2.1 Renewable and non-renewable energy application for process industries

Solar and biomass are two renewable energy resources considered for present black tea drying studies for local tea industries. Therefore, the different relevant literature are presented in the following sections. Solar air preheating for Longan drying had been reported in North Thailand and liquefied petroleum gas (LPG) was used conventionally for its drying purpose. It was observed that solar collectors could replace up to 19.6% of the thermal energy demand during the drying season. Bigger collectors and smaller air channels resulted in more useful heat, but attention was paid to both costs and pressure drop in air channels. Moreover, they observed that monetary savings varied greatly among different facilities. A higher solar fraction did not mean higher absolute savings. Therefore, maximizing use of the equipment was more important than the size. Some facilities could save significant amounts of money by substituting part of the fossil fuel requirement with solar energy. Longan drying lasted less than two months each year. Appropriate utilization of solar energy necessitated more feasibility of the system. Therefore, the drying facilities should operate a longer period over the year. The use of these facilities for drying alternative crops during other seasons might be a feasible solution [37]. Another study revealed the potential of solar industrial process heat application with five solar collectors, varying from the simple stationary flat-plate to movable parabolic trough ones. An estimation of the system efficiency of solar process heat plants operating in the Mediterranean climate were given for the different collector technologies. The annual energy gains of such systems were from (550 to 1100) kWh m$^{-2}$. The resulting energy costs obtained for solar heat were from (0.015 to 0.028) £/kWh$^{-1}$ depending on the collector type applied [38]. Energy demand and supply options for primary processing of rice in India had been reported and feasibility of using rice husk for meeting mechanical energy demand through gasification in dual fuel engine-generation route was explored. Moreover, the solar water heater for soaking of parboiled rice was accessed. For meeting the thermal energy demand, husk would continue as energy source until it was available as a free resource [39]. Another study reported technical
and economic evolution of solar dryer. They observed resources saving with such system by avoiding environmental pollution, product quality improvement, and increased energy effectiveness [40].

Wine industry wastes through thermal processing had been reported by proximate, ultimate, and calorimetric analysis (LHV 19.73 kJ kg$^{-1}$) of grape marc. It improved its fuel properties and revealed that their characteristics was similar to wood biomass, even higher energy impending. The product activation energy was 111.5 kJ mol$^{-1}$, and this was experimentally determined for industrial pyrolysis process conditions to provide a reliable value for real scale applications. The product equivalent chemical formula was established as $C_4H_7O_3$ and it could be used for thermal-chemical processes simulations. The pyrolysis solid, liquid, and gas products were investigated along with their formation mechanisms. For all treatment temperatures, the process energy balance was positive, and the process was self-sustained by the pyrolysis gas energy alone. The maximum net energy content found in pyrolysis products were achieved at 550 °C [41].

2.1.1 Energy conservation and efficiency

Energy use and energy efficiency in the European dairy industry had been reported and changes in energy efficiency were monitored in two different ways. One way was to look at the energy use by tonne of milk processed by dairies. Another way was by comparing the actual energy use with the energy that would have been used if no changes in energy efficiency had taken place. German, British, and Dutch dairy industries had achieved considerable improvements in energy efficiency, contrary to the developments showed by the French industry. Furthermore, by the end of the 1990s, Germany, Netherlands, and the United Kingdom were converging in their energy efficiency values [42]. Desiccated coconut industry of Sri Lanka for opportunities, energy efficiency, and environmental protection has been reported and it was estimated that the desiccated coconut sector in Sri Lanka consumed about 21,660 tons of firewood, 16.5 million liters of furnace oil and 10 GWh of electricity annually. This constituted about 0.16 % of the total energy consumption of 0.3 PJ of
Sri Lanka and about 0.2 % of the annual national electricity production. The implementation of energy saving devices and better energy management might lead to a reduction of CO₂ emission and reduced the cost of environmental cleanup [43]. Another study reported energy management method for the food industry by top-down modelling approach. This method was especially appropriate for non-energy intensive industry where the resources for energy management were often limited. The top-down approach had permitted to model the energy consumptions with multi-linear regression models [44]. Thermal energy management in the bread baking industry was reported using a system modelling approach. It quantified the energy required to bake the dough, and conducted a detailed analysis of the breakdown of losses from the oven. A computational fluid dynamics (CFD) optimization study was undertaken, resulting in improved operating conditions for bread baking with reduced energy usage and baking time. Overall, by combining the two approaches, the analyses suggested that bake time may be reduced by up to 10% and the specific energy required for baking each loaf reduced by approximately 2%. For UK industry, these savings equate to more than £0.5 million cost and carbon reduction of more than 5000 tonnes CO₂ per year [45].

A framework for estimation of specific energy consumption and carbon dioxide mitigation with solar drying was reported considering fossil fuels as coal, diesel, natural gas, and LPG. The results of investigation indicated that for all drying test conditions, the given dryer was capable to mitigate the maximum CO₂ emissions with the replacement of coal by solar energy. Larger values of absorbed energy and load density caused increased specific energy consumption and CO₂ mitigation potential whereas reverse trend was observed for sample thickness. However, the influence of airflow rate on these parameters was found to be quite different. In order to establish functional relationship between specific energy consumption and process variables, a correlation was developed using Levenberge Marquart algorithm. The statistical error analysis revealed that the proposed correlation was capable of satisfactory prediction of experimental results [46].
Food industry in Taiwan was labour intensive, cost of raw materials was high, and there was much product diversification. Although this industry was primarily small and medium scale, it was a large user of electricity in Taiwan's manufacturing sector. The concentration of greenhouse gases (GHGs) from manufacturing activities had increased remarkably. Energy audits were a basic and direct means by which energy efficiency could be improved, energy consumption reduced, and carbon dioxide emissions inhibited. This work summarized the energy saving potential of 76 firms and the energy savings implemented by 23 firms as determined by energy audit tracking and from the on-line energy declaration system in Taiwan’s food industry. The results of this study can serve as a benchmark for developing a quantified list in terms of potential energy savings and opportunities for improving the efficiency of the food industry [47]. Another study observed that industrial sector used more energy than any other end-use sectors and currently this sector was consuming about 37% of the world’s total delivered energy. Energy was consumed in the industrial sector by a diverse group of industries including manufacturing, agriculture, mining, and construction and for a wide range of activities, such as processing and assembly, space conditioning, and lighting. Energy saving technologies, such as use of high efficiency motors (HEMs), variable speed drives (VSDs), economizers, leak prevention and reducing pressure drop has been reviewed. Based on energy saving technologies results, it has been found that in the industrial sectors, a sizeable amount of electric energy, emissions and utility bill can be saved using these technologies. Payback periods for different energy savings measures had been identified, and it was found economically viable in most cases [48].

Environmental policies are largely devoted to nurturing the development and implementation of renewable energy technologies. One important aspect of this transition was the increased use of biomass to generate renewable energy. Agricultural residues were produced in huge amounts worldwide, and most of this residue was composed of biomass that could be used for energy generation. As a result, converting this residue into energy could increase the value of waste materials and reduced the environmental impact of waste disposal. Studies analysed the
situation of biomass energy resources in Andalusia, an autonomous community in the south of Spain. More specifically, biomass is a renewable source that prominently contributes to Andalusian energy infrastructure. The residual biomass produced in the olive sector is the result of the large quantity of olive groves and olive oil manufacturers that generate byproducts with a potentially high-energy content. The generation of agricultural and industrial residues from the olive sector produced in Andalusia was an important source of different types of residual biomass. They were suitable for thermal and electric energy since it reduced the negative environmental effects of emissions from fossil fuels, such as the production of carbon dioxide [49].

Thermal energy loss in the process industry was reported as a significant issue due to the high temperatures and multiple heat intensive processes involved. High-grade thermal energy was typically recovered within processes. However, lower grade heat was often rejected to the environment. The temperature of the low-grade heat stream was the most important parameter, as the effective use of the residual heat or the efficiency of energy recovery from the low-grade heat sources would mainly depend on the temperature difference between the source and a suitable sink. High and low-grade heat sources were defined according to the viability of recovery within the processes. Finally, different aspects that influenced the decision making for low-grade heat recovery in the process industry were discussed. It was concluded that organizational, financial, and economic barriers might be overcome and benefits from a holistic vision could be gained with stronger governmental policy and regulation incentives [50].

Fluid-milk processing industry around the world processes approximately 60% of total unprocessed milk production to create various fresh fluid-milk products. Fluid-milk processing data across number of countries and regions were compiled and analysed. The study had found that the average final energy intensity of individual plants exhibited significant large variations, ranging from 0.2 to 12.6 MJ kg⁻¹ fluid-milk products across various plants in different countries and regions. In addition, it was observed that while the majority of larger plants tended to exhibit higher energy
efficiency, some exceptions existed for smaller plants with higher efficiency. These significant differences had indicated large potential energy-savings opportunities in the sector across many countries. Furthermore, this study illustrated a positive correlation between implementing energy-monitoring programs and curbing the increasing trend in energy demand per equivalent fluid-milk product over time in the fluid-milk sector. It was opined that developing an energy-benchmarking framework, along with promulgating new policy options should be pursued for improving energy efficiency in global fluid-milk processing industry [51].

Energy saving opportunities in the food-processing industry through a combination of top-down and bottom-up approaches was reported. On the one hand, the top-down modelling method aimed at correlating the measured energy consumptions with the final products and auxiliaries as well as at allocating the energy bills among major consumers. This approach might set priorities for energy saving actions. On the other hand, the bottom-up approach, which was based on the thermodynamic requirements of the process operations, was used to define the energy requirements of these consumers. A comparison of the measured consumptions and the energy requirements enabled the identification of energy saving opportunities. In the case study presented in this article, these opportunities had been evaluated using thermo-economic modelling tools and range from good housekeeping measured and optimized process operations to energy saving investments [52].

