Chapter-7

Summary and Conclusions

The literature survey highlighted the fact that research has already been conducted to certain extent regarding energy conservation in tea drying. However, there is lack of sufficient research in the tea-leaf withering, especially in the local variety of Assam, India as evident from the literature. Thus, the present study focused on the energy aspect in the withering of fresh tea leaves. An assessment was first made on the energy consumption in the various tea processing stages in a local tea processing factory. The withering characteristics of local tea leaves were determined in an environmental chamber to learn the appropriate conditions of low-temperature drying followed by experiments in a newly developed laboratory set-up of solar thermal based tea withering trough. A comparative energy and exergy analysis of the tea-leaf withering trough was conducted using two different absorber plates in the SAH- first a corrugated plate and then with a plate having Al-can protrusions. The vital points concluded from the various studies done in this work are summarized below-

7.1 Assessment of energy consumption in a local tea factory

The energy expended in the different processing steps of CTC tea manufacturing was evaluated and compared with that of the South Indian tea industries. Energy management was assessed in terms of the cost of energy per unit volume of production. The average thermal energy consumed in some tea factories of Assam was around 20% higher than that in the Southern tea industries. The requirement of natural gas for thermal energy added a major portion to the production cost. The thermal energy consumed while drying 100 kg of fermented tea was 1791.11 MJ whereas that consumed to wither 100 kg tea leaves was estimated to be 179.10 MJ for the tea factory. The limited reserves of the conventional fuels are gradually making the tea production process costly both monetarily and energetically. However, an abundant stock of the non-conventional energy sources and their usage in the tea processing industries in future may help in recovering from this energy crisis situation.

Some methods that might be adopted to conserve thermal energy consumption in the tea factories in general are-

- Implementation of solar thermal energy.
- Using air heaters having good efficiency and insulation.

- Recovery of heat energy from dryer exhaust and flue gases.
- Using heat exchangers with better efficiency.
- Keeping an appropriate air-fuel ratio while operating the burner.
- Reuse of the exhaust air coming out of the dryer.

The electrical energy consumption in the tea processing industries could be saved by the following few measures-

- Usage of solar thermal energy.
- Using fiber reinforced plastic fans.
- Using automated rollers instead of manual ones.
- Using CFL bulbs, proper starter and electric control system.
- Using speed motor driven with variable speed and proper capacitor bank.

7.2 Withering characteristics of tea leaves in an environmental chamber

The low-temperature drying or simply withering of freshly plucked tea leaves were conducted in an environmental chamber. The drying air temperature as well as relative humidity had good impacts over the withering characteristics. The combination of 35 °C temperature and 80% RH showed the highest withering rate of 0.32 g water/g dry solid-h after 9 h. At 25 °C-90% RH, the minimum withering rate of 0.26 g water/g dry solid-h was observed. The first, second and third best fits were given by the Page, Lewis and Henderson and Pabis models respectively at drying air temperature of 30 °C and 90% RH. The R^2 and *RMSE* values for the models were (0.9989, 0.0051), (0.9988, 0.0054) and (0.9988, 0.0057) respectively. The corresponding adjusted R^2 values were 0.9988, 0.9988 and 0.9987. The mathematical models for the first, second and third best fits were obtained as follows:

$$MR = e^{\left(-0.0636t^{1.0020}\right)} \tag{7.1}$$

$$MR = e^{(-0.0640t)} \tag{7.2}$$

$$MR = 1.001e^{(-0.0641t)} \tag{7.3}$$

The specific energy consumed at drying air temperatures 25 °C, 30 °C and 35 °C for a constant RH of 90% were computed as 38.62, 32.55 and 26.34 MJ/kg respectively. Standard procedures were used to determine the overall phenolic and flavonoid contents of the tea-leaf samples withered at the same temperatures. The maximum TPC and TFC were obtained at 30 °C as (50.6 ± 0.02) mg GAE/g and (22.47 ± 0.01) mg QCE/g respectively.

