conditions stated earlier section is

$$\begin{aligned}&(CH_{1.6178}O_{0.7389}N_{0.0139})_{\text{biomass fuel}}+(1.9015(O_2+3.76N_2))_{\text{air}}+(0.1105H_2O(l))_{\text{moisture content}}\\&\Rightarrow (CO_2+0.9194H_2O+0.8665O_2+7.1567N_2)_{\text{product gas}}\end{aligned} \tag{5}$$

The solar parabolic collector efficiency can be determined from the heat removal factor and efficiency factor [14].

The instant heat from the solar collectors,

$$q_{\text{solar}} = \eta_{\text{collector,b}} I_b A_{\text{tot c}} \tag{6}$$

therefore feed water to solar collectors,

$$m_{13} = \frac{q_{solar}}{h_{14}-h_{13}} \tag{7}$$

the feed water to biomass boiler,

$$m_9 = m_8 - m_{13} \tag{8}$$

heat supply from biomass energy,

$$q_{\text{biomass}} = m_5(h_6-h_5)+m_9(h_1-h_9)+m_{14}(h_1-h_{14}) \tag{9}$$

the net power from the hybrid plant,

$$w_{net} = w_t - w_p = (m_1(h_1-h_2)+(m_1-m_2)(h_2-h_3))\eta_t\eta_{eg} - \frac{m_5(h_5-h_4)}{\eta_p} - \frac{m_8(h_8-h_7)}{\eta_p} \tag{10}$$

work output using solar contribution,

$$w_{solar} = \frac{w_{net}q_{solar}}{q_{solar}+q_{biomass}} \tag{11}$$

similarly work output using biomass contribution,

$$w_{biomass} = \frac{w_{net}q_{biomass}}{q_{solar}+q_{biomass}} \tag{12}$$

the cycle thermal efficiency,

$$\eta_{cy} = \left(\frac{w_{net}}{q_{solar}+q_{biomass}}\right)\times 100 \tag{13}$$

the plant fuel efficiency,

$$\eta_{pl\ \ fuel} = \left(\frac{w_{net}}{m_{biomass}\mathrm{HHV}}\right)\times 100 \tag{14}$$

the hybrid plant thermal efficiency,

$$\eta_{pl\ \ th} = \left(\frac{w_{net}}{m_{biomass}\mathrm{HHV}+I_gA_{tot\ \ c}}\right)\times 100 \tag{15}$$

3. Results and discussion

The performance characteristics of solar–biomass hybrid power plant without energy storage have been developed. The performance is simulated at variable solar and biomass conditions. Biomass combustion is solved to result air fuel ratio at 850 °C of temperature. The plant efficiencies are evaluated with reference to higher heating value (HHV) of biomass fuel (11750 kJ/kg). The adiabatic flame temperature for biomass fuel (rice husk) is 1300 °C. The combustion temperature is designed below the adiabatic flame temperature and combustion is solved for the complete combustion. The resulted air fuel ratio is 9.5 at 5.15 stiochiometric air fuel ratio. Therefore the resulted relative air fuel ratio (ratio of actual air fuel ratio to stiochiometri air fuel ratio) is 1.84. It shows nearly 84% of extra air to be supplied to get required combustion temperature. At this condition, the molar product gas composition is CO_2: 10.05%, H_2O: 9.25%, O_2: 8.72% and N_2: 71.98.

Fig. 2 shows the influence of boiler pressure and temperature on hybrid plant performance. The cycle efficiency, specific power, hybrid plant efficiency and plant fuel efficiency have been studied with pressure variation from 20 bar to 60 bar and steam temperature from 300 °C to 450 °C. Fig. 2(a) depicts the variations in specific power and cycle thermal efficiency and Fig. 2(b) shows the variations in plant fuel efficiency and hybrid plant thermal efficiency with a change in pressure and temperature. As expected, the cycle thermal efficiency and specific power are increased with increase in boiler pressure