An indicator to monitor energy efficiency developments in the food and tobacco industry based on physical production data at the firm level provided by the statistics office of the Netherlands in a confidential basis was reported. They measured energy efficiency by using an energy efficiency indicator that was the aggregate specific energy consumption. The results showed that the food and tobacco industry had improved their energy efficiency indicator in primary terms by about 1% per year (uncertainty range between 0.9 and 1.3). In terms of final energy, there had been a decrease on the indicator for final demand of fuels of about 1.8% per annum while there had been no improvement in the indicator for final demand of
electricity. The development in energy efficiency was coherent with the reported implementation rate of energy conservation projects. They concluded that the type and the quality of the data compiled by Statistics Netherlands for the food sector was sufficient to develop indicators as required by energy and climate policy [53].

Global cheese-making industry was reported to process approximately one quarter of total raw milk production to create a variety of consumer cheeses. Characterizing energy usage in existing cheese markets and plants might provide baseline information to allow comparisons of energy performance of individual plants and systems. The study had found that the magnitudes of average final energy intensity exhibited significant variations, ranging from 4.9 to 8.9 MJ kg\(^{-1}\) cheese across the few countries. Energy intensity variation ranged from 1.8 to 68.2 MJ kg\(^{-1}\) of cheese from the countries in this study. These significant differences had indicated large potential energy savings opportunities in the sector. Development and dissemination of an energy-benchmarking framework including a process step approach and efficiency measures might be recommended for evaluating energy performance and improving energy efficiency in cheese-making industry [54].

Tea processing is energy intensive operation i.e., withering, drying, grading, and packing tea requires 4 to 18 kWh kg\(^{-1}\) of made tea, which compares to 6.3 kWh for a kilogram of steel. Energy cost is about 30% of total cost therefore less importance is put for energy efficiency and conservation in tea manufacturing sectors. Total specific thermal energy consumption varies between 4.45–6.84 kWh kg\(^{-1}\) processed teas. Environment and climate impact show that total fuel consumption by the tea sector in India contributes annual CO\(_2\) emissions of 1,352,000 tons [55].

2.1.2 Justification for renewable energy resources for tea industries

Energy in general and thermal energy in particular has been a critical input to the tea processing sector which is one of the important food industries in Assam (India). Renewable energy has been identified as the alternative to the conventional fossil based energy system mostly for electrical generation as well as thermal application all over the world. The attempts to use renewable energy sources for tea
processing have been limited almost to research and development. The application of solar air heater to save about 25% of the conventional energy in tea processing has been reported for a specific case in Tamil Nadu (India) [56]. There are also similar reports on prospects of solar thermal energy to preheat combustion air that saved (25-34%) conventional fuel. Computer model was developed to evaluate the performance of a solar-powered drying system in relation to sunshine hours and air relative humidity and temperature [57, 58]. Biomass generated producer gas in tea processing based on analytical study and experiment concerning a specific case in Sri Lanka has been reported [59]. Principles and field experience on the open top biomass gasification technology developed at Indian Institute of Science has reported diesel savings in the range of 80% for dual fuel mode of operation in the entire power range. Thermal applications for low and high temperature uses in the range of (0.2 to 5) MW_{thermal} for drying and heat treatment applications were in operation. Cumulative experience of 80,000 h over a dozen systems has resulted in a fossil fuel saving of 350 tonnes; typical daily saving was approximately 18 m³ of fossil fuels. This replacement had resulted in a net reduction of approximately 1120 tonnes of CO₂ and this was a promising candidate for clean development mechanism [60].

The present studies consider prospect of biomass gasifier and solar thermal hybrid renewable thermal energy based tea-drying system in Assam. Biomass gasification is considered because tea industry is an agro based unit with own generation of waste biomass. Moreover, solar thermal energy is available except the a few summer and winter months (about 30-35% time over the year). Generation of electrical power from biomass gasifier and then use it for electric dryer is not recommended for higher overall cost and low overall efficiency. Cogeneration system with fluidized bed boiler or combined heat and power system are not consider because of complexity of technology for local tea industry to convince even though overall efficiency of the system is higher. Moreover, biomass preparation for fluidized bed boiler would increase fuel preparation cost. Therefore, a simple downdraft biomass gasifier and improved solar air heater technologies are considered for present studies.
2.2 Biomass gasification

Biomass gasification is a thermo chemical energy conversion technology that converts especially solid, liquid, and gaseous fuel (both fossil and non-fossil) into combustible gaseous products and useful chemicals. The primary objectives of gasification are to increase heating value of product fuel by rejecting non-combustible components like nitrogen, water, etc. As a result, it does not release these products to atmosphere. Moreover, gasification reduces carbon to hydrogen mass ratio in the fuel. Carbon to hydrogen ratio for anthracite coal is about 44, whereas for synthetic gas (CO: H₂) this value is 0.2 only. Normally gasification takes place in limited supply of air (sub-stoichiometric, $\phi = 0.20-0.35$). Four overlapping biochemical processes take place inside a gasifier (reactor). They are namely drying, pyrolysis, combustion, and reduction reactions. The principal attraction of gasification is evident from following discussion. A gasified fuel is useful in wide range of energy applications. Downstream cleaning in gasification is less expensive than coal fired plant, with flue gas desulphurization, selective catalytic reducers, and electrostatic precipitator, etc. Poly-generation is effectively possible with a gasification plant. It can supply steam for process heat generation, electricity to grid and gas for synthesis of chemicals. If the gasification feedstock has high sulphur, elemental sulphur is produced as byproduct, for high ash fuel slag or fly ash is recovered that may be used for cement manufacturing. Integrated gasification combined cycle plant achieve higher overall efficiency (38-41) percentage and therefore gasification provides lower power production cost. Moreover, transportation of synthetic fuel or liquid produced from it is less expensive than that solid fuel. Carbon dioxide capture and sequestration cost for integrated gasification combined cycle (IGCC) plant is half to that of pulverized coal fired system. The total water consumption in gasification-based power plant is much lower than coal fired plants. Moreover, the same water may be recycled for gasification both in thermal and electrical generation. Gasification plant produces lower amount of sulphur dioxide, oxides of nitrogen, and particulate matter. Its emission is similar to a natural gas fired plant [61, 62].
2.2.1 Drying

Gasification comprises of four energy conversion processes namely drying, pyrolysis, char gasification, and combustion. However, there is no separate boundary for each reaction and they are mostly overlapping with each other. Drying of biomass is utmost important for subsequent appropriate gasification reaction. For production of producer gas with reasonable calorific value, the moisture of the feedstock must be within the range \((10 - 20)\) percentage. The complete drying of biomass takes place when it enters into the gasifier. The heat available from combustion zone is utilized for drying purposes. Above 100 °C temperature, the loosely bound water removes irreversibly. As the temperature rises, low molecular weight extractives start to volatilize and the process continues until temperature reaches 200 °C [61].

2.2.2 Pyrolysis

After drying, next thermo chemical process is pyrolysis that takes place in absence of air. It involves thermal breakdown of large hydrocarbon molecules of large biomass into smaller gas molecules (condensable and non-condensable). There is no major chemical reaction with air, gas or any gasifying medium. Tar forms by condensation of vapour produced by pyrolysis. Tar is a sticky liquid that must be combusted for production of producer gas in subsequent process. The products of pyrolysis are solid, liquid and gas as given by following reaction [61].

\[
C_xH_yO_z + \text{Heat} \rightarrow \Sigma_{\text{liquids}} C_a H_b O_c + \Sigma_{\text{gases}} C_m H_n O_p + \Sigma_{\text{solids}} C
\]

(2.1)

2.2.3 Gasification reactions

The following chemical reactions take place inside a gasifier when it is operated at appropriate condition [61].
**Literature Review**

<table>
<thead>
<tr>
<th>Reaction Type</th>
<th>Reactions</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Carbon reaction</strong></td>
<td></td>
</tr>
<tr>
<td>R1 (Boudouard)</td>
<td>( C + O_2 \leftrightarrow 2CO + 172 \text{ kJ mol}^{-1} )</td>
</tr>
<tr>
<td>R2 (Water gas or steam)</td>
<td>( C + H_2O \leftrightarrow CO + H_2 + 131 \text{ kJ mol}^{-1} )</td>
</tr>
<tr>
<td>R3 (Hydro gasification)</td>
<td>( C + 2H_2 \leftrightarrow CH_4 - 74.8 \text{ kJ mol}^{-1} )</td>
</tr>
<tr>
<td>R4</td>
<td>( C + \frac{1}{2}O_2 \rightarrow CO -111 \text{ kJ mol}^{-1} )</td>
</tr>
<tr>
<td><strong>Oxidation reaction</strong></td>
<td></td>
</tr>
<tr>
<td>R5</td>
<td>( C + O_2 \rightarrow CO_2 - 394 \text{ kJ mol}^{-1} )</td>
</tr>
<tr>
<td>R6</td>
<td>( CO + \frac{1}{2}O_2 \rightarrow CO_2 -284 \text{ kJ mol}^{-1} )</td>
</tr>
<tr>
<td>R7</td>
<td>( CH_4 + 2O_2 \leftrightarrow CO_2 + H_2O -803 \text{ kJ mol}^{-1} )</td>
</tr>
<tr>
<td>R8</td>
<td>( H_2 + \frac{1}{2}O_2 \leftrightarrow H_2O -242 \text{ kJ mol}^{-1} )</td>
</tr>
<tr>
<td><strong>Shift Reaction</strong></td>
<td></td>
</tr>
<tr>
<td>R9</td>
<td>( CO + H_2O \leftrightarrow CO_2 + H_2 -41.2 \text{ kJ mol}^{-1} )</td>
</tr>
<tr>
<td><strong>Methanation Reaction</strong></td>
<td></td>
</tr>
<tr>
<td>R10</td>
<td>( 2CO + 2H_2 \rightarrow CH_4 + CO_2 -247 \text{ kJ mol}^{-1} )</td>
</tr>
<tr>
<td>R11</td>
<td>( CO + 3H_2 \rightarrow CH_4 + H_2O -206 \text{ kJ mol}^{-1} )</td>
</tr>
<tr>
<td>R14</td>
<td>( CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O -165 \text{ kJ mol}^{-1} )</td>
</tr>
<tr>
<td><strong>Steam Reforming Reaction</strong></td>
<td></td>
</tr>
<tr>
<td>R12</td>
<td>( CH_4 + H_2O \rightarrow CO + 3H_2 + 206 \text{ kJ mol}^{-1} )</td>
</tr>
<tr>
<td>R13</td>
<td>( CH_4 + \frac{1}{2}O_2 \rightarrow CO + 2H_2 -36 \text{ kJ mol}^{-1} )</td>
</tr>
</tbody>
</table>

