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Exergy Based Performance Improvement of Cogeneration Plant of Sugar Mills

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Abstract: Cogeneration, the combined generation of heat and power, is an efficient method to reduce cost or to save energy and hence, reduces the pollution. A large number of thermal process industries have this option to install cogeneration system and sugar mill is one of them. In this work, energy and exergy analysis of a sugar mill running on cogeneration system, having back pressure turbine system, has been carried out. Based on the operational data received from the industry, the detailed analysis of the system has been performed. It was found that the output power and excess power of the plant increases with increase in the boiler pressure and therefore, increases the cogeneration efficiency. Also, it was noticed that when the back pressure increases, the turbine output and cogeneration efficiency decrease and, Heat to Power Ratio (HPR) spans over a range of 2.79 to 4.07. From the exergy analysis of the plant, it is observed that the boiler is the main component for exergy destruction. The energy analysis of bagasse fired boiler was carried out and the results showed that energy efficiency was high up to 84.5%. However, the second law efficiency gave 28.5% and irreversibility rate associated with the combustion chamber was 62.19 MW which accounts 55.09% of the total fuel exergy.

Keywords: Sugar industry, Cogeneration, Back pressure turbine, Energy analysis, Exergy analysis,

1. Introduction

Thermal power plants are the main source of electricity supply in India. Most of the conventional power plant's efficiency is nearly 35%, and the remaining 65% of energy is lost [1]. The primary source of loss in the conversion process is the heat rejected to the surrounding water or air. Also, further losses are associated with the transmission and distribution of electricity.

Cogeneration is defined as the sequential generation of two different forms of useful energy from a single primary energy source, typically mechanical energy and thermal energy [2]. Mechanical energy may be used to drive an alternator for producing electricity or rotating equipment such as a motor, compressor, pump, or fan. Thermal energy can be used either for direct process applications or indirectly for producing steam, hot water, and hot air for dryers [3]. Combined heat and power generation permits the energy of the fuel to be more efficient utilization than in an electric and thermal separate generation. Compared to separate fossil-fired heat and electricity generation, cogeneration may result in consistent energy conservation (usually ranging from 10% to 30%) while reducing CO2 emissions [4].

India is the world's second-largest cane sugar producer (next to Brazil). India's sugar industry has the maximum cogeneration potential. There are nearly 600 sugar mills spread over nine states. Bagasse is a by-product of manufacturing sugar from sugar cane [5][4]. Bagasse is a useful source of energy with a gross calorific value of about 9200 kJ/kg, but it contains a very high level of moisture (around 50% by weight) and needs specially designed handling, feeding, and combustion systems [6]. The commonly used combustion systems are dumping grates and traveling grates. An integrated sugar mill/distillery process is heat-intensive. Many stages such as diffusion, evaporation, crystallization, and distillation need heat in the form of steam [7]. Electrical energy is consumed by material handling equipment, shredders, mill drives, centrifuges, and other process pumps. The sugar manufacturing process requires a large quantum of steam, and the bulk of the steam required for the processing is needed at low pressure, such as 2.5 bar. The CHP system generates the process steam and at least a significant part of the electricity for the mill. Such as the importance of investigating new possible power plants based on sugar cane trash and assessing energy and economic perspectives [3].

In the presence scenario, environmental constraints and depletion of fossil fuels are the major reasons which compels the consumers to switch towards the renewable energy source. The main source of renewable energy is solar PV, solar thermal, wind, tidal, geothermal, biomass, etc. [2][8][9][10]. As a biomass fuel, bagasse supplies raw material for producing natural, clean and renewable energy, enabling its use to further government targets for renewable energy use. In brief, the environmental advantages of bagasse cogeneration are low emission of particulates, SO2, NOx, and CO2 compared to coal & other fossil fuels [4][7]. In GHG terms, bagasse combustion emits less than composting. In the fuel efficiency term, the same amount of bagasse will give more power in cogeneration mode than in conventional combustion processes that do not recover heat; a large amount of fuel can be saved by introducing a heat recovery system [2][11].

2. Materials and Methods

Cogeneration technologies that have been widely commercialized include extraction/back pressure steam turbines, gas turbines with heat recovery boilers, and reciprocating engines with heat recovery boilers. However, sugar mills are associated with steam turbine-based cogeneration systems. The two types of steam turbines most widely used are the backpressure and the extraction-condensing types [3].