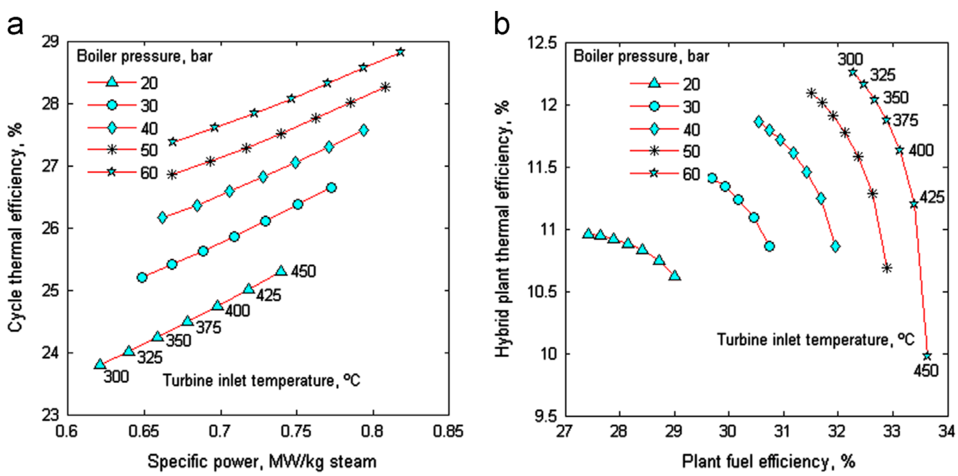

Fig. 2. Variations in (a) cycle efficiency-specific power and (b) hybrid plant efficiency-plant fuel efficiency with boiler pressure and turbine inlet temperature.

and temperature. Since the cycle performance is independent of solar–biomass sharing, it is changing with boiler pressure and temperature without noting the energy mix or share. The hybrid plant thermal efficiency decreases with an increase in steam temperature in boiler. It is because of increased solar collector's heat losses. The plant fuel efficiency is independent of solar radiation and is increasing with an increase in steam pressure and temperature. The hybrid plant thermal efficiency is increasing with an increase in boiler pressure. Therefore, the hybrid plant demands low steam temperature with high boiler pressure. The resulted variations in specific power and cycle thermal efficiency are 0.62–0.82 kW/kg steam and 24–29% respectively with a change in boiler pressure (10–60 bar) and turbine inlet temperature (300–450°). Similarly the variations in plant fuel efficiency and hybrid plant thermal efficiency are 27–34% and 10–12.3% respectively.

Fig. 3 shows the effect of solar energy share with boiler pressure on hybrid plant thermal efficiency and plant fuel efficiency. Obviously, the solar energy share in plant increases the plant fuel efficiency but it drops the hybrid plant thermal efficiency. It is because of low efficiency of solar collecting system compared to combustion efficiency. Interestingly, the boiler pressure is optimized at each solar energy share. The steam generation rate is different with a change in solar contribution in hybrid plant. The plant fuel efficiency increases with an increase in boiler pressure due to increase in power from steam turbine. At the same time, increase in boiler pressure also increases the mean temperature of heat addition and so more heat losses in solar concentrating collectors. It results a drop in hybrid plant thermal efficiency with solar role but a rise in turbine power with pressure increment. Therefore the hybrid plant thermal efficiency maximizes at a boiler pressure with a change in solar energy sharing as shown. The optimum boiler pressure decreases from 50 bar to 40 bar with an increase in solar share from 10% to 50%. The variations in plant fuel efficiency and hybrid plant thermal efficiency is 15–34% and 10–14.3% respectively with the changes in boiler pressure (20–60 bar) and solar energy sharing (10–50%).

Fig. 4(a) depicts the results of mass balance equations under variable solar radiation. The hybrid plant is designed at 50% solar energy share at noon time. The solar share will change from 0% to 50% respectively from sunrise or sunset to noon. The biomass share changes from 100% to 50% respectively from sunrise or sunset to noon. It avoids the no load condition in biomass plant. Biomass plant needs longer time to start. Therefore biomass plant can be operated continuously in day and night. It operates at full load condition in night time and part loads condition in day time. The solar collector's area is determined at peak solar condition and kept constant during simulation of plant operation. Water feed to solar collectors and biomass boiler is different due to fixation of different steam temperatures i.e. 350 °C and 450 °C respectively. The feed water flow to solar collectors (60%) is more than the biomass boiler (40%) to make equal contribution during peak sun time due to different steam temperatures. Therefore per unit mass of steam at turbine inlet, the water supply to solar collectors varies from 0 to 0.6 kg/s and it is 1 to 0.4 for biomass boiler. The fuel supply also changed from 0.42 kg/s to 0.2 kg/s in day time and it is kept constant at 0.42 kg/s in night operation. It is observed that the flow variations are slow in noon time and fast in forenoon and afternoon times. The biomass power plant is operated for 24 h with a flow variation in day time and constant in night time. The minimum and maximum steam generation in solar collector is 0 and 0.6 kg/s respectively. The minimum and maximum steam generation in biomass combustion boiler is 0.4 kg/s and 1 kg/s respectively. Similarly the minimum and maximum fuel feed to the biomass combustion chamber is 0.2 kg/s and 0.42 kg/s respectively. The biomass plant will work continuously for 24 h of operation without suffering much with the availability fuel. Since the mass flow