**Charcoal gasification**

Charcoal produced by pyrolysis of biomass is not necessarily a pure carbon. It may contain certain amount of hydrocarbon, hydrogen, and oxygen. Biomass char is normally more porous and reactive than coke. Gasification of biomass charcoal involves several reactions with carbon, carbon dioxide, steam, hydrogen, methane, etc., as discussed below.

\[ \text{Charcoal} + CO_2 \rightarrow CO_2 + CO \]  \hspace{1cm} (2.2a)
\[ \text{Charcoal} + CO_2 \rightarrow 2CO \] \hspace{1cm} (2.2b)
\[ \text{Charcoal} + H_2O \rightarrow CH_4 + CO \] \hspace{1cm} (2.2c)
Gasification reactions are generally endothermic, but some of them are exothermic also. Reactions R3, R4 and R5 are exothermic and reaction R1 and R2 are endothermic. The rate of gasification depends on its reactivity and reaction potential of gasifying medium. The rate of charcoal oxygen reaction is fastest among (R1 – R4) and it consumes oxygen immediately. The Boudouard reaction or char carbon dioxide reaction is six to seven orders slower [62]. The rate of water gas or water-steam gasification reaction (R2) is about two to five times faster than the Boudouard reaction [63]. The charcoal hydrogen that forms methane is slowest of all reactions. Walker estimated relative rate of four reactions at 800 °C and 10 kPa pressure, as $10^5$ for oxygen, $10^3$ for steam, $10^1$ for carbon dioxide, $3 \times 10^{-3}$ for hydrogen [64].

**Boudouard reaction**

According to Blasi [63], CO₂ dissociates at a carbon free active site. It releases carbon monoxide and forms a carbon-oxygen surface complex. This reaction can move in the opposite direction as well forming carbon active site and CO₂ in second step. In the third stage, carbon-oxygen molecules produce molecules of CO.

**Water gas shift reaction**

The gasification of charcoal in steam is known as water gas reaction. The first step involves the dissociation of water on free active site of carbon. It releases hydrogen and forms a surface oxide form of carbon. In second and third step, surface oxide complex produces a free new active site and a molecule of carbon monoxide. Balsi [63] suggested the possibility of hydrogen inhibition by C (H) or C (H₂) complexes. The presence of hydrogen has a strong inhibition effect on charcoal gasification rate in water.

**Shift reaction**

The shift reaction is an important gas phase reaction. It increases hydrogen content of gasification product at the expense of carbon monoxide. Reaction (R9) represents the syngas production downstream of gasifier, where ratio of hydrogen and
carbon monoxide in the product gas is critical. The shift reaction is slightly exothermic, and its equilibrium yield decreases slowly with temperature. Depending on the temperature, it may proceed in either direction of product or reactant. However, it is not sensitive to change in pressure [65]. Above 1000 °C, the shift reaction (R9) rapidly reaches equilibrium. Probestien and Hicks [66] showed that this reaction had a higher equilibrium constant at a lower temperature that is high yield of hydrogen at lower temperature. With increase in temperature, yield decreases, but reaction rate increases. Optimal yield takes place at 225 °C.

Hydrogasification reaction

This reaction takes place with gasification of charcoal in a hydrogen environment that leads to production of methane. The rate of this reaction is much slower than that of other reaction.

Charcoal combustion reaction

Most of the gasification reactions are endothermic. To provide the required heat of reaction as well as required drying, heating and pyrolysis, a certain amount of exothermic combustion reactions are allowed inside gasifier. Reaction (R5) yields highest amount of heat (394 kJ) per kilo-mole of carbon consumed. The reaction (R4) takes place with production CO (111 kJ) per kilo-mole carbon. Combustion reactions rates are about one order magnitude faster than gasification reaction. Fine charcoal particles react faster due to its high pore diffusion rate.

2.3 Characterization of biomass

Biomass refers to any organic materials that are derived from plants or animal [67]. The United Nations Framework Convention on Climate Change defines biomass as a non-fossilized and biodegradable organic material originating from plant, animal, and microorganisms. This shall also include product, byproducts, residues, and waste from agriculture, forestry, and related industries as well as non-fossilized biodegradable organic fraction of industrial and municipality waste [68]. This includes both primary biomass and derived biomass. Primary biomass directly comes
from plants and elements. Primary biomass includes woods, plants, and leaves (ligno-cellulose), crops, and vegetables (carbohydrates). Derived biomass includes solid and liquid waste, sewage human, and animals waste, gas derived from landfilling and agricultural waste.

Ligno-cellulosic biomass is non-starch fibrous part of the plant materials. Cellulose, hemicellulose, and lignin are its three principal constituents. Woody plants are lingo-cellulosic biomass and they may be of two types namely herbaceous and non-herbaceous. An herbaceous plant is one with leaves and stems that die annually at the end of the growing season. These plants do not have bark. Non-herbaceous perennials like wood plants have stem above the ground. The trunk and leaves of tree plants form the biggest group of biomass. Energy crops such as miscanthus, willow, switch grass, and poplar may be considered as very effective lingo-cellulosic woody biomass.

2.3.1 Constituents of biomass cell

The polymeric composition of the cell wall and other constituents of a biomass vary widely [69]. However, they are composed of three polymers hemicellulose, cellulose, and lignin. Cellulose is primary structural component of biomass and it varies from 90% in cotton to 33% in most other plants. The generic formula of cellulose is \((\text{C}_6\text{H}_{10}\text{O}_5)_n\) that has long polymeric chain with high degree of polymerization \((\approx10000)\) and a molecular weight \((\approx500000)\). It has crystalline structure of thousand units that are made of many glucose molecules. This gives cellulose high strength, permitting it skeletal structure of most terrestrial biomass [70].

Hemicellulose is another constituent of cell wall of the plant. The structure of hemicellulose is amorphous, random, and with little strength. It is a group of carbohydrates with branched chain structure and lower degree of polymerization \((\approx100-200)\). It may be represented by empirical formula \((\text{C}_5\text{H}_8\text{O}_4)_n\) [70]. Hemicellulose tends to yield more gases and less tar than cellulose. It constitutes about (20-30) percentage of the dry weight of wood [71].
Lignin is a complex highly branched polymer of phenyl-propane and it is an integral part of secondary cell wall of plants. This is a three dimensional polymer of 4 propenyl phenol, 4-propenyl-2- methoxy phenol, and 4 propenyl-2,5- dimethoxyl phenol [72]. Lignin is cementing agent for cellulose fibers holding adjacent cells together. Lignin is insoluble even in sulphuric acid. An average lignin content of hardwood is (18-25) percentage and that soft wood is (25-35) percentage of dry weight.

2.3.2 Physical properties of biomass

**True density**

True density is weight per unit volume occupied by the solid constituents of biomass. True density of most of the woody biomass cell wall is 1530 kg m\(^{-3}\) [73]. True density of selected biomass was determined with ultimate analysis data.

**Apparent density**

Apparent density of biomass is measured with volume displacement method. It includes the internal pores of biomass particles but not the interstitial volume of biomass particles packed together.

**Bulk density**

Computation of space occupied by a defined weight of biomass gives its bulk density. Bulk density may be measured as per ASTM (E-873-06). This involves pouring biomass samples into a standard size box (305 mm × 305 mm × 305 mm) from a height of 610 mm. The box is then dropped from a height of 150 mm three times for settlement. These three densities may be related by following two equations where \(\epsilon_p\) is porosity of biomass and \(\epsilon_b\) is bulk porosity.

\[
\rho_{\text{apparent}} = \rho_{\text{true}} (1 - \epsilon_p) \quad (2.3)
\]

\[
\rho_{\text{bulk}} = \rho_{\text{apparent}} (1 - \epsilon_b) \quad (2.4)
\]
2.3.3 Thermodynamic property

Thermal conductivity

Thermal conductivity of biomass changes with its moisture and density. Based on large number of samples the following correlation was proposed by MacLean, Kitani and Hall [74, 75], where S.G. is specific gravity of biomass.

\[
k_{\text{eff}} \left( \frac{w}{m_k} \right) = S.G. (0.2 + 0.004m_d) + 0.0238 \quad \text{for } m_d > 40\% \quad (2.5)
\]

\[
k_{\text{eff}} \left( \frac{w}{m_k} \right) = S.G. (0.2 + 0.0055m_d) + 0.0238 \quad \text{for } m_d < 40\% \quad (2.6)
\]

Specific heat

Specific heat is an indication of heat capacity of a substance. Both moisture and temperature affect the specific heat of biomass. Specific heat of large number of wood species (dry) may be expressed as following expression within temperature range of (0-106) °C [76]. T is temperature in degree Celsius.

\[
C_pT = 0.266 + 0.001167T \quad (2.7)
\]

The effect of moisture on specific heat is expressed as follows.

\[
C_pT = M_{\text{wet}} C_w + (1 - M_{\text{wet}})T \quad (2.8)
\]

Heat of formation

Heat of formation or enthalpy of formation is enthalpy change when one mole of compound is formed at 25 °C and one atmosphere pressure from its constituent’s elements in their standard state. One mole water is formed by combining one mole of hydrogen and half mole of oxygen, one mole of water is formed with release of (-421 kJ mol⁻¹) thermal energy.

