ABSTRACT

Tea is one of the principal and cheap soft drinks in the world. India is the second largest producer of tea, manufacturing about 1137 million kg of made tea (next to China with 1761 million kg annual production). India exports about 236 million kg tea with annual revenue of about $480 million (as per the statistics of the year 2012) from tea processing industry. Tea industry is about 200 years old and has about 0.58 million hectares of tea cropped land providing direct employment to about one million people. About half of the Indian tea production is contributed by the tea industries situated in Assam (a northeastern state of India). Black tea, which is a specially processed made tea, dominates Assam’s tea production.

Cost of tea processing has bearing influence on economy of tea production. Black tea processing consists of series of standard unit operations. They are withering (partial removal of moisture), rolling (size reduction), fermentation (biochemical reaction in presence of oxygen), drying, and sorting (fiber removal and grading). Energy is one major cost contributor in tea processing. About (90 to 95) % of total thermal energy is required in the form of hot air for tea drying. Traditionally, tea drying oil, natural gas, and coal are used as sources of thermal energy for tea processing in the factories located in Assam with some variation in specific energy consumption amongst the processing units. For example, about 24, 28 and 44 MJ of specific thermal energy were reported to be consumed by oil fired, gas fired and coal fired tea dryer, respectively for each kg of made tea processing.

There have been some issues concerning the uses of these conventional energy resources in tea processing such as, ever increasing cost of conventional fuel and adverse environmental impact. For example, the volatile prices of fossil fuel have badly affected the economy of Assam tea. Further, fossil fuel based tea processing industries in India has reported to emit about 3252 million kg greenhouse gas annually. Considering these issues, an alternative system of energy is essentially required for tea processing.

There have been several attempts to search for alternative energy sources comprising of cleaner new and renewable energy for different industrial applications.
There are many successful examples of renewable energy adaption both in thermal and electrical modes in industries. However, success of the application of renewable energy depends upon several local factors, primarily due to spatially and temporally varying availability and varying characteristics of the resources. Further, there are many renewable energy conversion technologies and the success of these technologies depends on appropriate research and development intervention.

Keeping in view of the above, the present research work has been directed to explore renewable energy resources and technological feasibility for substitution of conventional fuel in tea processing in Assam. Biomass gasification and solar thermal are two prominent renewable energy technologies. However, both of these sources have individual limitations with reference to uncertainty of spatial and temporal availability as per demand. Therefore, a hybrid mode of application for tea processing may be feasible, provided soundness of technologies is assured. The present investigation has focused to examine the usability of the said two renewable energy sources in three stages viz., (1) Characterization of some locally available biomass species, generation of appropriate mode of thermal energy through gasification, and tea drying experimentation and modelling with producer gas combustion product mixed with air as drying medium (2) technology for harnessing adequate quantity of solar thermal energy for tea processing and finally, (3) prospect of hybridization of gasification and solar thermal energy for fulfilling the need of tea processing.

Ten specific type of locally available biomass samples [Bambusa tulda, Delonix regia, Azadirachta indica, Ficus lepidosa, Dalbergia sissoo, Psidium guajava, Samanea saman, Camellia sinensis, Moringa oleifera and Polyalthia longifolia], were considered for proximate, ultimate analysis and determination of calorific values. Further, experiments were conducted using a 30 kW\text{thermal} (maximum output) biomass gasifier with selected species (Camellia sinensis, uprooted shrubs) of biomass to see technical feasibility and its performance to utilize as fuel for tea drying in a laboratory scale drying unit.
Laboratory scale tea drying experiments were also conducted in an attempt to investigate the comparative drying kinetics based on producer gas fueled drying and that of conventional mode of drying. An appropriate producer gas premixed burner was developed by modifying and existing 5 kW diffusion type gas burner. In the series of experiments, thin layer drying kinetics of fermented tea (*Camellia sinensis*) was investigated at both varying air temperatures (80, 90, 100, and 110) °C and varying flow rates [0.50, 0.65, and 0.75] m s⁻¹ of drying fluid using a producer gas burner laboratory scale tea dryer. The black tea drying data could be fitted to five different semi-theoretical models [viz., (1) Lewis, (2) Page, (3) Modified Page, (4) Henderson and Pabis and (5) Two Terms] to identify best-fit model. The best-fit model was further used to estimate activation energy required for tea drying while using producer gas as a fuel. During black tea drying experiment, rate of consumption of producer gas and fermented tea moisture loss were also recorded continuously to estimate specific energy consumption of the dryer.

In order to explore the prospect of another renewable energy source/technology, an attempt was made to design a suitable solar air heater for supplementing thermal energy for tea processing. The performance of a solar air heater mostly depends on surface geometry of absorber plate. Therefore, two types of surface geometries (viz., hemispherical, and smooth absorber) were examined and the best configuration was identified based on thermo hydraulic efficiency of hemispherical protruded absorber. The performance test result of the solar air heater with the best absorber plate configuration was further used to examine its usefulness to substitute thermal energy required for tea processing.