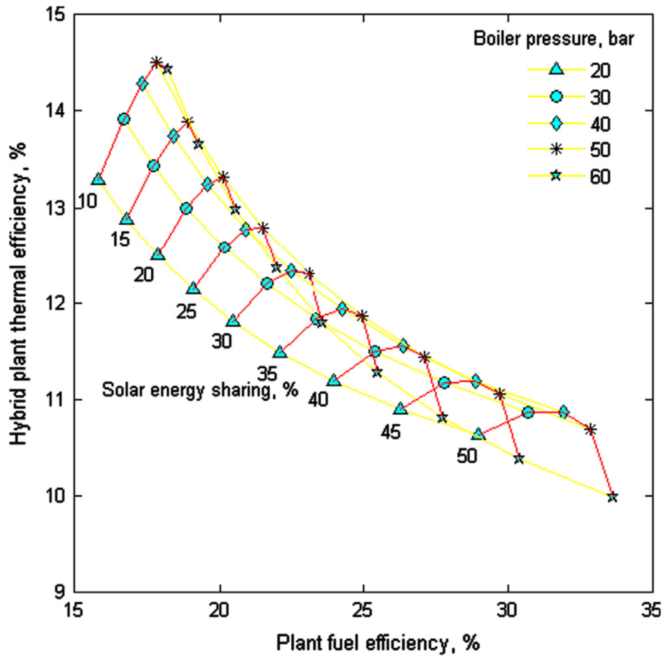

Fig. 3. Influence of solar contribution on hybrid plant thermal efficiency and fuel conversion efficiency with boiler pressure.

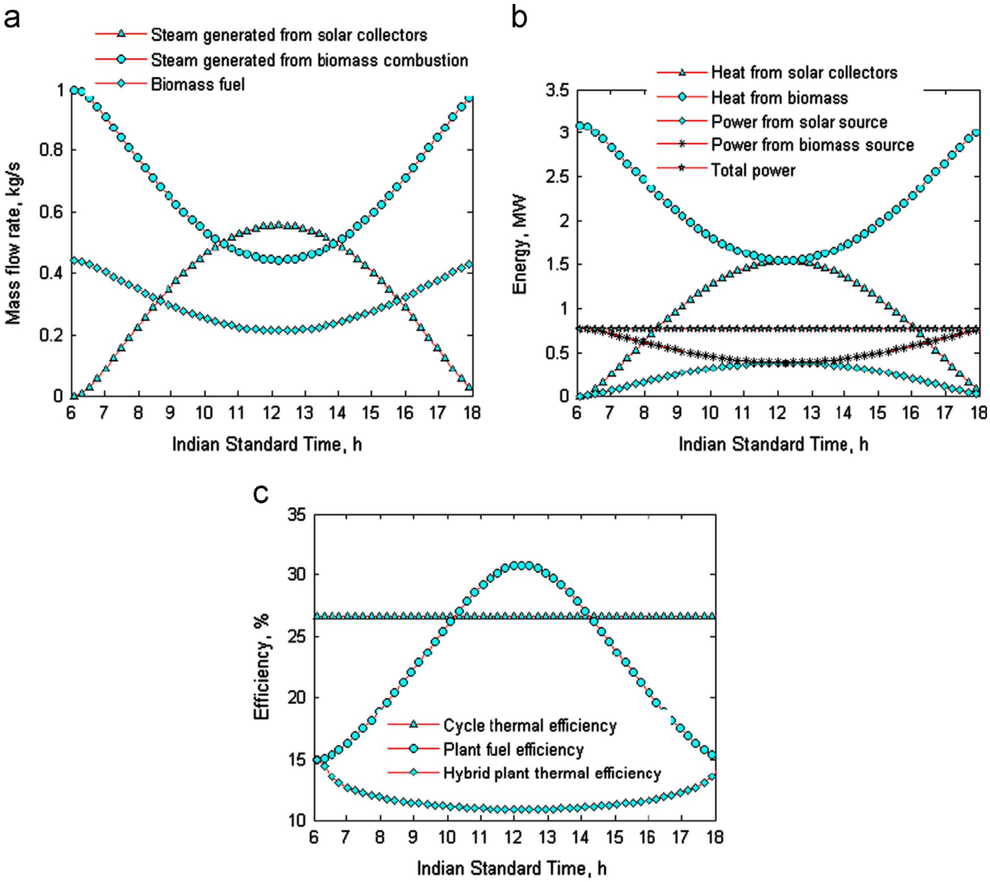

Fig. 4. Hybrid power plant performance variations during day time with 50% energy share at peak time

rates are designed at unit mass of steam at turbine inlet, the total steam can be determined from the plant capacity. Obviously, the flow rates will increase with increase in capacity of the plant.

