# Energy and Exergy Analysis Of a 44-MW Bagasse-based Cogeneration Plant in India

S. C. Kamate,
K.L.E.S. Polytechnic, India

P. B. Gangavati,
Basaveshwar Engineering College, India

## ABSTRACT

In this article, energy and exergy analysis of an ongoing, 44-MW, heat-matched, bagasse-based cogeneration plant of Ugar Sugar Works Ltd (USWL), located in Belgaum, India is presented. In the analysis, exergy methods with more conventional energy analysis are employed to assess the thermodynamic efficiencies and losses. The performance of the plant was estimated, and a detailed break up of energy and exergy losses for the considered plant has been presented. The fuel energy savings ratio of the cogeneration plant is estimated in comparison with separate generation plants. The plant performs with energy and exergetic efficiency of 65% and 25%, respectively. Energy losses mainly occurred in the boiler exhaust and condenser, where 35 MW and 27 MW is lost to environment, respectively. The percentage ratio of the exergy destruction to total exergy destruction was found to be maximum in the boiler system (71%) of fuel exergy input or 45% of the physical exergy input. The total exergy destruction in the plant's components is 58% of physical energy input. The plant's fuel energy savings ratio is 8.2%. Because of its inherent combustion irresistibility, the boiler is the major contributor to the plant's overall inefficiency. The inefficiencies in bagasse-fired boilers can be reduced to some extent by increasing the pre-heated, excess air supply and generating steam at possible high pressure and temperature. In terms of technology development, only cogeneration plants with exergetic efficiency close to that of overall efficiency of the conventional power plant be suggested

**Keywords**: bagasse, cogeneration, exergy, energy, efficiency.

## Nomenclature

| | | | |
|---|---|---|---|
| $\lambda_{CG}$ | Heat to power ratio produced | EUF | Energy utilization factor |
| $E_f$ | Fuel exergy input, kW | FESR | Fuel energy savings ratio |
| $\eta_2$ | Second law efficiency | HP | High pressure |
| $\eta_{ex}$ | Exergetic efficiency | HT | High temperature |
| $\eta_B$ | Heat only boiler efficiency | $W_{net}$ | Net power generated, kW |
| $\eta_C$ | Thermal efficiency of conventional power plant | PRDS | Pressure reducing and de-super heating station |
| mb | Mass flow rate of bagasse burned, kg/s | $\varepsilon_b$ | Exergetic value of bagasse, kJ/kg |
| $w_p$ | Pump work, kW | B | Boiler |
| DM | De-mineral water plant | $Q_{CG}$ | Process heat, kW |
| CF | Centrifugal | rej | Rejected |
| CEST | Extraction condensing steam turbine | $Q_{NU}$ | Non-useful heat rejected |
| F | Fuel energy input, kW | Cv | Calorific value, kJ/kg |
| $E_Q$ | Exergetic value of process heat, kW | BPST | Backpressure steam turbine |
| tcd | Tonnes of cane crushed per day | B1 to B4 | Boilers 1 to 4 |
| USWL | Ugar Sugar Works Ltd | | |

## INTRODUCTION

Bagasse–based cogeneration in the Indian sugar industries manufacturing white crystal sugar using a double sulfitation process is generally considered to be economically and environmentally attractive, because these plants burn waste fuel bagasse, a woody fibrous residue of the crushed cane [1]. The potential of this electricity source is substantial. Today India is the second largest producer of the sugar in the world (next to Brazil), accounting for around 10-12% of the world's sugar production, with more than 500 sugar mills in operation. The potential of power generation through bagasse cogeneration in India is estimated to be around 1500-5000 MW, with most estimates around 3500 MW [2-5]. Thus, sugar cane bagasse has strong potential in displacing fossil fuels and can be extensively used in the boilers and furnaces for power generation. Many researchers [6-8] have worked in this area and feel that this considerable amount of power should be generated efficiently

In this context, this article presents the results of an ongoing thermodynamic study of an existing 44-MW, modern bagasse-based cogeneration plant located in Belgaum, India. The cogeneration plant considered for the analysis has received USAID (U.S. Agency for International Development) grants and demonstrated advanced cogeneration operations and economic profitability. This plant could serve as model for other sugar mills interested in setting up cogeneration plants. The Ugar Sugar Works Ltd (USWL) is the first sugar factory in the country to have installed such a large capacity cogeneration plant.