2.1. Technical Options for Cogeneration

2.1.1. Back pressure steam turbine

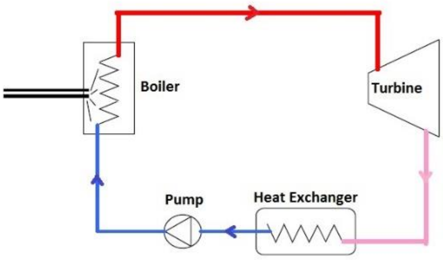

Figure 1. Back pressure steam turbine

It is a system in which steam exits the turbine at a pressure higher or at least equal to the atmospheric pressure.

2.1.2. Condensing-extraction steam turbine

It is a system in which steam is obtained by extraction from one or more intermediate stages at the appropriate pressure and temperature. The remaining steam is exhausted to the condenser pressure.

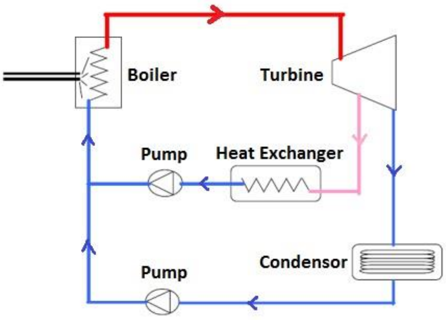

Figure 2. Condensing-extraction steam turbine

The selection between a backpressure turbine and an extraction-condensing turbine depends mainly on the power and heat demand, heat quality, and economic factors. The extraction points of steam from the turbine could be more than one, depending upon the temperature levels of heat required by the processes.

This paper presents the energy and exergy analysis of a sugar mill running on a back pressure turbine cogeneration system. This cogeneration-based power plant, “Ch. Devilal Cooperative Sugar mills ltd.” is situated in Gohana (Haryana). This work will show the importance of exergy analysis and help to identify the major sources of losses for exergy destruction in different parts of the cogeneration system. It will also provide the scope of improvement in the existing system. Finally, it will show the overall system performance and its variation with different operating parameters.

2.2. Governing Equations & Plant Description

2.2.1. Energy Analysis

As per the first law, the energy is conserved. The analysis which is done based on the energy conservation method is known as energy analysis of the corresponding system [12][9]. This is also termed as quantitative analysis as the law only talks about quantity and not the quality of the energy [13]. In the present work both energy and exergy-based performance improvement have been presented. Some of the important relations that has been used during the analysis are mentioned below [14][11][15].

Energy content (NCV) of fuel [6] =$\dot{m}_f * NCV$

Energy absorbed by water to convert into steam is,

$Q_{Total} = m_w(h_1-h_5)$

Turbine work output,

$$W_T = \dot{m}(h_1 - h_2) + \dot{m}_2(h_2 - h_3) \quad (1)$$

m and m_2 are the mass flow rate of steam into the turbine from the turbine inlet condition to 8 bar pressure and from 8 bar pressure to 2.5 bar back pressure, respectively. Process heat required for the plant is at 8 bar and 2.5 bar. m_1 and m_2 are the mass flow rate of steam used for process heating at 8 bar and 2.5 bar, respectively. Therefore, total process heat is a summation of both, as given in equation (2).

Process heat utilized,

$$Q = \dot{m}_1(h_2 - h_6) + \dot{m}_2(h_3 - h_4) \quad (2)$$

Pump work, $W_P = \dot{v}_f(P_5 - P_4)$ (3)

Net-work produced, $W_{net} = W_T - W_P$ (4)

$$\eta_{cogen} = \frac{W_{net}+Q}{\dot{m}_f * LCV} \quad (5)$$

2.2.1. Exergy Analysis

Energy and exergy analysis provides insight into losses in various components of a power generating system. Unlike energy, exergy is not generally conserved but is destroyed [16][2][17][18]. So, the causes of irreversibilities like heat transfer through a finite temperature difference, chemical reactions, friction, and mixing are accounted for by exergy analysis [19].

To carry out exergy analysis following assumptions have been taken. The kinetic and potential exergies are neglected, and the reference state for water/steam is saturated liquid at 25°C. The incoming fuel temperature is 25oC, and the Isentropic efficiency of pumps/turbine was taken as 85%, whereas the generator efficiency was 95% [3].