Fig. 4(b) depicts the energy variations in hybrid power plant at unit mass of steam at turbine inlet. The plot is shown with reference to local standard time and calculations are made at solar time. The trends are followed with solar radiation which is function of time. The maximum and minimum energy transfers are occurred at the solar noon time. These maximum or minimum points are observed after 12.00 noon watch time as per local conditions. The solar collector efficiency is less than the combustion efficiency due to more heat losses from collector compared to furnace heat losses. So, the support of solar to biomass augments the fuel efficiency but not total thermal efficiency. Heat from solar collectors and biomass combustion is 1.5 MW each at equal sharing. The total input of this 3 MW supply should be constant to generate 0.8 MW of specific power output. The heat from biomass is decreased from 3 MW to 1.5 MW and again reached to 3 MW in day time as per the availability in solar energy. The solar energy is increased from 0 to 1.5 MW from sunrise to noon and then decreased to 0 in sunset time. The total power is constant at any instant of time. At noon, the output is each 0.4 MW at equal sharing. Power from solar source is increasing from 0 to 0.4 MW and then decreased to 0. The power from biomass source decreased from 0.8 MW to 0.4 MW and then increased to 0.8 MW. So irrespective of availability of solar radiation, a uniform power output can be generated without the use of storage system.

Fig. 4(c) shows the performance changes with time during sun hours at a fixed solar collecting area designed at maximum of 50% solar share. The cycle thermal efficiency is constant at 27% due to constant total heat supply per unit mass of steam irrespective of sharing. The plant fuel efficiency increases from sunrise to solar noon and decreases from noon to sunset. The minimum plant fuel efficiency with 100% biomass supply is 15%. The maximum plant fuel efficiency is reached to 32% with hybridization. So the integration addresses the fuel scarcity problem by improving the fuel efficiency. But the hybrid plant thermal efficiency decreases with the solar sharing because of lower collector efficiency compared to combustion system. The hybrid plant efficiency decreases from 15% (with only biomass) to 11% (with biomass and solar).

4. Validation

A case study has been carried out at a 3.5 MW biomass power plant located at Andhra Pradesh, India to validate the current thermodynamics works. In the plant, rice husk is used as a fuel for power generation. The combustion temperature for biomass combustion is 845.4 °C. The total air drawn into the biomass furnace is 58326 kg/h. At the same conditions of biomass power plant, the thermodynamic work results 60840 kg/h of air. In the plant, the air is supplied at different temperatures for primary and secondary air. In the calculations, an average temperature is considered. At the exit of air pre heater (APH), the exit temperature of primary air is 172.2 °C and exit temperature of secondary is 212.4 °C with a temperature drop of flue gas from 290.7 °C to 199.7 °C. The flue gas temperature is decreased from 845.4 °C to 290.7 °C by transferring heat to water/steam in superheater, boiler bank and economizer. In the model, the temperature drop in boiler is from 850 °C to 300 °C. The steam supply to turbine is 15.25 t per hour (TPH) in running plant during the observation. At the same operating conditions, thermal model results 14.5 TPH of steam. The deaerator pressure in the plant is 0.55 bar. The results are compared at 0.2 deaerator temperature ratio. At this temperature ratio, the deaerator pressure is 0.64 bar. The steam pressure at turbine inlet is 63 bar at 500 °C. The condenser pressure reading from the running plant and simulation are 42 °C and 40 °C respectively. The oxygen content in the flue gas observed in the plant is 4.4%. But the solution of thermodynamic reaction results 8% of oxygen due to assumed fuel composition for rice husk in the work. The air exit temperature at APH at plant and model are 192.3 °C and 200 °C respectively. The resulted power is 3.52 MW at a capacity of 3.5 MW. The overall plant and thermodynamic results show a satisfactory match with the case study results.

5. Conclusion

Hybridization of solar and biomass energies is proposed for power generation to address the issues associated with individual technologies. The plant fuel efficiency increases with an increase in solar support, boiler pressure and temperature but the hybrid plant thermal efficiency decreases with an increase in steam temperature. The optimum boiler pressure decreases (50–40 bar) with an increase in solar sharing (10–50%). The changes in fluid flow, energy interactions and performance are plotted with local time under variable solar radiation conditions. Since the solar collector is designed at 350 °C of steam compared to 450 °C of steam at biomass combustion, a more quantity i.e. 60% water is supplied to solar collectors and the rest of 40% is supplied to biomass furnace for equal sharing of energies in peak time. The specific output from the plant is 0.8 MW/kg of steam with the total heat supply of 3 MW. The cycle thermal efficiency under the specified conditions is 27%. The fuel efficiency is increased from 15% to 32% with the participation of solar energy. During day operation, there is a drop in hybrid plant thermal efficiency from 15% to 11% with addition of solar collectors because of low collector efficiency compared to combustion.

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