The mill-wet bagasse obtained, having 50% moisture, is directly burned in the specially designed boilers to generate steam at the designed pressure and temperature, by supplying almost 25-30% excess air. The average bagasse generation from cane is around 30% [1, 6, 9]. For the analysis reported within this article, the calorific value and the chemical exergy of mill-wet bagasse are assumed to have an average value of 7650 kJ/kg and 9890 kJ/kg, respectively [6, 10-12]. Modern high-pressure, high-temperature (HP/HT) bagasse-fired boilers perform with thermal efficiency of around 80-85% under optimum conditions [6].

The research reported in this article includes the results of thermodynamic analyses of the cogeneration plant, cycle, and processes. Analysis based on the first and second laws of thermodynamics are first presented to acquaint the reader with the plant's components, and operation data used in the calculation are based on the actual operating data obtained at the cogeneration plant during this thermodynamic study carried out in 2007. Although, the first and second law analysis of cogeneration plants is not new, many researchers [13-23] have employed these concepts to analyze energy systems. But the application of this concept to analyze an actual bagasse-based cogeneration plant in the sugar industry and conclusions emerging from the analysis may provide some guidelines for design improvements, which will yield the best thermodynamic advantage. The data are average values and are indicative of plant's peak load operating state.

Secondly, using the concept of physical exergy [8, 24] associated with products of combustion, flue gas, steam/water flows and ambient temperature surrounding the component, an irreversibility study is outlined, and that estimates the amount of physical exergy destruction in the various components of the plant. The component contributing most to the plant's overall inefficiency is pinpointed. The exergy study is further extended to determine the second law efficiency of major power producing/consuming components of the cogeneration plant.

Cogeneration is advisable for industries if they can produce electricity cheaper, or more conveniently, than that brought from a conventional power plant. From energy resource point of view, cogeneration is beneficial only if it saves primary energy when compared with separate generation of electricity and steam (or heat) [25-26]. To be a rational choice, a cogeneration system must have an FESR > 0, from the point of fuel energy savings [27]. The quality index measures the energy savings by a cogeneration plant compared with separate generation of heat (in a high performance boiler) and electricity (in a power station using best available technology and the same fuel). If a cogeneration plant achieves fuel savings of at least 5%, then it is classified as high quality [28]. Therefore, the fuel savings analysis of the plant is also included in the study.

## DESCRIPTION OF THE COGENERATION PLANT

The schematic of the cogeneration plant and mass balance of steam is shown in Figure 1. Its representation on a T-S diagram is shown in Figure 2 and Figure 3 for a backpressure turbine and an extraction condensing turbine, respectively. These figures depict equipment and state point labels throughout the entire cycle and will be referred to frequently in the sections to flow. It is a 10,000 tcd sugar factory, satisfying its process steam demand from the backpressure steam turbine exhaust, and partially from one extraction drawn across a condensing turbine, as shown in Figure 1.