Boiler subsystem [2]

Exergy efficiency is evaluated as: $\eta_{ex} = \frac{\epsilon_s - \epsilon_w}{\epsilon_g}$ (6)

Irreversibility in the boiler;

$$I = \epsilon_f + \epsilon_{air} + \epsilon_w - \epsilon_{exhaustgas} - \epsilon_{steam} \quad (7)$$

Exergetic efficiency;

$$\eta_{ex} = 1 - \frac{I}{\epsilon_{fuel}} \quad (8)$$

Equations used in exergy calculations

Based on the state points mentioned in figure 1, exergy at each state point is evaluated, and using the relations mentioned below, irreversibility associated with each component has been calculated [3].

The physical energy for air and hot gases can be written as

$$Q = m(Cp_{(T)}T - CpT_0) \quad (9)$$

The specific physical exergy for air and combustion gases with constant specific heat is obtained from Kotas [6].

$$\Psi = C_{p(T)}[T - T_0 - T_0 \ln(T/T_0)] + RT_0 \ln(P/P_0) \quad (10)$$

In a boiler, considering the pressure of flue gases is constant and equal to P_o.

Specific exergy for hot gases is calculated by

$$\Psi = C_{p(T)}[T - T_0 - T_0 \ln(T/T_0)] \quad (11)$$

The specific physical exergy of the steam is calculated by

$$\Psi = C_{p(T)}[h - h_0 - T_0(s - s_0)] \quad (12)$$

Turbine subsystem

The operating parameters m and m_2 are the mass flow rates of steam into the turbine from the inlet condition of the turbine to 8 bar pressure, then 8 bar pressure to 2.5 bar back pressure, respectively.

Exergy balance:

$$m(\psi_1 - \psi_2) + m_2(\psi_2 - \psi_3) = W_T + I \quad (13)$$

$$\eta_{ext} = 1 - \frac{I}{m(\psi_1 - \psi_2) + m_2(\psi_2 - \psi_3)} = \frac{W_T}{m(\psi_1 - \psi_2) + m_2(\psi_2 - \psi_3)} \quad (14)$$

Process heat utilized

$$Q_1 = m_1(h_2 - h_6) \quad (15)$$

Q_1Heat is required at 8 bar and 200 °C, therefore exergy in process heat

$$\epsilon_1 = Q_1\left(1 - \frac{T_0}{200+273}\right) \quad (16)$$

$$Q_2 = m_2(h_3 - h_4) \quad (17)$$

Q_2 is process heat required at 2.5 bar and 120 °C, therefore exergy in process heat

$$\epsilon_2 = Q_2\left(1 - \frac{T_0}{400}\right) \quad (18)$$

Exergy destruction in process heating;

$$I = Q_s\left(1 - \frac{T_0}{T_s}\right) - Q_j\left(1 - \frac{T_0}{T_j}\right) \quad (19)$$

$$\eta_{HE} = 1 - \frac{I}{\epsilon_{Xin}} \quad (20)$$

Cogeneration plant at Ch.Devilal Cooperative Sugar mills ltd. Gohana (Haryana) was considered for analysis as academic research work. The cogeneration system is running on the back pressure turbine system. The plant's crushing capacity is 125 TCH (3000 TCD), and the existing boiler is 80 TPH operating at a pressure of 45kg/cm^{2}and a temperature of 415 °C. The combustion system consists of a dumping grate type. Two T.G. sets of back pressure type were available with a capacity of each 6000 kW. The plant consumes its own bagasse for power heat and power generation with 32 % average bagasse % on cane.

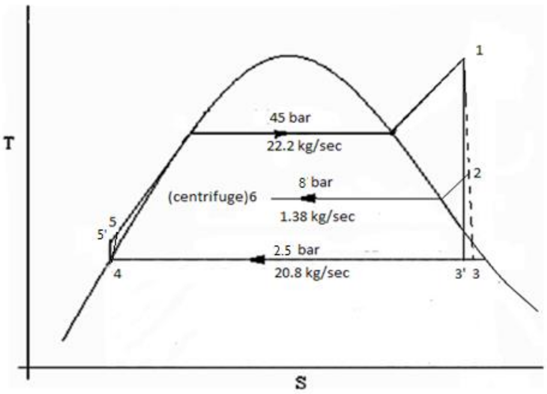

Figure 3. T-s diagram for Back pressure turbine

3. Results and Discussions

The cogeneration efficiencies of the sugar industry cogeneration plant are presented in Tables and graphs. The results show increased cogeneration efficiency with an increase in the boiler pressure and turbine inlet condition. Further analysis has been carried out on the back pressure turbine system to check the effect of back pressure on the power output of the turbine and cogeneration efficiency. It can be seen from the table that cogeneration efficiency decreases with an increase in back pressure because of decrease in both energy values i.e., power out and process heat.