Heat of combustion

Heat of combustion is defined as amount of heat released or absorbed in a chemical reaction without change in temperature. The following table gives heat formation for different compounds [77].
Table 2.1 Heat of formation of different compounds

<table>
<thead>
<tr>
<th>Compounds</th>
<th>H_2O</th>
<th>CO_2</th>
<th>CO</th>
<th>CH_4</th>
<th>O_2</th>
<th>CaCO_3</th>
<th>NH_3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat of formation at 25°C</td>
<td>-241.5</td>
<td>-393.5</td>
<td>-110.6</td>
<td>-74.8</td>
<td>0</td>
<td>-1211.8</td>
<td>-82.5</td>
</tr>
</tbody>
</table>

(kJ mole⁻¹)

Heat of reaction may be calculated from following relationship with heat of formation.

Heat of reaction = [Sum of heat of reaction of all products] – [Sum of heat of formation of all reactant]

(2.9)

2.4 Biomass gasification for process heat generation

Dutta and Baruah [78], observed that biomass gasification derived producer gas applications for process heat generation and purely electrical generation are now established technologies although there is sufficient deration in former mode of operation. However, it has been observed that optimum application of biomass gasification technology as a source of thermal energy for tea drying is on research and development stage until now. Tea manufacturing industry is a plantation product based unit. Thus, biomass is generated by shading trees, uprooted tea shrubs, etc., itself within tea estate. Thus, uprooted tea shrubs gasification had been considered an appropriate conversion technology for gaseous fuel production and substitution of conventional fuel in black tea industries in Assam, India. Singh et al. [79], observed that combustion of cashew nut shells in furnace, semi open pit and other open burning was poor with lower combustion efficiency, high smoke emission, therefore efficient process control was not convenient in such situation. Jayah et al. [80] investigated the prospect of using producer gas for processing heat generation in tea drying. Rubber wood feedstock was used for an 80 kW thermal output downdraft gasifier. The moisture content of rubber wood was considered as an important parameter that in turn affected gasifier performance through reactor temperature and heat loss. Bhoi et al. [81] observed that optimum gasification zones length was a governing factor for
maximum output in a given range of operating parameters. The principal gasification reactions were pyrolysis, oxidation, and reduction and they produced combustible gases like CO, H₂, CH₄, etc., with average calorific values of (4.18-4.62) MJ m⁻³ as reported by researchers. The use of producer gas for other industrial process heat generation was also reported. The generation of combustible producer gas from solid biomass makes gasification most suitable for diversified thermal energy applications [82]. Woody biomass gasifier energy balance was also performed for 454 kW gasifier and average cold gasification efficiency of 70 % was recorded using waste wood with moisture content (<20 %) [83].

Masek et al., [84] studied pyrolytic gasification of coffee grounds and its implication to allothermal gasification kinetics. They observed a high conversion rate (88 %) of coffee grounds into gaseous and volatile matter by fast pyrolysis at a temperature of 1073, K. Tar separation in allothermal gasification was done by combustion to produce additional process heat. Wilson et al., [85] reported coffee husk gasification using high temperature air steam in a batch facility that was maintained at three different gasification temperatures 900 °C, 800 °C, and 700 °C respectively. They observed that increased gasification temperatures led to a linear increment of CO concentration in syngas for all gasification conditions. They reported that kinetic parameters established the reaction mechanism of zero order with apparent activation energy of 161 kJ mol⁻¹ and frequency factor of 6.48×10² s⁻¹.

Zainal, et al., [86] made an experimental investigation of a downdraft biomass gasifier using furniture wood chip as feedstock to measure equivalence ratio, gas composition, calorific value, and gas production rate. A peak was seen at about 0.38 equivalence ratios for optimum CO and CH₄ yields; it showed first increasing then decreasing trends of these constituents. At equivalence ratio 0.38, they observed best performance of the downdraft biomass gasifier. They also observed that gas production per unit weight of fuel increased linearly with equivalence ratio and a maximum cold gas efficiency of 80 % was achievable. Tippayawong et al., [87] performed an experimental study on gasification of cashew nut shells for hot water
generation in a local food-processing factory. They found that cashew nut shells were excellent feedstock for gasification and it had high-energy content and similar composition as fuel wood. An economic analysis with the incorporation available literatures suitable to prospective renewable energy system was performed. Most of such studies estimated the probable saving in resources over existing technology as well as payback period for additional investment made in plant and machinery. Dasappa et al., [88] developed an open top gasifier that could replace 2,000-liter diesel per day completely. This system operated over 140 h per week on a nearly nonstop mode and over 4,000 h of operation for complete replacement of fossil fuel. Therefore, biomass fuels have important role in domestic and agricultural sectors in India. The substitution of fossil fuel with biomass for useful energy production results in reduction of greenhouse gas emission [89]. Patel et al., [90], studied on Sardar Patel Renewable Energy Research Institute, India (SPRERI's) open core gasifier (1.25 GJ h⁻¹) for steam generation in a dual fuel burner. Dual fuel burner was used with 60 % light diesel oil and 40 % producer gas. They observed that wood consumption was (70 – 80) kg h⁻¹ that replaced 40 % (20 l h⁻¹) light diesel oil. The system was tested for a cumulative period of 600 h using sawmill woody waste as feedstock in test runs of 15–18 h. Panwer et al., [91], studied low temperature food processing industrial thermal application through an open core biomass gasifier. The gasification system was essentially consisted of an open top down draft reactor lined with ceramic. The experiment reveals that 6.5 kg of liquefied petroleum gas (LPG) was fully replaced by 38 kg of sized wood on hourly basis. The maximum temperature attained was 367°C in 130 min at 100.7 Nm³h⁻¹ flow rates. Singh et al., [92] evaluated performance of a biomass gasifier as solar dryer back up heater.

2.5 Drying modelling

The hot drying air removes moisture from the core of the fermented tealeaves by diffusion process. The products colour change from coppery red to black to arrest the fermentation process. The final moisture content of black tea (3 % w.b.) is a crucial aspect to get the stable product quality for preservation. Botheju et al., [93]
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observed wide variation of the critical moisture content of the black tea that promoted reactivation of hydrolytic enzymes such as peroxidase, catechol oxidase, etc. These hydrolyse lipids and heat might accelerate biochemical reactions. On the other hand, deactivation of catechol oxidase occurs during the drying of fermented dhool. Therefore, tea drying is not a simple moisture removal operation. Many associated quality parameters are involved during drying process. Incorrect selection of drying conditions and equipment might adversely affect dryer performance, predominantly in quality of made tea.

It has been observed that many theoretical and empirical models are available in literatures for various foods and agro based materials [94-96]. The design and control of a tea dryer fired with producer gas necessitated modelling of the actual drying process in term of mathematical relationships. It helped to define optimum tea drying process parameters. Therefore, black tea drying kinetics data were obtained by operating a producer gas fired tea dryer. The process state parameters such as drying air temperature, moisture content, etc., were derived from heat and mass balance of the drying process. It was reported by thin layer drying and modelling of Assam variety black tea especially by combustion of producer gas as a source of thermal energy [97].

It was reported that vapour diffusion mechanism controls drying of hygroscopic material like fermented tea during falling rate period. Thin layer drying models describing the drying phenomenon of bio-hygroscopic material like fermented tea falls under three categories namely, theoretical, semi-theoretical and empirical models. The first one takes into account only internal resistance to moisture transfer while the other two consider external resistance to moisture transfer [98-99].

It is assumed that resistance to moisture migration distributes uniformly throughout the interior of the homogeneous isotropic fermented tea material. Therefore, diffusion coefficient $D$ is independent of the local moisture content. The corresponding volume shrinkage is considered negligible, and then Fick's second law may be derived as Eq. (2.10).
Crank [100] gave the analytical solution of Eq. (2.10) for various regularly shaped bodies such as rectangular, cylinder, and sphere, etc. Drying characteristics of many food products such as rice, hazelnut, and rapeseed were predicted successfully using Fick’s second law with Arrhenius type temperature dependent diffusivity coefficient [101-103].

Simplification of general series solutions of Fick’s second law gives different semi theoretical models. They are valid within the specific temperature, relative humidity, airflow velocity and moisture content ranges of development of the models. These models require little time compared to theoretical thin layer models. They do not need assumptions of the geometry, mass diffusivity and conductivity of a typical food. Among the semi-theoretical thin layer drying models, the two terms model, the Henderson and Pabis model, the Page model and modified Page model are widely used [104-106].

Sharaf-Eldeen et al., [105] presented a two term model to predict the drying rate of shelled corn fully exposed to air. This model is the first two terms of general series solution to the Eq. (2.10). However, it requires a constant product temperature and assumes constant diffusivity. The two term exponential model has the form as:

\[
MR = \frac{M-M_e}{M_0-M_e} = A_0 \exp(-k_0 t) + A_1 \exp(-k_1 t)
\]  

(2.11)

Where \( M, M_0 \) and \( M_e \) are the material, initial and equilibrium moisture contents respectively in dry basis, and \( A_0, k_0, A_1 \) and \( k_1 \) are the empirical coefficient. Since \( M_e \) is relatively small compared to \( M \) and \( M_0 \), therefore it may be neglected for computation of moisture ratio.

The Henderson and Pabis model is the first term of a general series solution of Fick’s second law [106].

\[
MR = \frac{M-M_e}{M_0-M_e} = A_0 \exp(-k_0 t)
\]  

(2.12)
This model was used successfully to predict drying characteristics of corn, wheat and peanut \([106-108]\). The slope of the model coefficient \(k_0\), relates to effective diffusivity, when drying process takes place only in falling rate period. The liquid diffusion phenomenon controls this process \([109]\). The Lewis model is a special case of Henderson and Pabis model with intercept unity \([110]\). He described that moisture transfer from the food products and agricultural materials was analogous to the flow of heat from a body immersed in a cool fluid. Therefore, the drying rate is proportional to the difference between the drying material and equilibrium moisture contents analogous to Newton's law of cooling:

\[
\frac{dM}{dt} = k_0(M - M_e) \quad (2.13)
\]

After integrating we have,

\[
MR = \frac{M - M_e}{M_0 - M_e} = A_0 \exp(-k_0t) \quad (2.14)
\]

Bruce \([111]\) studied drying behaviour of Barely with Lewis model. At the other hand, Page model is a modification of Lewis model to overcome its shortcomings. This model had produced good fits in predicting drying of rice \([112]\), white bean \([113]\), and short grain rice \([114]\).

\[
MR = \frac{M - M_e}{M_0 - M_e} = \exp(-k_0t^a) \quad (2.15)
\]

Overhults et.al \([115]\) also modified the Page model to describe the drying of Soybean as given in Eq. (2.16).

\[
MR = \frac{M - M_e}{M_0 - M_e} = \exp(-k_0t^a) \quad (2.16)
\]

The empirical models develop a direct correlation between average moisture content and drying time. They neglect the fundamentals of the drying process. Therefore, it is difficult to give a clear precise view of the essential processes occurring during drying. However, they may describe the drying curve for the conditions of experiment. Among them, the Thompson model (Eq. (2.17)) was used to
describe the shelled corn drying and Eq. (2.18) was applied to study the intermittent drying of the rough rice [115, 116].

\[ T = a \times \ln(MR) + b \times (\ln(MR))^2 \]  

(2.17)

And

\[ MR = 1 + at + br^2 \]  

(2.18)

It has been observed from above literature that there are number of good examples for application of biomass gasification in food processing industries as well as food drying process modelling. Next we will discuss on different literature on improved solar air heater for process heat generation to assist tea drying process with gasification.

