

Combined Steam Power Plant and Vapour Compression Refrigeration System Powered by Biogas Combustion Produced from tea Waste

Kamaljyoti Talukdar¹

¹Associate professor, Dept. of Mechanical Engineering, Dhemaji Engineering College, Dhemaji, Assam, India

Emails: kamaljyoti.talukdar@gmail.com¹

Abstract

The given combined system is used for producing 1 MW electrical power in steam power plant by burning biogas produced from tea waste in boiler and 15 kg/s of cold water/hot water in May(summer)/January(winter) by R-134a as refrigerant vapour compression refrigeration system by utilizing power from steam turbine. The steam power plant parameters remain same for both May and January. Steam condenser pressure is maintained at 0.1 bar, boiler at 100 bar which is superheated to 500°C by burning biogas produced from anaerobic digestion of tea waste. From steam turbine 1 MW power is extracted and remaining required power are used by compressor of refrigeration system for producing cold water/hot water. In May cold water of 12°C is obtained from ambient reference temperature of Dibrugarh town, Assam at a rate of 15 kg/s by circulating water in evaporator. The condenser and evaporator temperature is maintained at 30°C and 16°C respectively. Similarly, in January hot water of 80°C is obtained from ambient reference temperature at a rate of 15 kg/s by circulating water in condenser. The condenser and evaporator temperature is maintained at 90°C and 16°C respectively. In May it is observed that with increase in ambient reference temperature leads to increase in the refrigeration load, which consequently increases the compressor work requirement. As the compressor work increases, the volume of biogas required and the mass flow rate of tea waste in boiler also increase slightly. In January with decrease in ambient reference temperature leads to increase in the condenser load, which consequently increases the compressor work requirement and the volume of biogas required and the mass flow rate of tea waste in boiler also increases. In January compressor work, volume of biogas and mass flow rate of tea waste in boiler is much more than May due to greater difference in temperature of hot water and ambient reference temperature.

Keywords: Biogas, Boiler, Cold water, Compressor, Condenser, Evaporator, Hot water

1. Introduction

Tea is a beverage which is consumed by people of India. Assam is the prime producer of tea in India. With production of tea waste associated with tea is produced. Assam generates approximately about 35,600 kg of factory tea waste per day, based on standard regulatory ratios and average annual production and 13 million kg tea waste annually [1]. Such waste that is generated needs proper disposal and is not easy. If such tea waste can be utilized for useful purposes it would give an added advantages. Many researchers have worked on tea waste for beneficial purposes to society. Debnath et al (2021) [2] reviewed the emerging applications of tea waste

in different fields including environmental remediation, generation of energy, polymer composites' fabrication, generating environment friendly biomass and electrical devices preparation for the purpose of energy storage. Duarah et al (2024) [3] reviewed two different tea waste conversion. Thermochemical conversion of tea waste into biochar, biogas, bio-oil, and activated carbon; and biochemical conversion of tea waste into fertilizers, phytochemicals, and liquid bio-fuels. Çakmak et al (2024) [4] reviewed the general composition and bioactive compounds of tea waste. It was found that from tea waste valuable compounds could be

obtained by extraction methods, having the potential to be used for different purposes, such as biogas production, functional foods, food additives, silages, soluble packaging materials, and adsorbents. Nille et al (2021) [5] systematically summarized valorization of tea waste through chemical and physical activation, carbonization, and extraction resulting in generation of value-added products like adsorbent, activated carbon, magnetic adsorbent, and carbon-based nanomaterials including carbon nanodot, graphene oxide dot, etc which finds suitable applications in fields of sensing, detection, pollutant removal, separation, wastewater treatment, environmental remediation, catalysis, energy storage and harvesting, tissue engineering, agriculture, food industry, and green and sustainable nanotechnology. Jayakala et al (2025) [6] highlighted the valorization processes and value-added products from tea waste with application of value added products for energy generation, wastewater treatment, soil conditioners, adsorbents, biofertilizers, food additives, dietary supplements, animal feed bioactive chemicals, dye, colorant, phytochemicals, bioplastics, cutlery products, scope, and future directions in sustainable utilization. Singh [7] evaluated the recycling potential of tea waste as a dye (methylene blue) adsorbent and a substrate for production of industrially important enzymes.