3.1. Energy Analysis of back pressure turbine system

Cogeneration plant at Ch. Devilal Cooperative Sugar mills ltd. is running at 45 bar and 415 °C. The system requires process heating at two pressure values, 2.5 bar, and 8 bar. This sugar mill uses using own bagasse for power generation and process heating.

Finally, the energy analysis for the overall plant has been carried out, and the total plant energy losses have been computed. The energy losses of the components of each system have been determined using their mass and energy balance equations. The energy efficiencies have also been calculated for the overall plant at different boiler pressure. The energy losses of the subsystem components are determined using the energy balances of the first law and then using the energy losses, the energy efficiency is calculated.

Analysis of turbine output and cogeneration efficiency with changing back pressure

The results presented in the Tables listed below clearly show the power output and cogeneration efficiency by varying the pressure ranging from 1 to 6 bar at which process heat is required. Similarly, the same result was calculated at different boiler pressure and analyzed the plant's performance.

Table 1. *For P_B =45 bar; T=415 C*

P_b	Wt (KJ/kg)	qb (KJ/kg)	η_{cog} (%)
1	674.82	3315.42	72.50
2	581.40	3212.86	69.94
3	523.07	3146.10	68.28
5	445.38	3053.79	66.01
6	416.62	3018.24	65.14

As back pressure increases, turbine exit pressure and temperature increase, which means the turbine's output will decrease. At the same time, heat utilized by the process will be reduced since we are using latent heat of the water for process heating.

The graph shows that at high boiler pressure, turbine output and cogeneration efficiency will be higher for the same back pressure condition. However, as back pressure increases, specific turbine output decreases, and cogeneration efficiency will decrease (Figure 4 & Figure 5).

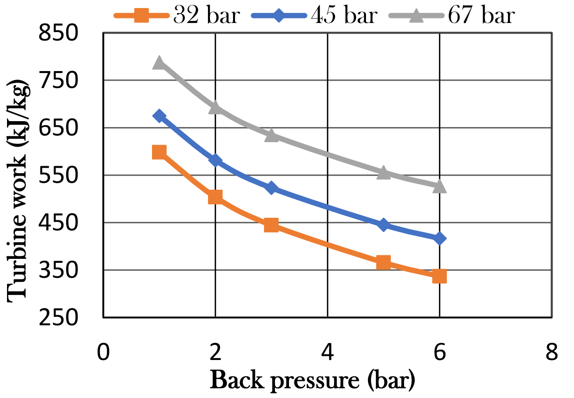

Figure 4. Effects of back pressure on turbine work output

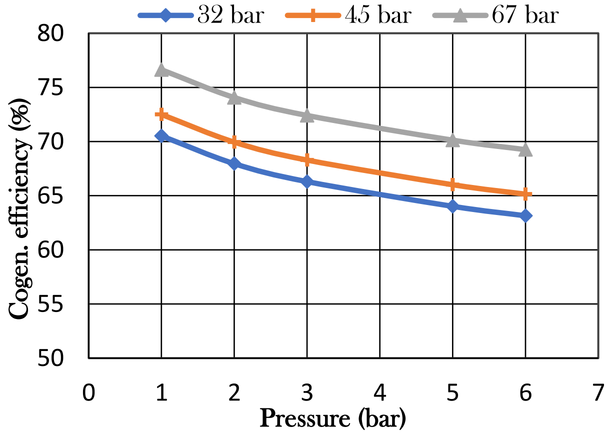

Figure 5. Effects of back pressure on cogeneration efficiency

The first analysis of this back pressure turbine system has been done on the data collected from the above industry. Then, keeping other parameters constant, turbine inlet conditions varied, and the following variation was observed from the results.

TABLE 2. Net power output, excess power, cogeneration efficiency, and H/P ratio at different turbine inlet conditions

P_1 (bar)	T_1 (C)	W_{net} (MW)	Power(ex.) (MW)	Cogen. Efficiency (%)	H/P
32	375	8.864	5.642	64.05	5.232
45	415	10.272	7.052	65.75	4.520
67	490	12.754	9.534	69.30	3.686
87	520	13.763	10.543	70.45	3.415

This graph (Figure 6) shows the variation of gross power and net power saving with the boiler pressure. The graph shows that when boiler pressure increases, turbine power output increases because of improvement in turbine inlet condition, and in the same pattern, power-saving also increases.