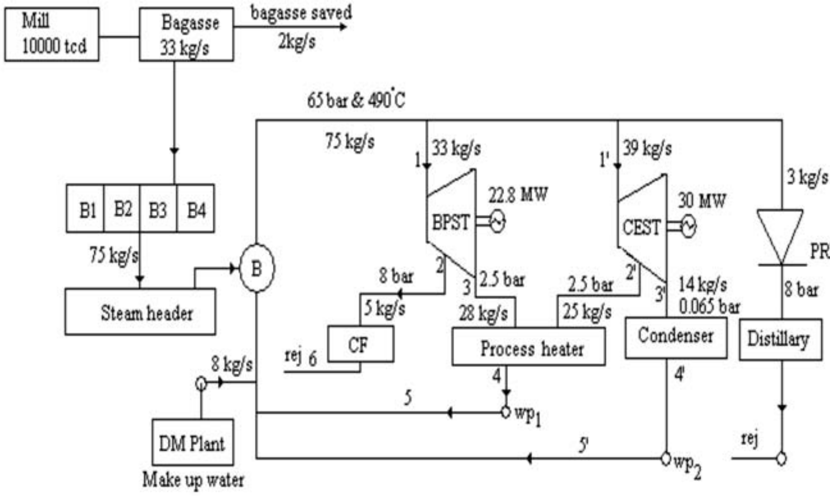

**Figure 1. USWL Cogeneration Plant.**

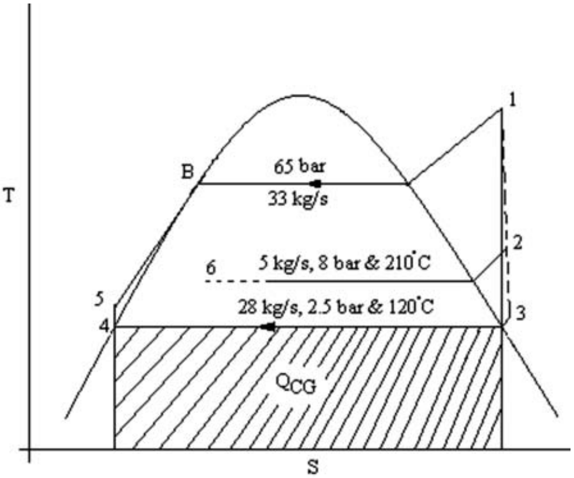

**Figure 2. T-S diagram for BPST**

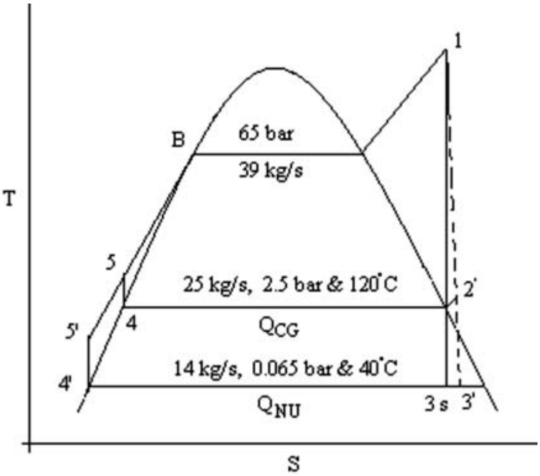

**Figure 3. T-S diagram for CEST**

Although, the plant requires saturated steam at 2.5 bars and 120°C for process heating, steam is drawn at 10°C superheat to avoid heat losses in pipes, bends, valves, etc.

The plant is designed to generate 44 MW of power using mill-wet bagasse produced during crushing season as fuel. To achieve this, the USWL has installed four bagasse-fired boilers of rated capacity 16.7 kg/s, 16.7 kg/s, 19.5 kg/s, and 22.1 kg/s generating steam at 65 bars and

490°C. Of the four boilers, two boilers of capacity 16.7 kg/s are of the dumping grate type and other two boilers of capacity 19.5 kg/s and 22.1 kg/s are of traveling grate type. The average steam-to bagasse-ratio is normally 2.25 for these pressure and temperature conditions [6-7, 9-10]. The boilers operate between 950°C to 1000°C furnace temperatures, and the exhaust flue gas temperature is limited to 150°C. The plant supplies around 30% of excess air to the boilers [9] to achieve complete and efficient combustion of bagasse.

Two turbines—one backpressure turbine of 22.8 MW capacity (manufactured by Shin Nippon) and another extraction condensing steam turbine of 30 MW rated capacity (manufactured by Siemens)—are installed in the plant. The captive power requirement of the plant is 16 MW, with the remaining 28 MW exported to grid. The cogeneration plant is equipped with a distributed control system. Grid interfacing is done using two 19.5 MVA, 11/110 kV power transformers.

The concept of combining the features of both backpressure and condensing steam turbines in the design of cogeneration plant has emerged based on the practical experience of plant engineers at USWL. During the off-season, only the condensing turbine is operated in full condensing mode to generate power similar to a conventional power plant. The USWL has two de-mineral (DM) plants with a 25 kg/s total capacity to maintain mass balance of steam/water rejected in the centrifuge, sulfur melting process and other losses.

## ANALYSIS

### Energy Analysis

Thermal efficiency, $\eta_C$, of a conventional power plant and energy utilization factor (EUF) (or first law efficiency or energy efficiency) of the cogeneration plant are determined using equation (1) and (2).

$$\eta_c = \frac{W_{net}}{F} \quad (1)$$

$$EUF = \frac{W_{net} + Q_{CG}}{F} \quad (2)$$

where, F is fuel energy supplied.