2. System Layout

Figure 1 shows two combined cycles where steam power plant undergoing process 1-2-3-4 is topping cycle producing 1 MW power and vapour compression refrigeration system with R-134a refrigerant undergoing process 1'-2'-3'-4' is bottoming cycle producing cold water. In topping cycle water is heated in boiler (maintained at 100 bar) by required combustion of biogas obtained from anaerobic digestion of tea waste to 500°C (superheated state). It is passed through steam turbine where generator is attached and 1 MW electrical energy is produced. Excess electric power is utilized by compressor of vapour compression refrigeration system for operating the bottoming cycle. In the refrigeration system 50 kg/s of water prevalent at temperature in Dibrugarh's town, Assam, India is passed through evaporator where due to exchange of

heat cold water of 12°C is obtained. The compressor power consumed which is obtained from generator fluctuates due to different temperatures in a day. As shown in FIGURE 1. Combined steam power plant and vapour compression refrigeration system for cold water production in May (Summer).

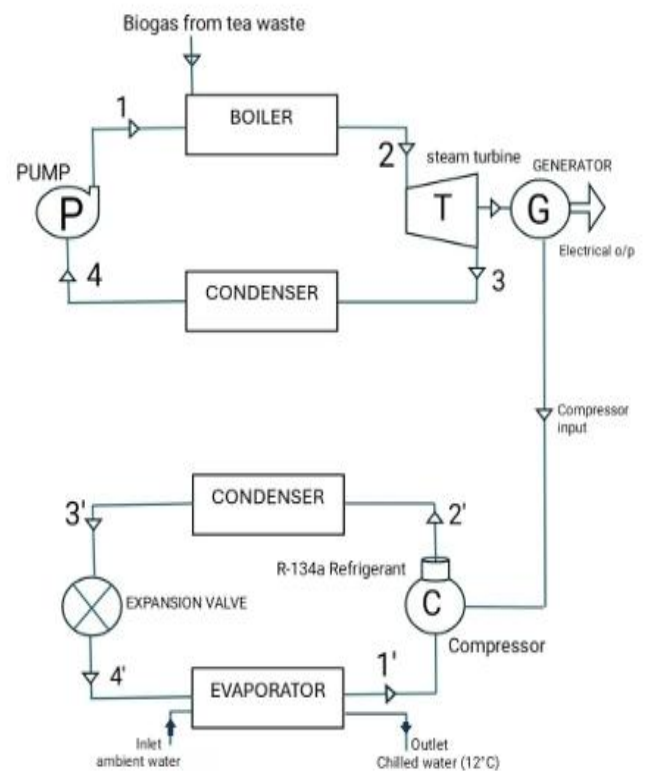


Figure 1 Combined steam power plant and vapour compression refrigeration system for cold water production in May (Summer)

Figure 2 is similar to figure 1, only difference is that water at 50 kg/s prevalent at temperature in Dibrugarh's town, Assam, India is passed through condenser of vapour compression refrigeration system to produce warm water of 80°C. Similarly, the compressor power consumed which is obtained from generator fluctuates due to different temperatures in a day. As shown in Figure 2 Combined steam power plant and vapour compression refrigeration system for warm water production in January (Winter)

