

Cogeneration in Sugar Industries

Technology Options and Performance Parameters—A Review

S.C. Kamate

K.L.E.S. Polytechnic, Hubli, Karnataka, India

P.B. Gangavati, Ph.D.

Basaveshwar Engineering College, Bagalkot, India

ABSTRACT

This article presents a review of different technological options that are presently being practiced by sugar mills, and technological options that are identified as potentially promising future technologies. Different indices used to gauge the thermodynamic performance of cogeneration plants and facilitate the comparison of alternative systems are discussed. The most important performance parameters used to assess the steam turbine cogeneration plants in general and sugar mill cogeneration plants in particular are defined and developed. Criteria such as energy utilization factor, heat-to-power ratio, fuel energy savings ratio, exergetic efficiency and power generated per tonne of cane (tc) prove to be more important and relevant.

Biomass-integrated gasifier/gas turbine cogeneration (BIG-GT) and biomass gasifier combined with steam injected gas turbine cogeneration (BIG-STIG) are considered as potentially promising future technologies. The existing modern, high pressure, high efficiency, steam turbine cogeneration plants generate 115-120 kWh/tc, while BIG-GT and BIG-STIG are potentially capable of generating up to 270-275 kWh/tc. Cogeneration plants using backpressure and condensing steam turbines perform with energy (First Law) and exergetic (Second Law) efficiency of approximately 60-70 % and 22-25%, respectively. The steam consumption in sugar mills at present varies from 480-550 kg/tc, while electricity consumption ranges between 16-22 kWh/tc (32-40 kWh/tc for electrified mills).

These performance indices will help plant designers and engineers in improving their choice of system configuration and developing alternative schemes.

Key words: bagasse, cogeneration, energy, exergy, efficiency

Nomenclature

B	Boiler
CF	Centrifugal
CHP	Combined heat and power, see also cogeneration
CG	Cogeneration, see also combined heat and power
Cond	Condenser
HP	High pressure
HT	High temperature
MNES	Ministry of Non-Convention Energy Sources
NCV	Net calorific value, kJ/kg
PH	Process heater
SG	Separate generation

INTRODUCTION

Manufacturing of white crystal sugar using a double sulfitation process in the Indian sugar industries requires steam for juice heating (using latent heat) and medium pressure steam for centrifuge [Hugot 1986, Gollakota and Sobhanbabu 2002]. Cogeneration as a (captive requirement) technology for meeting the plant's power and process steam requirements has been in practice in sugar industries since inception. In the existing cogeneration systems, steam is generated in low-pressure boilers by using mill-wet bagasse, the woody fibrous residue of crushed cane, as fuel. This system was developed when the possibility of export of power to the grid was not envisioned. Further, because the storage of large quantities of combustible bagasse in the premises of the sugar mills were not an advisable option, there is built-in energy inefficiency in the sugar factories using all the bagasse as fuel for their low-pressure boilers [Naidu 1996].

Although, sugar mills have always practiced the concept of bagasse-based cogeneration, there has, of late, been growing awareness in the sugar industry of the advantages of installing high efficiency

bagasse-based cogeneration systems. The sugar industry is now moving toward substantially improved power stations, by adopting HP/HT steam conditions and high efficiency steam turbines, so that it can export surplus power to grid when the prices are attractive, or otherwise can save (fuel) surplus bagasse, which can be utilized for many other productive purposes [Mbohwa and Fukuda 2003, Inkson and Misplon 2005, Kamate and Gangavati 2008]. If a cogeneration plant achieves fuel savings of at least 5% over separate generation, then it is classified as high quality cogeneration [www.electrabel.com].