Thermal efficiency, expressed in equation (1), has less relevance to a cogeneration plant, which provides process heat and generates electrical power. The better indicator of performance is the energy utilization factor (EUF), expressed in equation (2), which takes into account process heat produced [29]. The rate of turbine work produced $W_{net}$ is calculated using an energy and mass balance around the turbine. The isentropic efficiency, based on manufacturer's data, is 85% using the known output of the turbine/generator set as well as the generator's efficiency. The heat loss from the turbine is shown in equation (3).

$$Q_{turbine} = W_{turbine} + \Sigma_{exit}\,(mh) - \Sigma_{in}\,(mh) \qquad (3)$$

The rate of heat into the boiler is determined by multiplying the average calorific value of the mill-wet bagasse by the mass flow rate of the bagasse burned, as shown in equation (4).

$$F = mb\ Cv \qquad (4)$$

However, not all the energy provided during the bagasse combustion process is transferred to steam. The heat available to the steam, $Q_{steam}$, can be calculated using an energy balance at the boiler using equation (5).

$$Q_{steam} = \Sigma_{exit}\, mh - \Sigma_{in}\, mh \qquad (5)$$

In addition, the boiler efficiency can be calculated using equation (6).

$$\eta_{boiler} \quad \frac{Q_{steam}}{F} \qquad (6)$$

## Fuel Energy Savings Ratio

If a cogeneration plant substitutes a separate unit of a conventional power plant with an overall efficiency $\eta_C$, and a heat-only boiler with an efficiency $\eta_B$, meeting the same loads of electricity, W, and process heat, Q, then the fuel savings achieved by installing the cogeneration plant is expressed as the fuel energy savings ratio (FESR) and is calculated using equation (7), assuming $\eta_B = 0.85$, $\eta_C = 0.35$[29-30].

$$\mathrm{FESR} = 1 - \frac{1 + \lambda_{CG}}{\mathrm{EUF}\left[\frac{1}{\eta_C} + \frac{\lambda_{CG}}{\eta_B}\right]} \tag{7}$$

Here, $\lambda_{CG} = \left[\frac{Q_{CG}}{W_{CG}}\right]$ is the heat-to-power ratio provided by the cogeneration plant.

However, it is important to remember here is, the FESR achieved by a cogeneration plant, calculated using equation (7), is relevant only if both separate generation plants and the cogeneration plant are burning the same fuel (bagasse). Otherwise, to quantify the fuel energy savings, it is necessary to calculate the fuel equivalent values, when comparing the fuel savings with the plants burning fossil fuels like coal, gas, oil, etc. FESR is the most relevant in the evaluation of performance assessment of the cogeneration plant, because this can be used directly in the economic assessment of the plant.

## Exergy Analysis

Exergy is a measure of energy quality, and exergetic or second law efficiency is the measure of perfectness of the system [19-20]. Exergy is not conserved but can be readily destroyed through the presence of irreversible process or transferred to or from a system through mass or energy flow [31]. In the present study, the following assumptions were made.

(i) The chemical exergy of the fuel (bagasse) is considered as exergy input to determine the exergetic efficiency of the cogeneration plant as a whole.

(ii) The physical exergy of the products of combustion, flue gas and steam/water flow is used to determine loss of exergy in the components of cogeneration plant.

The results are determined using the actual data available from the plant.

### *Chemical Exergy of the Fuel and Exergetic Efficiency of Cogeneration Plant*

The chemical exergy flow rate of fuel (bagasse) is determined by multiplying the average exergetic value of mill-wet bagasse by the mass flow rate of bagasse burnt in the boiler.

$$E_f = m_b\, \varepsilon_b \tag{8}$$

The exergetic efficiency of cogeneration plant as a whole is determined as

$$H_{EX} = \frac{W_{net} + E_Q}{E_f} \tag{9}$$

where, $E_Q$ is the exergy equivalent of process heat [22-23].