2.6 Introduction to Solar Air Heater

Solar air heater is a distinct type of solar thermal energy conversion device where air is heated over a metallic collector by absorption of incoming solar radiations. This is a modest and economically viable heat exchanger to convert the incoming solar radiations into relatively higher thermal energy. The elevated temperature solar thermal energy is extracted by air flowing over a black coated metallic surface. A conventional solar air heater is essentially a flat plate collector with an absorber plate, a transparent cover system at the top and insulation at the bottom and four sides. The whole assembly is enclosed in a sheet metal container to protect the unit from any thermal and mechanical damage. The working fluid is air with different combination of passages according to the type of air heater.

2.6.1 Types and application of solar air heaters

Depending on the type of the absorber plate, the solar air heater can be porous and non-porous. A porous type solar air heater uses porous absorber that may include slit and expanded metal, overlapped glass plate absorber and transpired honeycomb. Wire mesh, porous bed formed by broken bottles and overlapped glass plates are examples of porous type of absorbers. In non-porous type, air stream does not flow through the absorber plate but air may flow above and/or behind the plate. Depending
on the number of passes for air flow, they may be classified as single pass solar air heater, double pass solar air heater or triple pass solar air heater, etc.

The main applications of solar air heaters are space heating, drying agricultural products such as fruits, seeds, and vegetables, seasoning of timber, curing of industrial products, crop drying, greenhouse heating, etc.

2.6.2 Advantages and limitations of solar air heaters

The solar air heaters have certain advantages such as necessity to transfer heat from the working fluid to another fluid is eliminated because; air is used directly as the working fluid. Moreover, the system is compact and less complicated. Corrosion, that may cause serious problems in solar water heaters, is completely eliminated. Leakage of air from the duct does not pose any major problem and freezing of working fluid virtually does not exist. The pressure inside the collector does not become very high.

Thus, air heater may be designed using cheaper as well as lesser amount of material and is simpler to use than the solar water heaters. The main disadvantages of solar air heaters are the poor heat transfer capacity of air. Moreover, it needs to handle large volumes of air due to its low density. Since the thermal capacity of air being low, it cannot be used as a storage fluid. The applicability of a solar air heater depends on various factors such as high efficiency, low fabrication, installation and operational costs and other practical aspects regarding the specific use.

2.7 Losses in solar air heaters

The thermal loss to the surroundings is an important factor in the study of the performance of a solar air heater. Heat is lost to the surroundings from the plate through the glass cover (referred as top loss) and through the insulations (referred as bottom loss and edge loss, etc.) These losses take place by conduction, convection, and radiation.
2.7.1 Top Loss:

Top loss is a combination of convective heat losses and radiation heat losses and it is given by Eq. (2.19). Convective heat loss occurs from absorber plate to cover and from cover to ambient. Radiation heat losses take place from absorber plate to cover and from glazing cover to ambient [117].

\[
U_t = \left[ \frac{N}{(C/T_m)(T_m-T_a)^{0.65}} + \frac{1}{h_w} \right]^{-1} + \frac{\sigma(T_e^2 + T_a^2)(T_p + T_a)}{e_p + 0.05N(1 - e_p) + 2NF + 1 - N}
\]  

(2.19)

\[
f = (1 - 0.04h_w + 0.0005h_w^2)(1 + 0.091N)
\]

(2.19a)

\[
C = 365.9(1 - 0.00883\beta + 0.0001298\beta^2)
\]

(2.19b)

\[
h_w = \frac{0.6\beta^{0.6}}{1.64}
\]

(2.19c)

The minimum value of wind heat transfer co-efficient for still air is 5 W m\(^{-2}\) °C.

2.7.2 Bottom Loss:

Heat loss from the plate to the ambient takes place by conduction through the insulation and then subsequently by convection and radiation from the bottom surface casing, and is given by Eq. (2.20). The general acceptable value of back loss coefficient varies (0.3-0.6) W m\(^{-2}\) °C.
2.7.3 Edge Loss:

It is the energy lost from the side of the collector casing and is exactly same as the back loss if the thickness of the edge insulation is the same as that of the back insulation. Edge loss coefficient varies from (1.5-2) W m\(^{-2}\) °C.

\[ U_e = \frac{1}{\frac{1}{k_e} + \frac{1}{h_{eb}}} \]  \hspace{1cm} (2.20)

2.7.4 Overall Heat Loss:

It is the sum of top, bottom and edge losses of a solar air heater. There is about (33-50) \% heat loss in most commercial flat plate collectors, the breakup of which can be given as (22-30) \% convective and (5-7) \% radiation loss from the back surface. In order to improve the collector efficiency, the heat losses should be minimized. To minimize the heat loss from the back surface, a highly reflective coating may be used on the back surface of the collector. Mainly convective and radiation losses take place from the front space of the absorbing plate. These two losses are minimized by altering the spacing between cover and plate, and using absorbing surface of different emissivity. The optimum gap width is different for different absorbing surfaces.

2.8 Improving heat transfer coefficient between absorber plate and air

Conventional solar air heaters have low thermal efficiencies primarily due to the low convective heat transfer coefficient between the absorber plate and the flowing air stream over it. There are two basic methods for improving the heat transfer coefficient between the absorber plate and air. (1) Increasing convective heat transfer by creating turbulence at the artificially roughened heat-transferring surface and (2) by increasing the area of heat transfer by using corrugated surfaces or extended surfaces called fins.

There are various methods of increasing convective heat transfer by creating turbulence. They are artificial roughening by ribs, wire meshes, and geometric...
protrusions. To improve heat transfer in solar air heaters, artificial roughness, in the form of repeated ribs, is used to disturb the laminar sub-layer. The ribs are one of the most desirable methods because of their ability to combine enhanced heat transfer coefficient with limited frictional losses. The most important effect produced by the presence of a rib on the flow pattern, is that generation of two flow separation regions, one on each side of the rib. The vortices so generated are responsible for the turbulence and hence the enhancement in heat transfers as well as in the friction losses takes place. Another way to provide artificial roughness on the surface of absorber plate is by forming dimple/protrusion shape geometry. Formation of dimples/protrusions on absorber plate can be considered an innovative technique as dimples/protrusions are easy to fabricate and do not add extra weight to the absorbing plate.

To improve the heat transfer from the plate to air stream, and hence the efficiency of the heater, fins are added to the rear side of the absorber. This, however, introduces some extra pressure drop. In addition, the number of fins and their depth cannot increase beyond a limit because then compressor power requirement will also increase. The heat transfer model of such an air heater may be easily developed since heat transfer from finned surfaces is very common in convective heat transfer problems. However, the limitation of this model is that there are hardly any appropriate correlations for heat transfer coefficients corresponding to situations encountered in air heaters. Test results of air heaters with staggered galvanized fins and U-shaped staggered aluminum fins attached to the rear side of the absorber plate have been reported. The efficiencies with fins are substantially higher than conventional air heaters [115-118].

2.8.1 Double pass solar air heater

The double pass solar air heater consists of two passages; first passage is formed between the two glass covers and the second passage, where air flows in the reverse direction, is formed between the bottom glass cover and the absorber plate. Both the passages normally have identical length. The application of double pass
arrangement reduces the top heat loss coefficient considerably that improves the thermal efficiency. Additionally, this kind of solar air collectors may be fabricated with a little additional expenditure over the conventional air collectors.

Ramadan et al., [119] studied thermal performance of a packed bed double pass solar air heater. Sopain et al., [120] carried out the simulation study and thermal performance of double pass solar air heater with and without porous media. The double passes counter flow arrangement with porous material in the second air passage was one of the effective alternatives to improve its thermal performance. The major reason of interest in porous material includes high effective heat transfer area per unit volume resulting in high heat transfer capability. Moreover, solar radiation was absorbed gradually by layers of porous matrix, resulting in effective heat transfer between the porous material and the flowing air. Different investigators had proposed use of porous packing material for improving the performance of solar air collector [121-125]. Some pioneering research work regarding heat transfer on wire mesh screens as packing elements may be considered. These researches have led to the conclusion that double pass counter flow solar air collector with porous material in the second pass gives higher thermal efficiency in comparison to double pass counter flow solar air collector without absorber matrix and conventional single pass solar collector. This is because the porous material provides a very large surface area for heat transfer and therefore, the volumetric heat transfer coefficient is very high. Further, in the double pass solar air heater, the air flowing in the first passage picks up heat from the glass covers reducing their temperatures and then flows over the absorber plate/matrix. The heat energy extracted by the flowing air in the first pass from the glass covers is used to preheat incoming air. This decreases the temperature of glass covers which in turn reduces the heat losses to the surroundings and hence the performance of such collectors have been found to be superior compared to conventional solar air collector where air flows in one pass either above or below the absorber plate [126 - 128].
2.8.2 Solar air heater with artificially roughened absorber plate

In order to make a solar air heater more effective solar energy utilization system, thermal performance needs to be improved by enhancing the heat transfer rate from the absorber plate to the air flowing in the duct of the solar air heater. One of the methods for enhancement of convective heat transfer is by creating turbulence at heat transfer surface with the help of artificial roughness on absorber plate. Ribs are provided by artificial roughness to break laminar sub-layer. This creates local wall turbulence due to flow separation and reattachment between consecutive ribs. As a result, thermal resistance decreases and heat transfer rate is greatly enhanced. However, simultaneous increase in friction loss also takes place in the duct with application of artificial roughness. In order to reduce friction loss with application of artificial roughness, turbulence should be created in the region very close to the heat-transferring surface i.e. in laminar sub-layer only. Therefore, height of roughness element should be kept small in comparison with duct dimensions.