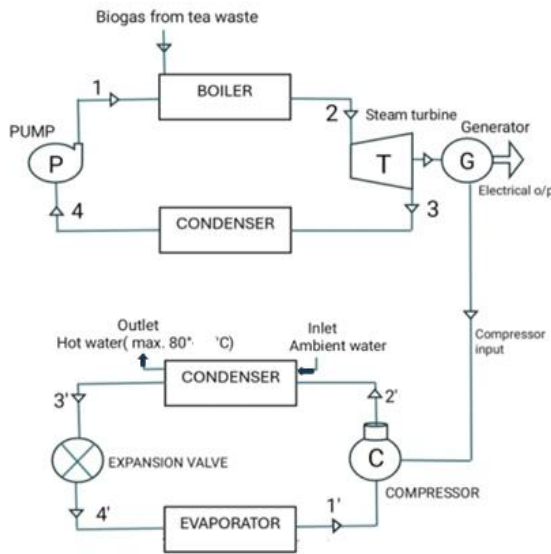


Figure 2 Combined steam power plant and vapour compression refrigeration system for warm water production in January (Winter)

Following are the values assumed:

- Boiler pressure of steam power plant= 100 bar
- Exit temperature of steam from boiler=500°C (Superheated at 100 bar)
- Condenser pressure of steam power plant=0.1 bar
- Evaporator temperature of compression refrigeration system= 16°C
- Condenser temperature of compression refrigeration system=30°C

The cooling load of evaporator (Q_E) for water cooling is given by:

$$Q_E = (15 \times 4.2) \times (T_{amb, May} - 3 - 12) \quad (1)$$

Where, 15-water cooled in kg/s, 4.2-specific heat of water in kJ/kg, $T_{amb, May}$ -Ambient temperature of Dibrugarh town in May[8], 3-3°C temperature of water lower than ambient(assumed), 12-Temperature of water cooled in °C Mass flow rate of refrigerant(R_{134a}) required(m_r) for maintaining required Q_E :

$$m_r = \frac{Q_E}{h_{1'} - h_{4'}} \quad (2)$$

Where, $h_{1'}$ -enthalpy of refrigerant at the exit of evaporator(kJ/kg), $h_{4'}$ -enthalpy of refrigerant at inlet to evaporator(kJ/kg) Actual compressor work

($W_{C, Actual}$) needed from generator is:

$$W_{C, Actual} = \frac{m_r \times (h_{2'} - h_{1'})}{0.85} \quad (3)$$

Where, $h_{2'}$ - enthalpy of refrigerant at the exit of compressor(kJ/kg), $h_{1'}$ - enthalpy of refrigerant at the inlet to compressor(kJ/kg), 0.85-isentropic efficiency of compressor[9] Total turbine work in kW needed (WT) from power generated by generator:

$$W_T = W_{C, Actual} + 1000 \quad (4)$$

Where, 1000- electrical power utilized besides $W_{C, Actual}$ in kW. Mass flow rate of steam(MS) to be produced(kg/s) for required purpose:

$$M_s = \frac{W_T}{(h_2 - h_3) \times 0.42 \times 0.95} \quad (5)$$

Where, h_2 -enthalpy of superheated steam at 500°C(100 bar) at entry to turbine(kJ/kg), h_3 -enthalpy of steam at exit from turbine turbine(kJ/kg), 0.42-efficiency of steam turbine[10], 0.95-efficiency of generator [11]. Boiler heat (BH) required for producing MS is:

$$B_H = M_s \times (h_2 - h_1) \quad (6)$$

Where h_2 - enthalpy of steam at exit from boiler (500°C, 100 bar) in (kJ/kg), h_1 -enthalpy of water at inlet to boiler(kJ/kg). Biogas mass required to be burned(kg/s) for producing required boiler heat:

$$Biogas_{Mass} = \frac{B_H}{20 \times 1000 \times 1.2} \quad (7)$$

Where, 20-Calorific value of biogas (MJ/m³) [12], 1.2- density of biogas(kg/m³) [13] Volume of biogas(m³/s) required:

$$Biogas_{volume} = \frac{Biogas_{Mass}}{1.2} \quad (8)$$

Where, 1.2- density of biogas(kg/m³)[13]

Mass of tea waste MTW(kg/s) required for producing required volume of biogas:

$$M_{TW} = Biogas_{volume} \times 5 \quad (9)$$

Where, 5 means 5 kilograms of dry tea waste is needed to produce 1 cubic meter (m³) of biogas [14]