Generation of exportable electricity from bagasse in sugar mills is universally accepted as desirable, economic, and environment friendly; and the potential of this electricity source is substantial. Today India is the second largest producer of 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 [Naidu 1996, Smouse et al. 1998, Sharma and Sharma 1999, Purohit and Michelowa 2007]. Thus sugar cane bagasse has strong potential in displacing fossil fuels and can be extensively used in the boilers and furnaces for power generation. Obviously, this considerable amount of power should be generated efficiently. The sugar industry employs different cogeneration schemes to satisfy the plant's process steam demand and generate surplus power by upgrading the steam inlet parameters [Goel 1994, Naidu 1996, Mbohwa and Fukuda 2003, Gwang'Ombe 2004].

The thermodynamics of thermal power plants has been a classical area of study for engineers. The objectives of such work have traditionally been the determination and maximization of thermal efficiency, i.e., the most efficient and economic production of power from a fuel source [El-Wakil 1984, Bejan 1988, Nag 2001]. A further development in the search for high thermal efficiency of conventional power plants has been the introduction of the cogeneration plant [Horlock 1987]. The thermal efficiency defined for a conventional power plant has less relevance to cogeneration plants, which provide both process heat and electrical power from a common fuel source. Therefore, the search for higher thermal efficiency is not so relevant in the study of cogeneration plant.

The objectives of the designer of a cogeneration plant are both heat and power production. In the cogeneration plant, both the power

and process heat can be sold, so the CHP designer is not solely interested in high thermal efficiency, although the power sales attract a higher price than the process heat. Therefore, both thermodynamics and economics will be of importance.

In the light of this, the article presents a review of different technological options that are presently being practiced by sugar mills and technology options that are identified as potentially promising future technologies. The article discusses certain indices, which reveal the thermodynamic performance of a cogeneration system and facilitate the comparison of alternative systems. This article provides information on the indices used to measure the performance of cogeneration power plants in general and sugar mill cogeneration plants in particular.

THE TECHNOLOGY

The concept of cogeneration for exporting electricity from sugar mills dates back to 1950s in Hawaii, USA [Natu and Zade 2002]. By definition, cogeneration is the simultaneous generation of electrical and thermal energy (normally steam), in an industrial site by the sequential use of energy from a common fuel source, the idea is simple. Depending upon the quality of process heat required, it may be based on the topping cycle or bottoming cycle.

- In the bottoming cycle systems, heat is required for process at high temperature and hence power is generated through suitable waste heat recovery systems.
- On the other hand, in topping cycle systems, heat is required for the process at low temperature and therefore, power generation is taken first. All sugar mills employ this cycle for cogenerating power and heat.

The prime technology used in the bagasse-based cogeneration power plants using steam turbines is the conventional "Rankine cycle," modified to cogenerate power and process heat [Gollkata and Sobhanbabu 2002, Kamate and Gangavati 2008]. The subsequent sections will describe the sugar manufacturing process and cogeneration of power and process steam in Indian sugar mills.

Sugar Manufacturing Process

A flow diagram representing the manufacturing of crystal sugar in a typical sugar mill is shown in Figure 1. The whole process is as briefly described here under [Hugot 1986, Gollakota and Sobhanababu 2002].

Harvested cane received from the fields is cut into small pieces in the cane preparation section, and shred into fine fibers. The fibrized cane is converted into raw juice in the cane milling section, in which more than 95% of sugar in the cane is extracted. The juice collected in different sections of the milling tandem, called mixed juice, ranges between 100% and 110% by weight of the cane processed (because water is added in