*Physical Exergy Flow and Exergy Destruction*

The physical exergy change associated with the mass flow rate of fluids through each component is dependent on the exergy in ($E_{in}$), the exergy out ($E_{out}$), and the exergy destroyed, E(destroyed), during the process.

$$\Delta\varepsilon = \varepsilon_{in} - \varepsilon_{exit} - \varepsilon_{dest} \tag{10}$$

By assuming a control volume of interest, this can be expanded into

$$\left[\frac{dE}{dt}\right]CV = \Sigma\left(1 - \frac{To}{Ti}\right)Qi + W_{CV} + m\,(ef_1 - ef_2) - \varepsilon_{dest} \tag{11}$$

The change in exergy, $\left[\frac{dE}{dt}\right]CV$, is therefore a function of the heat, work, mass flow rate, and exergy destruction occurring within a component. The term Qi is the heat transfer rate from the control volume at the location where Ti is the boundary temperature. The specific flow of exergy, term ($ef_1$-$ef_2$) accounts for the exergy transfer rate associated with the mass flow into and out of the control volume [20].

$$(ef_1 - ef_2) = (h_1 - h_2) - To\,(s_1 - s_2) + \frac{V_1^{\,2} - V_2^{\,2}}{2} + g\,(z_1 - z_2) \tag{12}$$

The exergy destroyed is a function of entropy generation and the ambient air temperature (To) surrounding the component. It is important to note that the surrounding temperature varies significantly from one component to another in the plant. For example, the temperature surrounding the boiler is much higher than the temperature surrounding the condenser.

The exergy concept is extended to determine the exergetic or second law efficiency of major components. This efficiency compares the actual work produced/consumed by device to the work interactions associated with reversible device. The general expression for exergetic efficiency or second law efficiency of power producing/consuming device is

$$\eta_2 = \frac{W_{act}}{W_{rev}} \tag{13}$$

While, equations (14) and (15) are the expressions for the second efficiency of turbine ($\eta_{2t}$) and boiler ($\eta_{2b}$), respectively

$$h_{2turbine} = \frac{(W_{net})_{ST}}{ws\ (ef_1 - ef_2)} \tag{14}$$

$$h_{2boiler} = \frac{ws\ [(h_1 - hs) - To\ (S_1 - S_5)]}{E_f} \tag{15}$$

However, equation (15) can be modified suitably corresponding to Figure 3.

## ANALYSIS PROCEDURE

The criterion adopted in the design of plant and procedure following the analysis is briefly summarized in this section. The maximum steam generation capacity of the plant is limited to 75 kg/s based on the 10,000 tcd peak cane crushing capacity of the plant. Mass balance of steam is made in such a way that maximum steam is diverted to a condensing turbine for power generation, satisfying the minimum process steam requirements of the plant. Figure 1 shows the mass balance of steam and describes the major process. The steam power cycle used in the plant is the conventional Rankine cycle, modified to cogenerate power and process heat. Thus, how the energy efficiency of the cogeneration plant improves at the cost of reduction in thermal efficiency of conventional power plant in a modification is illustrated.

The steam expands in the turbines from inlet conditions of 65 bars and 490°C to 2.5 bars and 120°C in backpressure turbine and to 0.065 bars and 40°C in condensing steam turbine, respectively. The turbine isentropic efficiency is 0.85, and turbo-generator efficiency is 0.92 process steam obtained at 2.5 bars and 120°C from both the turbines for juice heating. Process steam at 8 bars and 210°C is obtained from extraction drawn across backpressure turbine for sulfur melting and centrifuge.

The cogeneration plant is complex and includes numerous pumps, fans, and blowers that are not monitored for energy consumption. Therefore the boundary for this system is the entire plant. Applying steady flow energy equations and mass balance to each of the components and processes in Figure 1 and Figure 2 are evaluated neglecting the changes in the kinetic energy and potential energy the work and heat quantities. Energy efficiency and exergetic efficiencies of the plant, cycle, and major components are determined and are compared.

The heat-to-power ratio of the plant is determined. Fuel energy savings ratio of the cogeneration plant over a separate generation plant is calculated assuming the thermal efficiency of conventional power plant, $\eta_C$=0.35 and separate heat only boiler of thermal efficiency $\eta_B$=0.85.