From this result, we can say that installing high-pressure boilers and high-pressure turbo generators have enhanced the power generation from 8.86 MW to 13.76 MW. Thus, the surplus power of 4.9 MW is available for exporting to the grid.

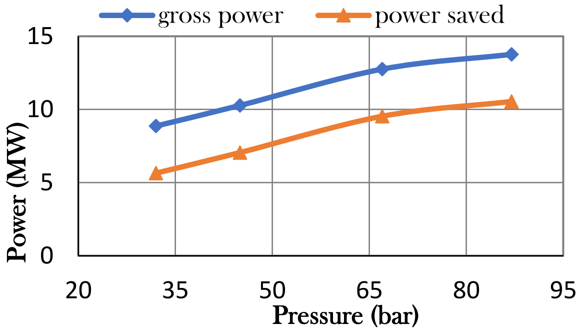

Figure 6. Effects of power Output with Boiler pressure

In graph (Figure 7), we can see that heat to power ratio of the system is decreased with an increase in boiler pressure. HPR is the ratio of heat utilized in the process to turbine power output, and with an increase in boiler pressure, turbine output will increase, but heat utilized will be almost the same, which leads to a decrease in HPR.

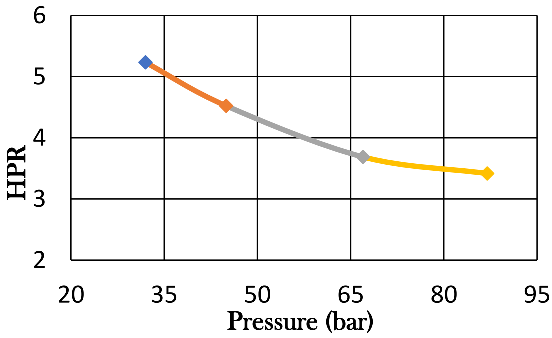

Figure 7. HPR with boiler pressure

As shown in the graph (Figure 8), cogeneration efficiency rapidly increases with the improvement in the turbine inlet condition up to 67 bar pressure but slowly increases after that. So, for a little gain of cogeneration efficiency, its turbine improved inlet condition will not justify it. It is a matter of further analysis of the economic background to check whether improvement in turbine inlet condition is justified or not.

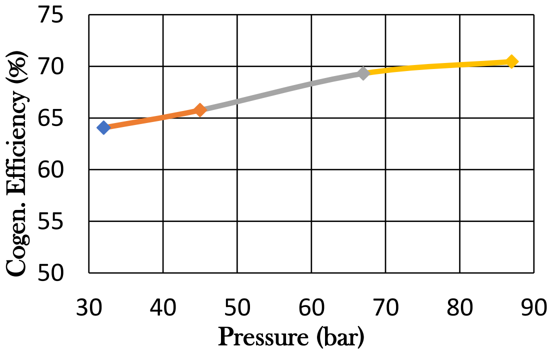

Figure 8. Effects of Cogeneration efficiency with boiler pressure

3.2. Exergy Analysis of back pressure turbine system

Exergy is the maximum theoretical useful work attainable from an energy carrier under the conditions imposed by an environment at a given pressure P_o and temperature T_o [3][6][19][20]. Exergy analysis generally aims to identify the location, source, and magnitude of actual thermodynamic inefficiencies in process plants such as power plants and cogeneration systems [2][18][21][22].

In this cogeneration plant, part of the exergy from the fuel is lost in the heat transfer system, including the boiler, the bleeds heat exchangers, and the economizer. The rest of the exergy goes into the turbine system as the exergy input for generating power. Some of the exergy input is lost in running the turbines and pumps [23][24][25].

Exergy analysis of same back pressure turbine system has been done then keeping constant other parameters, turbine inlet condition varied, and following results are observed from results. In the tables listed below exergy value at each point has been calculated at different pressure and temperature of the boiler for the back pressure turbine system. In this system, steam is extracted at 8 bar, and the rest of the steam is allowed to go through the back pressure of 2.5 bar to utilize its heat energy for process heating [3].

Exergy at each state point of the plant is given in the tables listed below, making reference to the ambient P_o, T_o (Refer to Figure 3).