7.3 Performance evaluation of a solar thermal based tea-leaf withering trough for low-temperature drying of tea leaves (*camellia assamica*)

The tea-leaf withering process was carried out in a newly developed solar thermal assisted withering trough. The withering of fresh tea-leaf samples took 7 h at 27 °C and 4 h at 32 °C. It was observed that the low temperature drying of tea leaves took place mostly in the falling rate period initially. The maximum rate of withering was 0.93 g water/g dry solid-h at the beginning at 32 °C and the minimum rate was 0.18 g water/g dry solid-h at the end of 4 h. The activation energy was estimated as 104.05 kJ/mol. The average velocity of air in the tea withering trough being much lower (0.10 m/s) than the tea drying fluidization velocity, the activation energy estimated was somewhat higher in case of green tea-leaf withering. The total energy input to the tea withering trough was calculated as 0.91 kWh with a specific energy consumption of 1.76 kWh/kg. The overall thermal efficiency of the solar-powered tea-leaf withering trough was computed as 40.98%. The average thermal efficiencies of the corrugated SAH during October and November' 2019 are evaluated as 63.15% and 56.06% respectively. For a life-span of 20 years, the economic payback period of the whole arrangement was computed to be 0.90 years. The Midilli-Kucuk model gave the best fit results at 27 °C with R^2 and *RMSE* values of 0.9976 and 0.0024 respectively. At 32 °C, the Two-term model gave the best fit with R^2 and *RMSE* values of 0.9977 and 0.0025 respectively. The best fit tea-leaf withering models at 27 °C and 32 °C air temperatures are as follows respectively-

$$MR = 1.001e^{-0.122t^{0.7586}} + 0.0292t \tag{7.4}$$

$$MR = 0.7097e^{-0.0082t} + 0.2908e^{-0.4492t} \tag{7.5}$$

7.4 Energy and exergy analyses of a solar powered tea-leaf withering trough with a corrugated plate SAH

The energy and exergy analyses of the tea-leaf withering trough were conducted by coupling the trough with a corrugated plate SAH. Experiments were conducted for three mass flow rates of 0.03, 0.04 and 0.05 kg/s. The maximum temperatures at the outlet obtained at 0.03 and 0.04 kg/s were 42.2 °C and 49 °C along with the respective temperature differences of 7 °C and 13.8 °C. The corresponding useful heat gains were

211.1 W and 554.8 W. Accordingly, the highest thermal efficiencies obtained at these two flow rates were 24.68% at solar radiation of 751 W/m^2 and 64.2% and 759 W/m^2. At 0.05 kg/s, the maximum outlet temperature was 46.6 ℃ with a temperature difference of 11.2 ℃. The peak thermal efficiency was 51.29% with the useful heat gain of 450.2 W at 755 W/m^2. The exergy efficiencies in the SAH varied within the ranges of (0.94-2.02) %, (1.61-3.82) %. and (1.88-3.8) % for the three flow rates.

In the tea-leaf withering trough with corrugated SAH, the average exergy loss values for the mass flow rates of 0.03, 0.04 and 0.05 kg/s were obtained as 1.41 W, 0.65 W and 1.28 W respectively. At 0.03 kg/s, the variation of exergy efficiency of the withering trough ranged from 25.98% to 81.09% during the day whereas these values varied within (52.11-94.23) % at 0.04 kg/s. The range of exergy efficiency of the trough comparatively reduced to (44.65-92.20) % at 0.05 kg/s mass flow rate. The improvement potential decreased from 0.78 J to 0.22 J as the mass flow went up from 0.03 to 0.04 kg/s. But it increased to 0.51 J at 0.05 kg/s. The waste exergy ratio values were respectively 0.49, 0.29 and 0.33. The sustainability index increased from 2.37 to 4.90 as the mass flow rate rose to 0.04 kg/s but again reduced to 3.92 at 0.05 kg/s. A simple economic analysis of the whole system was performed which resulted in a payback period of 0.90 years, making it economically viable.