## RESULTS AND DISCUSSION

The results of an ongoing, 44-MW, bagasse-based, heat-matched combined backpressure and extraction condensing steam turbine cogeneration plant of 10,000 tcd capacity sugar factory working in Belgaum, India are presented in this article. Mass balance of steam and fuel (bagasse) supply the four boilers of the cogeneration plant and are shown in Figure 1.

The energy balance of the cogeneration plant is presented in Table 1. It shows that the thermal efficiency of the cogeneration power plant (16.5%) is low compared to the thermal efficiency of modern power plants (0.35). However, the energy utilization factor or energy efficiency of the cogeneration plant is (64.7%); this is because the cogeneration plant utilizes the low temperature exhaust/extracted steam for process heating. Thus, the high value of energy efficiency is at the sacrifice of thermal efficiency of power plant in a modification to the cogeneration plant. Further, these efficiencies were not based on the specific heat input to the steam; rather, it was based on the lower heating value of the fuel (bagasse) to incorporate the losses occurring in the furnace-boiler system caused by energy lost with hot gases, incomplete combustion, etc. The energy balance also reveals that 48% of the fuel energy input is utilized in process heating, as a low pressure saturated steam (utilizing latent heat for juice boiling). The energy rejected to the environment through condenser and boiler exhaust gases is 10% and 13%, respectively. The estimated value of fuel energy savings ratio of the cogeneration plant is 8.2% at this heat-to-power ratio (2.85), over separate generation, thus reflecting high quality cogeneration. Nonetheless, efficiencies based on energy can often be non-intuitive or even misleading [19-24, 32], in part because it does not provide a measure of the quality of energy. In addition, utilization/loss of energy can be in large quantity, while it is thermodynamically insignificant because of its low quality. Exergy based efficiencies and loss assessments, however, provide measures of qualitative approach for evaluation of energy systems.

**Table 1. Energy Balance of the Cogeneration plant Components and Percentage Ratio to Fuel Energy Input**

| *Component* | *Energy Flow Rate (kW)* | *Percentage* | *Comp Efficiency (%)* |
|---|---|---|---|
| Net power, $W_{CG}$ | 44,000 | 16.55 | — |
| Process heat, $Q_{CG}$ | 127,918 | 48.12 | — |
| Plant energy efficiency | 171,918 | 64.67 | — |
| Boiler exhaust, $Q_{ex}$ | 35,328 | 13.29 | 86.7 |
| Turbine | — | — | 85.0 |
| Condenser | 27,391 | 10.30 | — |
| Piping/others | 31,201 | 11.00 | — |
| Fuel energy input | 265,838 | 100.00 | — |
| FESR | | 8.20 | — |

Exergy and percentage of exergy destruction, along with exergetic efficiencies, are summarized in Table 2 and Table 3 for all components present in the cogeneration plant. It was found that the exergy utilization rate in process heating was the least in the cycle. It accounts for only 10% of the fuel exergy input. According to the first law analysis, energy utilization rate in process heating is dominant, accounting for 48% of fuel energy input, and energy efficiency of the cogeneration plant is 65%. Therefore, energy efficiency based on first law reflects only the quantitative side of energy flow associated with the system. The exergy destruction of the boiler is dominant over all other component's irreversibility of the plant. It alone accounts for 45%, while total losses in the plant are 57.67% of physical exergy input. The exergy destruction rate in the condenser is only 0.80%. The physical exergy rate available in the boiler for steam generation process is 182,370 kW, while the chemical exergy of fuel (bagasse) burned is 343,678 kW. The difference (343,678 – 18,370 =) 161,308 kW or 47% of the fuel exergy input is lost in the boiler because of its inherent combustion irreversibility. Therefore, there is sufficient scope for research to reduce combustion irreversibility associated with boiler and explore economic ways to optimize these losses.