Following are the values assumed:

- Boiler pressure of steam power plant= 100 bar
- Exit temperature of steam from boiler=500°C(Superheated at 100 bar)
- Condenser pressure of steam power plant=0.1 bar

- Evaporator temperature of compression refrigeration system= 16oC
- Condenser temperature of compression refrigeration system=90oC

Condenser load (QC) for water heating is:

$$Q_C = 15 \times 4.2 \times [80 - (T_{amb, Jan} - 5)] \quad (10)$$

Where, 15-water heated in kg/s, 4.2-specific heat of water in kJ/kg, Tamb,Jan-Ambient temperature of Dibrugarh town in January[8], 5-5oC temperature of water lower than ambient(assumed),80-Temperature of water to which heated in oC Mass flow rate of refrigerant (R-134a) required(mr) for maintaining required QC:

$$m_r = \frac{Q_C}{h_{2'} - h_{3'}} \quad (11)$$

Where, h2'-enthalpy of refrigerant at inlet to condenser (kJ/kg), h3'-enthalpy of refrigerant at exit from condenser. Actual compressor work (WC,Actual) needed from generator is:

$$W_{C, Actual} = \frac{m_r \times (h_{2'} - h_{1'})}{0.85} \quad (12)$$

Where, h2'- enthalpy of refrigerant at the exit of compressor(kJ/kg), h1'- enthalpy of refrigerant at the

inlet to compressor(kJ/kg), 0.85-isentropic efficiency of compressor[9] Similarly, turbine work, mass flow rate of steam needed in boiler, boiler heat required, biogas mass, volume of biogas needed and mass of tea waste needed can be obtained from equations 4, 5, 6, 7, 8 and 9 respectively.

3. Results And Discussions

Table 1 shows the different values of vapour compression refrigeration compressor work, biogas volume required and mass flow rate of tea waste needed in May. It is seen that compressor work, biogas volume required and mass flow rate of tea waste is more for higher ambient temperatures. This is due to the fact that the term (Tamb, May-3-12) increases with higher Tamb, May as shown in equation 1. As a result QE increases resulting in increase of mr in equation 2 and increase of compressor work as shown in equation 3. Similarly the other variables in equations 4, 5, 6, 7, 8 and 9 increases proportionally. As shown in Table 1. Requirements needed in May(summer) for cooling water Table 2 Requirements needed in January(winter) for heating water

Table 1 Requirements needed in May(summer) for cooling water

TIME	TEMPERATURE(°C)[8]	ACTUAL COMPRESSOR WORK(kW)	VOLUME OF BIOGAS REQUIRED (m3 /s)	MASS FLOW OF TEA WASTE (kg/s)
12:30 AM	23.71	53.642	0.234	1.172
3:30 AM	25.39	63.988	0.237	1.184
5:30 AM	25.39	63.988	0.237	1.184
8:30 AM	24.83	60.540	0.236	1.180
11:30 AM	24.27	57.091	0.235	1.176
2:30 PM	23.33	51.301	0.234	1.169
5:30 PM	23.15	50.193	0.234	1.168
8:30 PM	23.71	53.642	0.234	1.172

Table 2 Requirements needed in January(winter) for heating water

TIME	TEMPERATURE(°C)[8]	ACTUAL COMPRESSOR WORK(kW)	VOLUME OF BIOGAS REQUIRED (m3 /s)	MASS FLOW OF TEA WASTE (kg/s)
12:30 AM	12.88	4318.464	1.183	5.916
3:30 AM	16.61	4095.116	1.133	5.667
5:30 AM	21.47	3804.104	1.068	5.344
8:30 AM	23.33	3692.73	1.044	5.22
11:30 AM	18.48	3983.142	1.108	5.543
2:30 PM	15.68	4150.803	1.146	5.729
5:30 PM	14.00	4251.399	1.168	5.841
8:30 PM	13.44	4284.932	1.175	5.879