7.5 Energy and exergy analyses of a solar powered tea-leaf withering trough with an SAH having Al-can protrusions in the absorber plate

Three mass flow rates of 0.03, 0.04 and 0.05 kg/s were considered to analyze the energy and exergy performances of the tea-leaf withering trough having Al-can protruded SAH. the maximum temperatures were respectively 52.1 ℃, 58.7 ℃ and 53.2 ℃ at the outlet for the mass flow rates of 0.03, 0.04 and 0.05 kg/s. At 0.03 kg/s, the useful heat gained was 575.8 W at a radiation of 752 W/m^2. The useful heat gains were computed as 972.8 W at 760 W/m^2 for 0.04 kg/s and 924.6 W at 756 W/m^2 for 0.05 kg/s. At 0.03 and 0.04 kg/s, the maximum thermal efficiencies obtained were 44.73% and 74.77% respectively. However, at 0.05 kg/s mass flow rate, the maximum thermal efficiency dropped down to 71.44%. The decrease in the energy efficiency was the result of less temperature rise due to more heat loss in this case as compared to the former. The variation of exergy efficiency of the SAH at 0.03 kg/s was between (1.87-3.16) %. At 0.04 and 0.05 kg/s, the exergy efficiency varied within the range of (2.28-5.84) % and (2.81-5.49) % respectively.

In the withering trough with Al-can SAH arrangement, the mean exergy loss values for the mass flow rates of 0.03, 0.04 and 0.05 kg/s were obtained as 1.29 W, 0.62 W and 0.87 W respectively. The exergy efficiency of the withering trough varied from 50.98% to 89.26% during the day at 0.03 kg/s. The values varied within (69.06-95.63) % and (52.28-95.20) % respectively at 0.04 and 0.05 kg/s. Here again, the improvement potential first decreased from 0.51 J to 0.15 J with the surge of mass flow rate from 0.03 to 0.04 kg/s. But it went up to 0.31 J at 0.05 kg/s. The corresponding waste exergy ratio values were 0.34, 0.20 and 0.33. Similarly, the sustainability index increased from 3.57 to 8.14 as the mass flow rate increased from 0.03 to 0.04 kg/s but dropped down to 4.41 at 0.05 kg/s. It indicates that the withering trough has better sustainability for the mass flow rate of 0.04 kg/s as compared to the other two in both the considered cases of absorber plates.

7.6 Environmental assessment of the withering trough with Al-can SAH arrangement

The total embodied energy was estimated to be 959.99 kWh for the entire system of arrangement. For a lifetime of 20 years, the energy payback period was obtained as 1.26 years. The CO_2 emission and mitigation for a lifespan of 5 to 20 years was computed respectively as (392.06-98.01) kg/year and (5.79-29.05) t. The earned carbon credit of 145.25 $ to 581 $ was estimated for a lifetime of 20 years. The assessment overall proved that the solar based tea-leaf withering process is an environmentally sound one.

7.7 Limitations of the work

The present work had certain limitations because the experiments were conducted in a scaled down laboratory experimental set-up of tea-leaf withering trough. The industrial data could not be directly taken in the experiments due to lack of such renewable energy based tea withering system in the industries working in the region (Assam). As such, many assumptions had to be taken while conducting the experiments. Moreover, the payback period and the carbon credit results might also differ to some value if actual data are taken.

7.8 Future scope

As a future work, the 4E (energy, exergy, economic, environmental) analyses for tea-leaf withering may be done for another type of geometrical protrusion in the absorber plate of the SAH and compared with the present results. Testing can be done for longer duration using a hybrid drying mode of solar and biomass energy. A factory roof-integrated SAH can be experimented for withering of tea leaves. The overall quality of the final made tea can be estimated by conducting the solar integrated tea withering along with the other stages of tea manufacturing. Moreover, other varieties of tea can also be experimented by using the similar technique.