**Table 2. Exergy Utilized in the Plant's Components and Percentage Ratio to Fuel Exergy Input**

| *Component* | *Exergy Flow Rate (kW)* | *Percentage* |
|---|---|---|
| Net power, $W_{net}$ | 44,000 | 14.87 |
| Process heat, $EQ_{CG}$ | 33,207 | 10.17 |
| Exergetic efficiency of plant | — | 25.04 |
| Boiler | 100,267 | 29.18 |
| Fuel exergy input | 343,678 | 100.00 |

**Table 3. Exergy Destruction Rate in the Cogeneration Plant's Components and Percentage Ratio to Physical Exergy Input**

| *Component* | *Exergy flow Rate (kW)* | *Percentage* | *Component Efficiency (%)* |
|---|---|---|---|
| Boiler | 82,103 | 45.00 | — |
| Exhaust gas | 6,915 | 3.79 | — |
| Turbine | 9,019 | 4.95 | 87 BPST |
| Condenser | 1,455 | 0.80 | 71 CEST |
| Piping/others | 5,971 | 3.10 | — |
| Total | 105,163 | 57.67 | — |
| Physical exergy input | 182,370 | 100.00 | — |

The plant performs with energy and exergetic efficiency of 65% and 25%. The calculated exergetic efficiency of the cogeneration plant is 25%, which is much lower than the normal value of overall efficiency for a modern conventional power plant (35%). This indicates that tremendous opportunities are available for improvement. However, part of this irreversibility can not be avoided because of physical, technological, environmental and economic constraints.

## CONCLUSIONS

In this study, an energy and exergy analysis of an actual 44-MW, bagasse-based cogeneration plant of 10,000 tcd capacity sugar factory in Belgaum, India has been presented. A remarkable difference is seen between the energy and exergetic efficiency of the plant. In the considered cogeneration power cycle, the energy efficiency of the cogeneration plant is 65%, with 48% of the fuel energy input utilized in the low temperature process heating. The energy losses in the boiler, condenser and piping are 13.29%, 10.30%, and 11%, respectively. In addition, the fuel energy savings ratio of the cogeneration plant is 8.2% over separate generation. On the other hand, exergy analysis of the plant showed that the high value of energy efficiency reflects only the quantitative side of associated energy flow and not the quality of energy. The low temperature energy utilized in process heating, rejected to environment through condenser, exhaust gases, etc, is thermodynamically insignificant because of its low quality.

In terms of exergy destruction, the major loss was found in the boilers' system, where 71% of the fuel exergy input, or 45% of the physical exergy input, is destroyed. Next to it was the turbine (5%), followed by boiler exhaust (4%), and piping (3%). The least is lost in the condenser (0.80%). Total exergy loss of the cogeneration plant is 57.67% of physical energy input. Therefore, the boiler is the major component contributing most to the plant's overall inefficiency. As a results, there is enough reason to investigate the causes of irreversibility and to determine economic opportunities for reducing it. The physical exergy input rate available for steam generation in the boiler furnace is mainly affected by the quantity of pre-heated excess-air supplied to the boiler furnace for clean and complete combustion of mill-wet bagasse. In addition to this, the steam-to-bagasse ratio improves substantially [6-8] for steam generation at HP/HT conditions. Thus, the inefficiencies in bagasse-fired boilers can be reduced to some extent by increasing the quantity of preheated excess-air supply, and generating steam at possible high pressure and temperature. The calculated exergetic efficiency of the cogeneration plant was 25%, which is much lower than the normal value of overall efficiency of a modern conventional power plant (0.35). Hence, in terms of technology development, only cogeneration plants with exergetic efficiency close to that of overall efficiency of the conventional power plants are to be suggested.

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## About the Authors

**Professor S.C. Kamate, Ph.D.**, is a principal of K.L.E. Polytechnic, located in Hubli, India. Formerly, he was the managing director of the Basaveshwar Sugar and Allied Products Ltd. He obtained his M.Tech in energy systems engineering specialization in 2002 and Ph.D. from VTU (Vishweshwariah Technological University) for his work on thermodynamics of sugar mill cogeneration. His areas of research interest include bagasse-based cogeneration, energy conservation in sugar industries and thermodynamics. Professor Kamate may be contacted via e-mail at kamateksk@rediffmail.com.

**Professor P.B. Gangavati, Ph.D.**, is a mechanical engineering professor at the Basaveshwar Engineering College, located in Bagalkot, India. He obtained his M.E. specialization in thermal sciences from the University of Roorkee (presently IIT-Roorkee) in 1987 and Ph.D. from IIT-Roorkee for his work on gasification of biomass in fluidized bed. His areas of interest include renewable energy, cogeneration and combustion/gasification. Professor Gangavati may be contacted at pbgangavativati123@rediffmail.com.