Table 2 also shows the different values of vapour compression refrigeration compressor work, biogas volume required and mass flow rate of tea waste needed in January. It is seen that compressor work, biogas volume required and mass flow rate of tea waste is more for lower ambient temperatures. This is due to the fact that the term $[80-(T_{amb,Jan}-5)]$ increases with lower $T_{amb,Jan}$ as shown in equation 10. As a result QC increases resulting in increase of m_r in equation 11 and increase of compressor work as shown in equation 12. Similarly other parameters mentioned in equations 4, 5, 6, 7, 8 and 9 increases proportionally. It is seen that compressor work, biogas volume required and mass flow rate of tea waste is more in January than may due to greater values of $[80-(T_{amb,Jan}-5)]$ in January than $(T_{amb,May}-3-12)$ in May.

Conclusion

The study makes constructive use of tea waste for producing both power and 15 kg/s of water heating/cooling in January/ May. It needs lot of preparation for the desired outcome. The study is made in May and January because if the system works well in May(hottest month) and January(coldest month) the system will work well throughout the year in Dibrugarh town.

However, the volume of biodigester needed for producing required biogas from tea waste can be considered as a future study.

References

[1].<https://tinyurl.com/5bmpdryj> (Accessed on 11.06.2026)

- [2].Debnath, B; Haldar, D; & Mihir Kumar Purkait, M.K.(2021). Potential and sustainable utilization of tea waste: A review on present status and future trends . Journal of Environmental Chemical Engineering, 9(5), 106179.
<https://doi.org/10.1016/j.jece.2021.106179>.
- [3].Duarah, P., Haldar, D., Singhania, R. R., Dong, C. D., Patel, A. K., & Purkait, M. K. (2024). Sustainable management of tea wastes: resource recovery and conversion techniques. Critical Reviews in Biotechnology, 44(2), 255–274.
<https://doi.org/10.1080/07388551.2022.2157701>.
- [4].Çakmak, T. G., Saricaoglu, B., Ozkan, G., Tomas, M., & Capanoglu, E. (2024). Valorization of tea waste: Composition, bioactivity, extraction methods, and utilization. Food Science & Nutrition, 12, 3112–3124.
<https://doi.org/10.1002/fsn3.4011>.
- [5].Nille, O.S; Patil, A.S; Waghmare, R.D.; Naik, V.M; Gunjal, D.B; Kolekar, G.B.;& Gore, A.H.(2021). Chapter 11 - Valorization of tea waste for multifaceted applications: a step toward green and sustainable development. Valorization of Agri-Food Wastes and By-Products, Academic Press, 219-236.
<https://doi.org/10.1016/B978-0-12-824044-1.00046-5>.
- [6].Jayakala Devi R., Usha R., Rajkishore S. K.

- & Raveendran M.(2025). Development of economic value-added products from tea waste by thermal and microbial process for environmental sustainability.Biomass Conv. Bioref. 15, 5111–5140. <https://doi.org/10.1007/s13399-024-05410-x>.
- [7].Singh S.(2025). Circular economy inspired utilization of tea waste in dye pollution mitigation. The Journal of Solid Waste Technology and Management, 51(4),777-87. Weather History & Data Archive | Weather Underground, <https://www.wunderground.com/history>. (Accessed on 30.05.2026)
- [8].Compressor Isentropic Efficiency: What, How, Several Types ...; <https://lambdageeks.com/compressor-isentropic-efficiency/> (Accessed on 30.01.2026) <https://tinyurl.com/yrs9zvm> (Accessed on 30.01.2026) <https://tinyurl.com/46pftfv> (Accessed on 30.01.2026) <https://tinyurl.com/2nmwfv8> (Accessed on 30.01.2026) <https://tinyurl.com/5ckhx2ex> (Accessed on 30.01.2026)
- [9].Manyuchi, M.; Mbohwa, C; & Muzenda, E.(2018) Biogas and Bio solids Production from Tea Waste through Anaerobic Digestion. Conference: 2nd IEOM European Conference on Industrial Engineering and Operations Management, Paris, France.