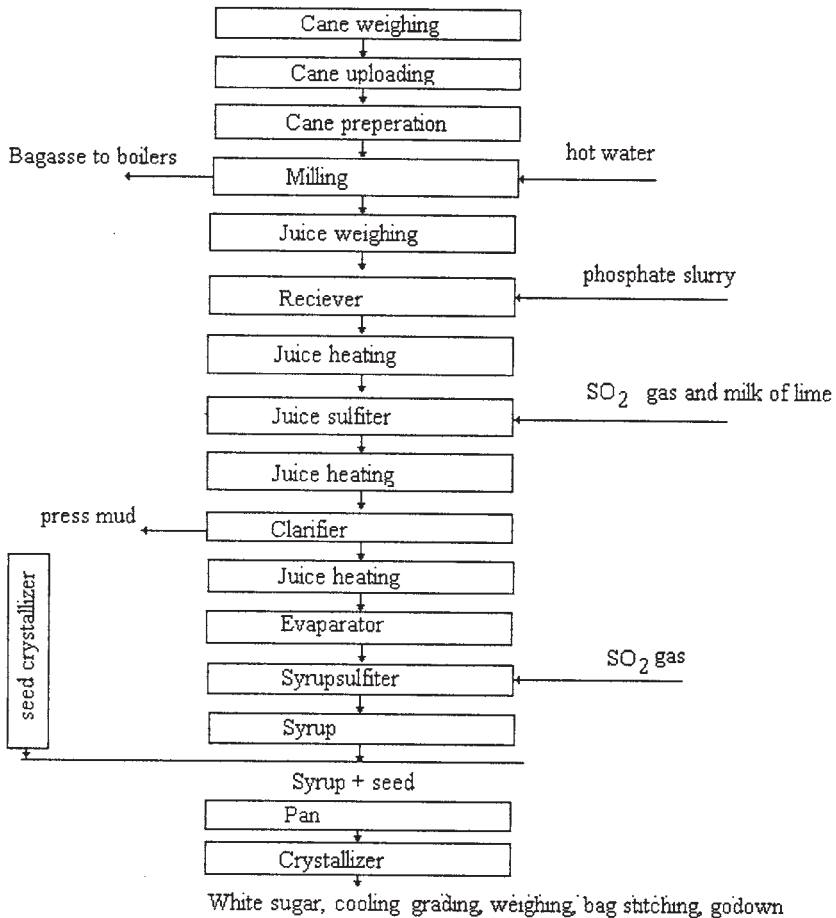


Figure 1. Typical steps in a sugar manufacturing process

the milling process).

The mixed raw juice from the milling section is fed to the treatment and clarification section. The juice is treated with lime and other chemicals, and heated further. The heated juice receives sulfur dioxide (SO_2) treatment in the juice sulfiter, and is then sent to clarifier where solid impurities are removed. The purified juice from the rotary vacuum filter is boiled in a multiple effect evaporation system in the boiling house. Here the juice is concentrated to 65% brix when it is called syrup.

The syrup from the boiling house is again treated with SO_2 in the syrup sulfiter. The sulfited syrup is then sent to vacuum pans for further concentration and crystallization. Centrifugal machines then separate the sugar. This process is called the double sulfitation process because the sugar cane juice is treated with SO_2 twice, first at the raw juice sulfiter, and later at the syrup sulfiter.

Cogeneration of Power and Process Steam

Recovering energy from waste heat or utilizing it for system efficiency improvement is fast becoming a common scientific temper and industrial practice, such an effort is the cogeneration [Robert and Collins 2007]. In sugar mill cogeneration, the mill wet bagasse obtained (having 50% moisture) is directly burnt in the specially designed boilers to generate steam at the designed pressure and temperature. Bagasse has excellent fuel characteristics with very low ash content. The extra high-pressure steam generated is fed either to a backpressure steam turbine or to an extraction condensing steam turbine operating at similar inlet steam conditions [Nath 1996, Bhat and Rajkumar 2001, Prasad 2004].

The exhaust steam from the backpressure turbine or the steam extracted from the extraction condensing turbine at the desired pressure and temperature, meets the steam requirements for the sugar process, other by products and cogeneration plant equipments, such as high pressure heaters, de-aerators, and soot blowers. Because of the extra high-pressure and temperature, as well as extraction and condensing modes of the turbine, surplus power is generated far in excess of the sugar factory requirement. Because the sugar industry operates seasonally, the boilers are normally designed for multi-fuel operations, to ensure year-round operation of the power plant.