Finally, the possible hybridization of producer gas and solar hot air systems was analyzed by mixing solar hot air with producer gas combustion products. This was investigated based on the data assessed from laboratory scale experiments with a view to examine overall performance of the hybrid renewable energy system.

The analysis of the biomass characteristics data indicated the prospect of using all the ten biomass samples through gasification routes for generation of thermal energy although they exhibit some varying degree of fuel characteristics. Based on
their highest calorific value characteristics, *Camellia sinensis* (18.400 MJ kg⁻¹), *Psidium guajava* (18.403 MJ kg⁻¹) and *Bambusa tulda* (18.401 MJ kg⁻¹) were selected for further testing on gasification system for tea drying experiments.

For each atom of C, the variation of H atoms ranged between 1.866 (*Delonix regia*) and 1.580 (*Ficus lepidosa*). Such variation for N was *Azadirachta indica* (0.051) to *Camellia sinensis* (0.03). The variation of O atom was 0.698 (*Ficus lepidosa*) and 0.599 (*Bambusa tulda*). These results of fuel characteristics were useful to understand the behaviour of the fuels for gasification. While fueling the experimental downdraft gasifier using *Camellia sinensis*, output producer gas could be obtained with 4.5 MJ Nm⁻³ calorific values (measured using a Junker gas calorimeter). Further, the composition of producer gas with *Camellia sinensis* was analyzed and it was found in line with characteristics of the input fuel. Since all three fuels have almost similar calorific value, therefore, thermally all could be considered as suitable fuel for gasification. Therefore, use of these fuels as mixture may be recommended.

The suitability of producer gas (obtained from the mixture of *Camellia sinensis, Psidium guajava* and *Bambusa tulda*) for tea drying was ascertained from the drying experiments. Thin layer experimental studies of fermented tea with producer gas as a fuel gave the modified Page model [with drying rate constant \(k = 25.91 \times 10^{-4} \text{ s}^{-1}\) and exponent \(n = 1\) at 100 °C] as the best-fit model. In general, both the temperatures of drying media and its flow velocities influenced to drying rate constant \(k\) and exponent \(n\). Further, the modeled data was used to compute the diffusivity constant \(D_o = 0.746 \times 10^{-3} \text{ m}^2 \text{ s}^{-1}\) and activation energy \(E_a = 52.104 \text{ kJ mol}^{-1}\). Specific energy consumption of producer gas fired tea drying has been estimated as 10.20 MJ kg⁻¹ of water removed.

As mentioned earlier, the feasibility of using solar thermal energy for tea processing was examined through an optimally designed low cost flat plate solar air heater at solar radiation (790 W m⁻²). The size of the hemispherical protruded plate solar air heater single duct was 2400 mm × 375 mm × 37.5 mm. Thermal efficiency of
roughened solar air heater was found to be a strong function of air mass flow rate. Mass flow rate of air (0.028 kg m\(^{-2}\) s\(^{-1}\) from one duct) and with the surface roughness geometry (hemispherical protruded) of dimensionless relative roughness height \(\frac{e}{D} = 0.035\), relative roughness pitch \(\frac{p}{e} = 12\) and around Reynolds number 12000, the best thermo-hydraulic efficiency (74\%) was recorded.

Experiment was conducted with above configuration solar air heater and up to 65 °C outlet air temperature was achieved in summer at Tezpur University campus. Analytical studies based one experimental results showed that minimum contribution of solar energy was 12.9\% at (9.00-9.40) a.m., while maximum contribution was 27.23\% at (12.00-12.40) p.m in solar biomass hybrid mode. By using five 1.65 m\(^2\) improved solar air heater, average 20\% saving in biomass energy was possible.

Finally, based on the results of (i) gasification cum tea drying experiments and (ii) performance results of solar air heater for the test location, a techno-economic analysis was done to examine the prospect of hybrid mode of renewable energy use for tea drying. It was estimated that for a 0.99 M kg made tea factory, 28\% of tea drying thermal load may be covered by plantation of 22.5 ha *Bambusa tulda*, through biomass gasification in a 454 kW downdraft gasifier. It has been perceived that if 400 m\(^2\) of tea factory galvanized roof were converted by using black painting, plywood insulation and tempered glass enclosure to convert into solar air heater then average 20 \% of biomass energy may be saved. The annual carbon-dioxide reduction 2189 t is achievable. The payback period of the hybrid renewable thermal energy based system is less than fifteen months and benefit to cost ratio is 1:1.

There is potential benefit for application of biomass gasification and solar air preheating technology in tea manufacturing industries in Assam. However, proper government policy is required for long-term fast growing biomass plantation and its assured supply at regulated prices. Factory roof integrated efficient solar air heaters may effectively trap solar thermal energy. It is concluded that biomass gasification and solar air heater combined renewable energy technology is feasible for partial thermal energy substitution in tea manufacturing industries in Assam, India.