Artificial roughness on the surface of the absorber plate may be provided by fixing small diameter wires, ribs formed by machining process, wire mesh, or expanded metal mesh and by forming dimple/protrusion shape geometry. However, it has been observed that creating artificial roughness on absorber plate is a tedious task and may not be economically feasible for large-scale production of solar air heaters. Therefore, a suitable geometry of roughness element needs to be selected, which should be easy to fabricate on the surface of absorber plate [129-132]. Saini and Verma [133] reported an experimental investigation for fully developed turbulent flow in rectangular duct having dimpled absorber plate. Experimental data of heat transfer and friction in the roughened duct as a function of system and operating parameters have been reported. They have observed that under a given set of operating conditions, Nusselt number was a strong function of relative short way length, relative long way length, and relative print diameter. For given value of roughness parameters, Nusselt number increases monotonously with an increase of Reynolds number.
Various researches have proved that Nusselt numbers for protruded absorber plate is considerably higher as compared to those obtained for smooth absorber plate. Protrusions on absorber plate result in enhancement in heat transfer coefficient. Enhanced heat transfer occurs due to main flow impingement, vortex generation on both sides of the protrusions and flow separation. Because, decelerating motion is accompanied by adverse pressure gradient that promotes separation, instability, eddy formation, and large energy dissipation [134, 135].

2.8.3 Solar air heater duct artificially roughened with V-ribs

In order to improve heat transfer in solar air heaters, artificial roughness, in the form of repeated ribs, is used to disturb the laminar sub-layer. The ribs are one of the most desirable methods because of their ability to combine heat transfer-coefficient enhancement with limited friction losses. Protruded wires for improving the plate efficiency factor of solar air heaters from 0.63 to 0.72 resulted in 14% improvement in the performance. Multiple v-ribs along the width of heat exchanging surface of a solar air heater to create artificial roughness enhanced heat transfer. They reported Nusselt number and friction factor enhancement of 6 and 5 times respectively, compared to a smooth duct [129, 132, 136, 137]. An enhancement in Nusselt number and friction factor over smooth duct of the order of 2.38 and 4.25 times, respectively, corresponding to relative roughness height value of 0.033 and relative roughness pitch value of 10 has been reported. An arc shaped ribs reported to enhance Nusselt number and friction factor of order 3.6 and 1.75 times, respectively, in comparison with the smooth duct [136-138].

Various researchers had reported enhanced heat transfer-coefficient between the hot metallic surface and fluid flowing over it with artificial roughness of defined geometries [139-143]. Several research works are available on augmentation of heat transfer coefficient by using different geometries in solar air heaters [144-153]. Khattab evaluated performance study of a perforated solar air heater. He concluded that optimal perforation geometry had great role on thermal and hydraulic efficiency of said solar heater [154]. Languri et al., [155], studied energy, and exergy analysis of
double pass solar air heater with and without porous medium. They concluded that the porous medium embedded inside the lower channel led to an increase in the thermal efficiency of the collector of more than 30% compared with the case without porous medium. Therefore, studies showed the importance of employing porous medium in thermal solar collectors. On the other hand, the pressure drop in the air caused by friction with porous medium was not negligible and this was studied with second law analysis. Imbriale et al., [156] investigated the effect of periodic patterns of protrusions (ribs) on the free-convection heat transfer of a vertical plate, with a uniform heat-flux rate boundary condition. The convective fluid was considered as air. Two-dimensional, high-resolution heat transfer measurements were performed by using infrared thermograph and the heated thin foil technique. Experiments were performed on two types of ribs pattern topology: single or two staggered rows of ribs inclined at different angles and single or two-staggered rows of V-ribs. Bharadwaj et al., [157] experimented to determine the effect on the heat transfer and friction characteristics of an equilateral triangular solar air heater duct using inclined continuous ribs as roughness element on the absorber plate. The experimental study encompassed the range of Reynolds numbers from 5600 to 28,000, relative roughness height \( \frac{e}{D} \) 0.021–0.043, relative roughness pitch \( \frac{P}{e} \) 8–16, and angle of attack (\( \alpha \)) 30–60°. The duct had an aspect ratio \( \frac{W}{H} \) of 1.15. The effect of flow parameters and roughness parameters on heat transfer and friction factor was discussed. The thermo-hydraulic performance parameter had been determined for the given range of flow parameters and roughness geometries. Rallabandi et al., [158], studied heat transfer, and pressure drop correlation on 45° ribs at high Reynolds number ranged from 30,000 to 400,000. The rib height (\( e \)) to hydraulic diameter (\( D \)) ratio ranged from 0.1 to 0.18 for experimentation. The rib spacing (\( p \)) to height ratio \( \frac{P}{e} \) ranged from 5 to 10. Results showed higher heat transfer coefficients at smaller values of \( \frac{P}{e} \) and larger values of \( \frac{e}{D} \), though at the cost of higher friction losses. Saha and Dutta [159] studied thermo-hydraulic of laminar swirl flow through a circular tube fitted with twisted tape. Thermo-hydraulic performance showed that twisted-tapes with multiple
twists in the tape module were not much different from that with single twist in the tape module. Friction factor and Nusselt number were approximately 15 percent lower for twisted-tapes with smooth swirl having the average pitch same as that of the uniform pitch (throughout) twisted-tape. The twisted-tapes with gradually decreasing pitch performed worst compared to uniform pitch counterpart. Saha [160] made another study on thermo-hydraulics of laminar flow through rectangular and square ducts with axial corrugation. He observed that based on constant pumping power, up to 45% heat duty increase occurred for the combined axial corrugation and twisted-tape insert case compared with the individual axial corrugation and twisted-tape insert cases in the measured experimental parameters space. On the constant heat duty basis, the pumping power had been reduced up to 30% for the combined enhancement geometry than the individual enhancement geometries. Sebaii et al., [161] investigated thermal performance of a double pass solar air heater. They observed that the double pass V-corrugated plate solar air heater was (9.3–11.9) percentage more efficient compared to the double pass-finned plate solar air heater. It was also indicated that the peak values of the thermo-hydraulic efficiencies of the double pass-finned and V-corrugated plate solar air heaters were obtained when the mass flow rates of the flowing air equaled to 0.0125 and 0.0225 kg s⁻¹, respectively. Aharwal et al., [162] experimented on heat-transfer enhancement due to a gap in an inclined continuous rib arrangement in a rectangular duct of solar air heater. The duct had a width to height ratio (W/H) of 5.84, relative roughness pitch ($\frac{\varepsilon}{D}$) of 10, relative roughness height ($\frac{\delta}{D}$) of 0.0377, and angle of attack ($\alpha$) of 60°. The gap width, ($\frac{\delta}{W}$) and gap position ($\frac{\varepsilon}{W}$) were varied in the range of (0.5–2.0) and (0.1667–0.667), respectively. The heat transfer and friction characteristics of this roughened duct had been compared with those of the smooth duct under similar flow condition. The effect of gap position and gap width had been investigated for the range of flow Reynolds numbers from 3,000 to 18,000. The maximum enhancement in Nusselt number and friction factor was observed 2.59 and 2.87 times that of a smooth duct. The thermo-hydraulic performance parameter was found maximum for the relative gap width of
1.0 and the relative gap position of 0.25. Mohammed et al., [163] studied effects of geometrical parameters of a corrugated channel within out of phase arrangement. The corrugated channel with three different corrugated tilt angles of 20°, 40°, and 60° with different channel heights of 12.5, 15, and 17.5 mm and different wavy, heights of 2.5, 3.5, and 4.5 mm were tested. This investigation covered Reynolds number and heat flux in the range of 8,000–20,000 and 0.4–6 kWm⁻², respectively. The numerical results indicated that the wavy angle of 60° and wavy height of 2.5 mm with channel height of 17.5 mm were the optimum parameters and they had a significant effect on the heat transfer enhancement. It was observed that wavy channel was a suitable method to increase the thermal performance. Moreover, it gave higher compactness of the heat exchanger [164].

Since air is a bad conductor of heat, therefore rate of heat transfer from conventional solar air heater absorber to air flowing over it is not significant. It has been observed that different researchers put effort for performance evaluation of solar air heater by incorporation by enhancing turbulence of air [165, 166]. The evaluation of thermo-hydraulic efficiency of roughened solar air heater had been performed. They observed that system operated optimally with a specified set of Reynolds number [167].

2.9 Biomass energy and solar air heater hybridization

Solar thermal energy based air heater or dryer frequently encounters with natural variation of solar radiation over the day as well as over season. This gives rise to an unsteady and varied quality of hot air in terms of temperature and relative humidity to a given thermal load. Therefore, solar dryers alone continue to struggle for its independency in industrial drying applications over fossil fuel fired or electric dryer. Since specific heat capacity of air is much lower than water and air is a bad conductor of heat, it is almost impossible to raise air temperature around 100 °C in conventional solar air heater. However, specific geometry of black coated aluminum absorber such as protruded one gives rise overall higher thermal efficiency and air temperature in the range of (60 –65) °C in summer at Tezpur University campus. At
the other hand, black tea drying process needs average hot air temperature \((100 \pm 10)\) °C for continuous operation and quality. As it has been already stated thermal energy requirement for black tea manufacturing in tea industries are provided by coal, natural gas, tea drying oil, or diesel. There is hardly any scope for only solar thermal energy based dryer application in black tea manufacturing. Therefore, an effort has been directed to study the possibility of solar thermal and biomass gasification as the renewable sources of energy for tea drying application in hybrid mode.