Evolution of HP/HT Steam Turbine Cogeneration Technology

The technology for generating electricity using solid fuels, through

the “Rankine cycle” route, is adopted by the power industry world over, as well as in India. The technology required for generating an exportable surplus power in sugar mills is generally selected to accommodate the type of fuel used. The characteristics of bagasse/biomass and its combination with fossil fuels include moisture content, density, specific storage/transport and handling requirements. All these have to be taken into account while designing the firing grate in the boiler. All other technology and equipment are similar to conventional power plants using the other solid fuels.

Conventional coal-fired power plants use extra-high pressure (up to 150 bar or even more). The first attempt to increase pressure and temperature configuration in bagasse-fired cogeneration power plants from traditionally used values started at 40 bar and increased later to 60 bar. The high pressure normally generates more power for the same quantity of bagasse or biomass fuel, and hence, for increasing the exportable surplus power from these power plants, increasing the pressure and temperature configuration became important. In India, the presently established temperature and pressure configuration over the last five years is 495°C and 67 bars. Some plants recently have employed extra high-pressure and temperature configurations of 87 bar and 510°C. The average increase in power exports achievable by increasing the pressure from 40 bar to 60 bar or to 80 bar is in the range 7-10% [Gollakota and Sobhanababu 2002]. No doubt, the introduction of higher HP steam inlet conditions has more thermodynamic advantages because these steam inlet parameters yield better performance results. However, the improvement in performance values of these plants at steam inlet conditions above 61 bar and 475°C are marginal, although there is substantial increase in steam pressure. Therefore, for little gains, adopting very high HP/HT steam conditions is meaningless, unless its economic returns are justified [Kamate and Gangavati 2008]. The technology and know-how for design, manufacture and supply; construction; and operation and maintenance of bagasse/biomass/fossil-fuel-fired sugar mill cogeneration power plants is indigenously available.

POSSIBLE TECHNOLOGY OPTIONS

Cogeneration plants are normally designed either to satisfy the process steam demand or power demand of the plant [Mande and Kishore

1996]. In the sugar industry, satisfying process steam demand is the basic requirement, and power generated is a by-product, because these are all heat-matched cogeneration plants. Hence, bagasse-based cogeneration plants are designed primarily to provide process steam and generate possible surplus power by upgrading the steam inlet parameters. A number of technology options are available in the literature. Further, the MNES task force has also recommended some possible models for the design of cogeneration plants in new sugar mills [Hollomon 1993, Goel 1994, Naidu 1996, Ramajutan et al. 1999, Larson et al. 2001, Gollakota and Sobhanababu 2002, Mbohwa 2003, Mbohwa and Suichi Fukuda 2003, Gwang'Ombe 2004]. However, only a few important, promising technology options are discussed here.

Extraction and Backpressure Steam Turbine Route [BPST]

This cogeneration system is the simplest and has been in use in several sugar mills in India. In this system, shown in Figure 2, the sugar factory produces only as much steam as is needed for its process, and surplus bagasse is saved. Further, surplus power is generated only during crushing season. This is the most efficient option from the energy utilization point of view. The turbine exhaust provides the process steam required, and power generated is a by-product.

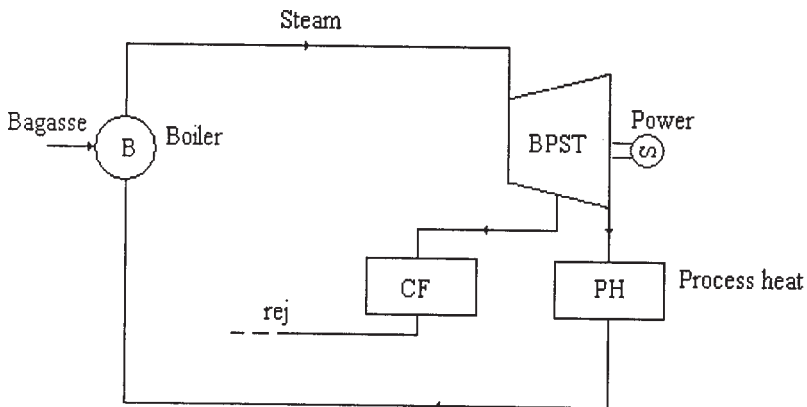


Figure 2. Extraction and backpressure steam turbine cogeneration plant

Extraction Condensing Steam Turbine Route [CEST]