TABLE 3. Exergy value at different points in TS diagram at PB =45 bar

Points	$\dot{m}$ (KJ/sec)	Ψ (KJ/kg)	$\dot{X}$ (MW)
1	22.2	1232.33	27.357
2	1.38	801.038	1.105
3	20.8	614.078	12.772
4	20.8	61.064	1.2701
5	20.8	65.724	1.367
6	1.38	108.143	0.149

TABLE 4. Irreversibility associated with Components for back pressure turbine system

Pressure (bar)	Boiler (kW)	Turbine (kW)	Exhaust gas (kW)	Total (kW)	η_{ex}	$\eta_{cog.}$
32	33151.1	2680.73	1215.61	37047.4	18.97	65.14
45	31347.4	3094.66	1215.61	35657.0	20.24	66.81
67	28300.3	3500.44	1215.61	33016.6	22.61	70.30

87	26922.3	3930.45	1215.61	32068.3	23.50	71.26

Irreversibility associated with Components at different boiler pressure

Based on the state points mentioned in figure 1, the exergy loss and efficiency for the Rankine cycle components at different boiler pressure are calculated, and a graph has been drawn.

Figure 9 shows the comparison between the overall energy utilization and exergetic efficiency of the plant. This graph shows that as boiler pressure increases, both cogeneration efficiency and exergetic efficiency increase. Its cogeneration efficiency varies from 65.14% to 71.26%, while its exergetic efficiency ranges from 18.97% to 23.50%.

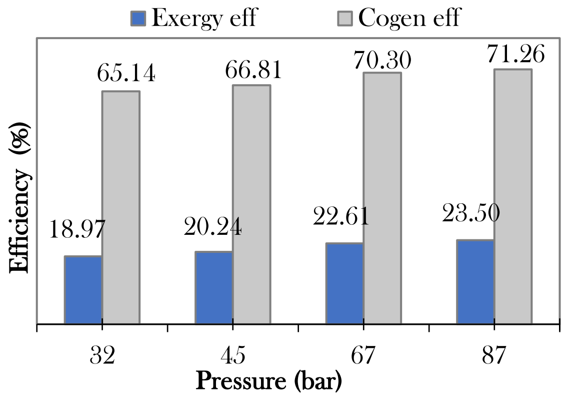

Figure 9. Effects of Efficiencies with boiler pressure

The exergy destruction for each component can be seen from the graph (figure 10), and it is clear from the graph that the boiler itself contributes to the maximum exergy destruction. However, very less exergy destruction takes place in the turbine and other parts of the plant. So, numerous opportunities are present in the boiler to improve its performance.

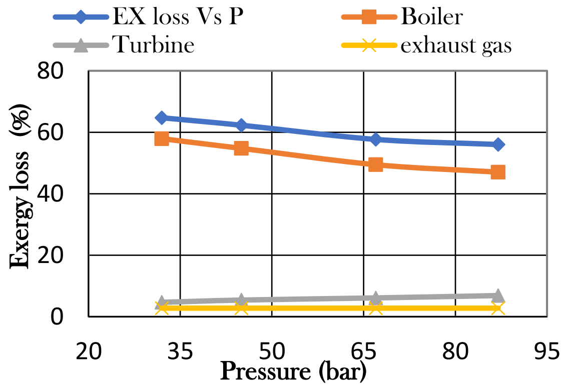

Figure 10. Effects of boiler pressure with exergy destruction (%) in the components

4. Conclusions

The analysis shows that a unit mass of steam produces more work in the turbine when we improve the turbine inlet condition. In the back pressure turbine system, the turbine's output increases rapidly when the inlet steam pressure of the turbine changes from 32 bar pressure to 67 bar. In contrast, it slowly increases when pressure increases further. When the back pressure is 1 bar, cogeneration efficiency enhances from 70.5% to 76.6% when turbine inlet condition improves from 32 bar pressure, 375 oC temperature to 67 bar pressure, 490 oC temperature. But as we increase the back pressure, cogeneration efficiency decreases because both (turbine work output and process heat) decrease simultaneously. From the exergy analysis of the plant, it has been seen that the boiler is the main component for exergy destruction. Overall energy utilization of the plant for the back pressure type system varies from 65.14% to 71.26%, while exergy efficiency varies from 18.97% to 23.50%.

The results of this analysis open its applicability to all process industries, and further investigation in several more areas is also helpful to give the complete picture of the cogeneration plants. That may be the economic analysis of the plant to see the exact picture of the running cogeneration plant. It is also worth checking the possibility of improving the boiler and its subsystems.

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