Different research works are available on hybrid drying of different agricultural produces for reliability and enhanced efficiency. Leon and Kumar [168] designed and studied performance of solar assisted biomass drying system with a thermal storage. They observed that solar assisted biomass air heating system with rock bed thermal storage could supply load fraction of hot air exceeding 90% for 24 hours. Application of biomass gasifier and an unglazed transpired solar collector were supposed to deliver hot air at \((55-60)\) °C at the flow rate of hot air in \((70-100)\) m\(^3\) h\(^{-1}\) continuously for drying of chilli. The system could reduce the drying time of chilli by 66% compared to open sun drying with superior quality product. It was concluded that almost 100% of the drying energy demand was met from renewable sources of energy. Hirunlabh et al., [169] studied a new type of modular dryer powered with solar energy and producer gas. An updraft charcoal gasifier was considered for the study. They used a 0.6 m\(^3\) modular cabinet that supported a solar collector of 2.5 m\(^2\) surface area. Producer gas at 60 °C for four hours and solar energy at 40 °C for six hours to dry beef were used. The energy consumed for drying of 16 kg beef was 7.5 MJ kg\(^{-1}\) of water removed. The fraction energy contributed from solar, producer gas and blower were 8.72%, 31.44% and 59.84% respectively. The initial moisture of beef was 75% (w.b.) and final moisture was 25% (w.b.). Since two renewable energies solar and biomass may be used most effectively from morning to evening in appropriate combination, therefore such a hybrid drying energy system produced better quality product at lesser time uninterruptedly. Gupta et al., [170] studied energetic utilization of solar energy for feed water preheating in a thermal power plant. They observed that solar thermal energy was an added utility source for feed
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water preheating. It helped to reduce exergy loss in feed water heater of Rankine cycle and developed more work that could have been produced in a solar thermal power plant. They computed the work output from a 50 kW solar thermal power plant as 59.312 kW and that from a 220 MW fuel fired thermal power plant with 50 kW solar thermal power plants as solar feed water heating was 90.27 kW. Lokeswaran and Eswaramoorthy [171] performed and experimental study on a solar drying system with a biomass backup heater. They had dried coconut in four different drying systems namely a solar greenhouse dryer with a biomass back up heater, a biomass heater, a solar greenhouse dryer and open sun drying. It was observed that hybrid-drying system took 26 hours, whereas open sun drying took 88 hours to reduce moisture of coconut from 53.4 % to 9.2% on wet basis. The drying efficiency of solar greenhouse dryer was about 19% in average. Prasad et al., [172] evaluated performance of hybrid drying of turmeric (Curcuma longa L.) at village scale. They developed a direct type natural convection solar cum biomass dryer. The system was capable of generating an adequate and continuous flow of hot air temperature between 55 and 60 °C. Turmeric rhizomes were successfully dried in developed system. Dried turmeric rhizomes obtained under solar biomass drying by two different treatments that is water boiling and slicing were similar in respect to physical appearance, texture, and colour with significance variation in volatile oil. They observed that eight-kilogram fuel wood was burned and 12.6 kg of water was removed to dry fifteen kilogram of fresh rhizome to 9% moisture. The dryer overall thermal efficiency was (28.5%). Bena and Fuller [173] studied on a natural convection solar dryer with a biomass back up heater. It demonstrated the drying technology suitable for small scale processing of fruits and vegetables in non-electrified areas of developing country. The dryer capacity was (20 - 22) kg of fresh pineapple arranged in a single layer of 0.01 m thickness and overall drying efficiency of the unit was 9 % only. However, drying efficiency of solar component was 22% and 27% for burner that produced useful heat in other experiments. Installation of an internal baffle lengthened the exhaust gas exit-path with a variable air inlet valve. It was observed that for same load of dryer, energy used only by solar component was 112 MJ and that by biomass alone is 463 MJ.
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Almost four times more energy requirement for biomass furnace is because of indirect heating of drum over combustion chamber. They suggested for necessity of further investigation to improve the combustion and heat transfer efficiencies for biomass burner. Khairiddinov et al., [174] studied heat balance of cotton dryer with combined fuel solar recuperative heat supply. They performed general material balance and heat flux in the drying system. They computed the drying agent heat loss as (47-51) % and a portion of this heat was utilized in recuperative process. This was returned to the dryer together with solar radiation. This amount of heat is designated by substitution coefficient typically varied from (10 - 21) % and thermal efficiency of dryer was (36.8 - 43.7) % and solar recuperation was (39.4 - 50.2) % respectively. There was an efficiency increment of (7.1 - 15.7) % due to utilization of heat of solar recuperative natural gas fired cotton dryer. Srinivas and Reddy [175] performed a study on hybrid solar-biomass power plant without thermal energy storage. They observed that both solar thermal and biomass had limitation. Solar radiation is uncertain and high initial investment of solar technology (parabolic collector system). Biomass power plant demands a huge amount of feedstock that may not be radially available. The feed control of biomass fuel saves the cost of thermal energy storage. They observed that plant fuel efficiency increased with an increase in solar support, boiler pressure, and temperature but hybrid plant thermal efficiency decreased with an increase in steam temperature. The optimum boiler pressure decreased (50-40) bar with an increase in solar sharing (10-50) %. They designed the solar collector for 350 °C steam temperature compared to 450 °C for biomass combustion. Therefore, more quantity of water (60%) was supplied to solar collector and rest 40% was supplied to biomass furnace. The specific output of the plant was 0.8 MW kg⁻¹ of steam with total heat of 3 MW supplied. The cycle thermal efficiency under the specified condition was 27% and fuel efficiency increased to (27-32) % with participation of solar energy. During the day, hybrid thermal efficiency drop from 15% to 11% with solar collector because of low collector efficiency.