The system shown in Figure 3 is the most established method of cogeneration currently in use in sugar factories. In this model, steam required for process heating is extracted at the desired pressure and temperature and the balance of steam goes to the condenser. This system has the following features.

- The sugar factory produces steam by using the entire quantity of bagasse produced during the crushing season.
- Surplus power generation can be extended during the off-season by operating the turbine in the condensing mode.
- This system ensures a stable power supply during the crushing season there by reducing fluctuations in sugar plant operation

The sugar industry can generate approximately 115-120 kWh/tc of power using this technology option.

Condensing Route Based on Dual Fuel System

This option, Figure 4, has the ability to ensure a year round, stable surplus power supply through the use of a support fuel. Its main features are

- This is a viable option for sugar mills located near a source of secondary fuel.

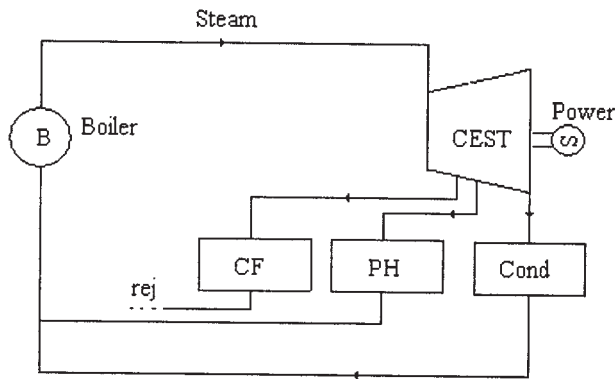


Figure 3. Extraction condensing steam turbine cogeneration plant

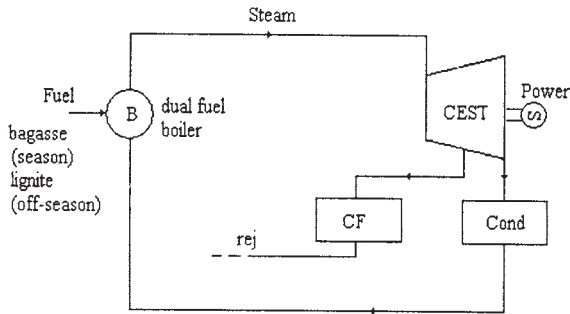


Figure 4. Condensing turbine cogeneration plant based on dual fuel

- The boiler furnace is suitably designed for multi-fuel combustion.

Biomass Integrated Gasifier/Gas Turbine Cogeneration System (BIG-GT)

This technology involves the gasification of bagasse and sugar cane trash. The producer gas generated is burnt to drive the gas turbine; the exhaust of the gas turbine is utilized in the waste-heat recovery boilers to generate steam. This steam is further expanded in the steam turbine to generate power and process steam. This technology is still under development because gasification of bagasse has yet to be tried on a commercial scale. The biomass-integrated gasifier/gas turbine combined cycle (BIG-GTCC) technology was first identified over a decade ago as an advanced technology with the potential to be cost-competitive with conventional CEST technology using bagasse as fuel, while dramatically increasing the electricity generated per unit of sugar cane processed [Larson et al. 2001].