They considered a mixed mode type forced convection solar tunnel dryer. Flat plate collector absorber with transparent plastic cover constituted the solar air heater in series with tunnel dryer. The moisture content of red chilli was reduced from 2.85 to 0.05 kg kg$^{-1}$ (db) in 20 h and it took 32 h to reduce moisture content to 0.09 and 0.40 kg kg$^{-1}$ (db) in improved and conventional sun drying method. The corresponding values for green chilli were 7.6 to 0.06 kg kg$^{-1}$ (db) in 22 h and 35 h to reach moisture content to 0.1 and 0.7 kg kg$^{-1}$ (db) in improved and conventional sun drying. Sreekumar [178] studied techno-economic aspect of a roof-integrated solar air heating system for drying fruits and vegetables. The initial moisture contents of 82% were reduced to the desired level (< 10%) within 10 hours. The drying cost of 1 kg pineapple was computed as Rs.11, that was about 20% of an electric dryer and payback period was worked out as 0.54 year. Palaniappan and Subramanian [179] performed economics of solar air preheating in South Indian tea factories. They observed that requirement of hot air temperature (100 – 130) °C for tea drying and withering was obtained by burning firewood or coal in those factories. Roof integrated solar air heater system was introduced in some of these south India tea factories. The solar air heater was fabricated from galvanized iron sheet. This was painted with commercial, heat resistant dull black paint. The collector transparent cover was 4 mm thickness transparent tampered glass. They performed an economic analysis of a 212 m$^2$ solar air heater collector area operated for 2.75 years. The system was reported to reduce specific energy consumption from 0.932 to 0.71 kg/kg of dry matter. This saving was approximately 25% of conventional fuel energy. They computed the payback period as two to four year depending on whether the company is profit making or not profit making. Modhlopa and Ngwalo [180] designed and studied a solar dryer with thermal storage and biomass backup heater. The major components of the dryer were biomass burner with a rectangular duct flue-gas chimney, collector storage thermal mass and drying chamber. The dryer was fabricated with simple material, skill, and tools. This was tested in three modes namely, solar, biomass and solar biomass combined by drying twelve batches of pineapple weighing 20 kg each. They observed that thermal mass was capable of storing a
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part of solar energy. In solar biomass hybrid mode, the dryer reduced moisture content of sliced pineapple from 66.9 % to 11 % (db). The average values of dry moisture pick up efficiencies were 15 %, 11 % and 13 % respectively for solar, biomass and solar biomass hybrid drying. Khanna [181] studied design data for solar heating of air using a heat exchanger. Heat transfer took place both natural and forced convection. This design data assisted the final design of a shell and tube heat exchanger used in drying application. Ayensu [182] developed a solar dryer with rock bed storage. He observed that rock bed storage could hold enough energy to enhance nocturnal drying. Aboul- Enein et al., [183] developed a solar air heater and experimented this with and without thermal storage for drying of agricultural products. They observed that drying process could be continued during night by using thermal mass. Prasad and Vijay [184] developed a direct solar and biomass powered dryer. The biomass burner had a rock slab on the top that helped in moderating the temperature of the drying air. The dryer designs had a backup heater without thermal storage of captured solar energy. As a result, the air temperature in the drying chamber dropped down to ambient level immediately after sunset. This necessitated backup heating even when the preceding day was sunny. Hossian et al., [185] developed a prototype solar dryer to dry good quality tomato. It consists of a flat-plate concentrating collector, heat storage with auxiliary heating unit, and drying unit. The dryer had a loading capacity of 20 kg of fresh half-cut tomato. The dryer was tested in different weather and operating conditions. The performance of the dryer was compared with an open sun-drying method. Drying performance was evaluated in terms of drying rate, color, ascorbic acid, lycopene, and total flavonoids. Tomato halves were pre-treated with UV radiation, acetic acid, citric acid, ascorbic acid, sodium metabisulphite, and sodium chloride. Sodium metabisulphite (8 g L⁻¹) was found to be effective to prevent the microbial growth at lower temperature (45 °C). Chavan et al., [186] studied mathematical modelling of drying characteristics of Indian Mackerel (Rastrilliger kangurta) in solar-biomass hybrid cabinet dryer. The temperature of hot air in solar biomass hybrid dryer could be controlled automatically. The hybrid dryer was constructed of bricks and mortar. This had been found to be
more efficient than a conventional solar cabinet dryer made of steel and aluminum. The hot flume gases from the biomass gasifier stove was used to heat the process air inside the drying chamber, with a pipe heat exchanger. The temperature of air inside the drying cabinet was maintained in the range (55–60) °C. The gasifier stove consists of four main parts: fuel chamber, reaction chamber, primary air inlet, and combustion chamber. Thus, the solar-biomass dryer allows the continuous drying of the product. They conducted eight trials for drying mackerel by a solar biomass hybrid cabinet dryer (S-BHCD) and open sun drying (OSD) at air temperatures of (32.39–57.69) °C, relative humidity (23.9–85.8 %), and air flow rate of 0.20–0.60 m s⁻¹. The solar radiation ranged between 287 and 898 W m⁻² during the time of experimentation. At nighttime, drying was carried out by combusting biomass. The initial moisture content of the processed mackerel was 72.50 ± 0.44 % (w.b.) and was reduced to the final moisture content of 16.67 ± 0.52 % (w.b.) in S-BHCD and 16.92 ± 0.54% (w.b.) in OSD. Eleven drying models were used and the coefficients of determination (R²) and constants were evaluated by nonlinear regression to estimate the drying curves of dried mackerels. The Midilli model was found to more satisfactorily describe the drying process of mackerel in S-BHCD with R² of 0.9999, χ² of 0.0000374, and RMSE of 0.0057. In the OSD, a two-term drying model satisfactorily described the drying process with R² of 0.9996, χ² of 0.0000519, and RMSE of 0.0072. The variation of Free Fatty acid (FFA), Peroxide value (PV), Thiobarbituric acid (TBA), Total volatile bases nitrogen (TVB-N), Trimethylamine nitrogen (TMA-N), and Histamine contents of dried Mackerel by using S-BHCD showed very high corresponding coefficients of determination, where all R² were greater than 0.90, except TBA value. There was no discoloration of the product during 4 months of storage. Contour plots of S-BHCD and OSD dried mackerel also showed that for all sensory attributes examined, panellists preferred fish dried with S-BHCD. The organoleptic analysis showed that the S-BHCD drying methods have a highly significant effect (P<0.01) on texture and overall acceptability. Biochemical, microbial analysis, and sensory evaluation showed that the product was in prime acceptable form for 4 months of storage at ambient temperature. Kumar and
Bhattacharya [187] studied on technology packages with solar, biomass and hybrid dryer. Gunasekaran et al., [188] performed modelling and analytical study of hybrid solar dryer integrated with biomass dryer for drying *Coleus Forskohlii* stems. They observed that by using solar biomass hybrid dryer, the moisture content of the stems had been 12.3%, whereas solar dryer produced 33% and biomass produced 19.6% respectively. Sopain et al., [189] had developed four solar assisted drying systems namely (a) the V-groove solar collector, (b) the double-pass solar collector with integrated storage system, (c) the solar assisted dehumidification system for medicinal herbs and (d) the photovoltaic thermal (PVT) collector system. The common problems associated with the intermittent nature of solar radiation and the low intensities of solar radiation in solar thermal systems could be remedied using these types of solar drying systems. These drying systems have the advantages of heat storage, auxiliary energy source, integrated structure control system and could be used for a wide range of agricultural produce. Reyes et al., [190] dehydrated Mushrooms (Paris variety) in a hybrid solar dryer (HSD) provided with a 3 m² solar panel and electric heaters. Mushrooms were chipped into 8mm or 4mm thickness slices. At the outlet of the tray dryer (80–90) % air was recycled and the air temperature was adjusted to the pre-defined levels (50 or 60 °C). At the outlet of the solar panel the air temperature raised between (2 and 20) °C above the ambient temperature, subjected to the variation of solar radiation level. They observed that temperature, slices thickness and air recycle level had statistically significant effects on critical moisture content ($X_c$), as well as on the time necessary to attain a moisture content of 0.1 (wb). The color parameters of dehydrated mushroom indicate a disreputable darkening, in all runs. Rehydration assays at 35 °C showed that in less than 30 min rehydrated mushrooms reached a moisture content of 0.8 (wb). The simplified *Constant Diffusivity Model* (SCDM) estimated effective diffusivity ($D_{eff}$), and it ranged between 6E-10 and 40E-10 m² s⁻¹, with $R^2$ higher than 0.98, complying with literature. The adjustment of experimental drying kinetics with the empirical Page's model resulted in $R^2$ higher than 0.997. The input of solar energy resulted in (3.5–12.5) % conventional energy saving. These values could even be improved by
very small compared to the life of the dryer 15 years. Farkas [192] studied an integrated use of solar drying system. Factors such as energy efficiency, the quality of products, and environmental aspects were necessary to account during the drying of agricultural produce.

2.10 Dryer and factors affecting its performance

The drying capacity of a dryer varies with the type of product and the amount of moisture to be removed. Tray area indirectly refers to the loading or drying capacity of the dryer. Since the products need to be spread in a single layer for efficient drying, total tray area available in the dryer for spreading the product is important. In the case of cabinet type dryers, that have more than one layer of trays, number of layers will be an additional parameter that needs to be indicated. The conditions of drying air, flow rate and the product loaded will determine the number of tray layers for a particular dryer. Dryer capacity also depends on the aperture area or collector area and the size of the drying chamber. Loading density determines the capacity of a dryer (together with total tray area and drying time) for a particular product. Placing products one above the other rather than a single layer tends to limit the area of exposure of product surfaces to drying air, resulting in poor drying [193, 194]. Loading density depends on the type of product, its moisture content, and airflow rate, and may be assessed by rules of thumb, as average dryer loading is 4 kg of fresh produce per square meter of tray area. The solar collector size is $0.75 \times$ total tray area and airflow rate is $0.75 \text{ m}^3 \text{ min}^{-1} \text{ m}^{-2}$ of tray area [195- 198].

Higher drying air temperature will increase the drying rate in two ways. (1) This increases the ability of drying air to hold moisture. (2) The heated air will heat the product, increasing its vapour pressure. This will diffuse the moisture to the surface faster [196]. Operation of dryers at high temperatures is normally constrained by the thermal sensitivity of most fruits and vegetables. If the temperature is too high in the beginning, a hard shell known as case hardening may develop on the outside trapping moisture inside the shell [199]. Temperatures that are too high at the end of the drying period may cause food to blacken. Irreversible changes of colloidal
components of fruit and vegetable tissue occur if the product is held for prolonged periods at high temperature, even if the exposure is insufficient to produce browning or scorching\cite{194}. A high drying air temperature could also result in more heat loss by conduction and radiation from both the collector and drying cabinet, resulting in overall reduction in system efficiency. Mahapatra and Imre \cite{200} had summarized the maximum allowable drying temperatures for a variety of agricultural food products.

Relative humidity of drying air is a crucial parameter to the drying process. If the exit air from the drying chamber still has considerable drying potential, mixing a fraction of the warm, humid exit air with fresh air and recirculating it in the dryer will help to utilize part of the thermal energy in the exit air. Thus, the thermal efficiency of the system is thus improved \cite{201,202}. Crapiste and Rotstein \cite{203} observed that the fraction of air recirculate can often be high, in the range of about (80–95) %. Soponronnarit et al., \cite{204} reported that there is a 50% drop in drying energy consumption of banana, when a fraction of 95 % air was recycled.

2.11 Critical review of literature

This chapter initially discusses different renewable and non-renewable thermal energy applications for different process industries. We try to present a critical appreciation and summery of cited works briefly. It was reported that improved solar air heater could save 19.60% thermal energy (LPG) for Logan drying in Thailand. Similar energy saving result has been reported in Mediterranean climate for different flat as well as parabolic trough type collectors. Desiccated coconut industry in Sri lank reported to have great potential for solar thermal application to mitigate carbon di-oxide emission. These works are impressive however; authors did not consider thermo-hydraulic efficiency of solar air heater. Energy efficiency of diary industries in German, British, and Dutch had improved compare to France (30% energy saving potential). A systematic energy audit reported in 76 food processing farm in Taiwan revealed fair potential for improving energy efficiency. Energy intensity has been reported ranged from 0.2 to 12.60 MJ kg\(^{-1}\) fluid milk products across various countries. Global cheese making industries got energy intensity 4.9 to 8.9 MJ kg\(^{-1}\) of
cheese across the few countries. These are appreciable reviews on energy conservation and efficiency for food processing industries even though details experimental technological intervention was not recommended.

India tea processing industries annually emit 1.35 M t CO₂ with energy cost is 30% of total cost. There is a scope for application of renewable thermal energy in tea industries. The few tea factories in Tamilnadu reported to use solar air heater that saved 25% conventional energy. Rubber wood waste is reported to use as gasification feedstock for both analytical and experimental study for black tea drying in Sri Lanka. However, it is clear from the reviews that hybrid biomass gasification cum solar thermal is not experimented for black tea drying as of today. It has been reported that gasification plant produces less sulphur, carbon di-oxide, oxides of nitrogen and particulate matter. Gasification of waste biomass may be used for process heat generation conveniently. Uprooted tea shrubs has been reported to gasify for black tea drying process heat generation by us. Since tea industry is an agro based unit, therefore other surplus biomass from its own generation may be utilized and therefore other combination of renewable energy have not been considered at present.

Thin layer drying model for different agricultural produces have been reported. However, thin layer drying model of black tea with producer gas fired dryer has not been reported so far. Different designs artificially roughen improved solar air heaters have been reported. Our design considers hemi-spherically protruded improved solar air heater on aluminum plate where a correlation was developed for Nusselt number. Hybridization of biomass and solar thermal energy for drying chili, pineapple, coconut, turmeric, etc., are available. However, none of them refers to black tea processing in hybrid energy mode that is addressed by our present study.

Therefore, we conduct experimental study of characterization of ten biomass samples, gasifier performance, black tea drying experimentation, and modelling, improved solar air heater development, testing and possible hybridization of solar thermal and biomass gasification technology for black tea drying in Assam (India).