Biomass Gasifier Combined with Steam Injected Gas Turbine [BIG-STIG] Cogeneration System

Cogeneration with a steam-injected gas turbine has higher thermodynamic efficiency compared to CEST technology. While gasification and the use of STIG technology for wood and other biomass has been successfully tried on commercial scale. However, a suitable gasifier for bagasse is yet to be developed on a commercial scale. In BIG-STIG technology, steam is produced in an exhaust heat recovery boiler, and steam left after meeting process steam demand is injected into the bagasse gasifier for down stream use for running a gas turbine to augment power

output. By adopting BIG-GTCC or BIG-STIG cogeneration technologies, sugar industries are potentially capable of generating 270-275 kWh/tc [Ching 1999]. Integration of BIG-GTCC or BIG-STIG technologies to a sugar mill is quite difficult or impossible, though. The exergetic efficiency of the biomass integrated gasification combined cycle (BIG-CC) would be approximately 30% greater than the ones found in Brazilian sugar cane mills based on the Rankine cycle because the steam required in the process (500 kg/tc) cannot be supplied by this system alone [Pellegrini et al. 2007].

Anderson Power Cycle

Conventional technologies offer cogeneration during the crushing season only. The Anderson power cycle could allow the sugar/distillery complex to offer power to the grid year round with the backpressure turbine only. Bringing extra coal or lignite to run a condensing turbine in the off-season makes very little logic and destroys the very concept of a renewable energy power plant [Goel 1994].

Conventional technologies lack the ability to provide zero pollution to the sugar/distillery complex. With adoption of Anderson flue gas coolers, the waste heat energy in flue gases is fully recovered, and the flue gas is completely cleaned of particulates and acids. Spent-wash from the distillery is a perennial source of pollution and in the Anderson cycle power complex, this effluent is evaporated in a multi-effect evaporator and the concentrated pollutant is fired in a boiler along with bagasse to generate more power.

The potash fertilizer is recovered from the cyclone filters and flue gas is cleaned for zero pollution yielding ammonium bi-sulphate liquid fertilizer. Other round about methods of gasification and bio-methanation contribute much less for power generation. Anderson flue gas coolers could be adopted for flue gas heat recovery and sugar cane juice heating, thus minimizing process steam requirements for juice heating, and conserved steam can be used for power generation.

PERFORMANCE PARAMETERS

Cogeneration of process heat and power implies production of two different kinds of energy from a common fuel source. Therefore, a common denominator should be first established to analyze the efficiency

of a cogeneration plant. A number of criteria are used to assess the plants' performance [Horolock 1987, Korobitsyn 1998, www.educogen.com 2001]. The most important of these are defined and their relevance is discussed here.

The Cogeneration Plant Efficiency

The first and most straightforward criterion is based on the *First Law of Thermodynamics*, which deals with the quantitative side of the energy, also known as the energy utilization factor, first law efficiency, and total energy efficiency. [Porter and Mastaniah 1984, El-Wakil 1984, Horlock 1987, Korobitsyn 1998, Nag 2001].

$$\eta_{CG} = \frac{W_{CG} + Q_{CG}}{F_{CF}} \quad (\text{eq 1})$$

Where, Q_{CG} is the useful heat provided, which meets a required heat load at temperature T_u ; W_{CG} is the net electrical power output; and F_{CG} is the fuel energy consumed by the cogeneration plant. Here, the heat is a low-grade energy and electricity is high-grade energy [Nag 2001]. Therefore, first law energy efficiency is not the most satisfactory performance criterion because it gives equal weight to W_{CG} and Q_{CG} .

Exergetic Efficiency

Although first law energy efficiency is most commonly used up to now, a thermodynamically more accurate evaluation and a fairer comparison between systems can be based on exergetic efficiency [www.educogen.com 2001]. Exergy is a measure of energy quality, and exergetic or second law efficiency is a measure of perfectness of the system [Kotas 1985, Bejan 1988, Nag 2001]. Thermodynamics suggest the use of exergetic factor, which takes into consideration the quality of heat in terms of its work potential. An even more correct performance value is obtained if the exergy content of the fuel is also taken into account [Nesheim et al. 2007, Ertesvag 2007]. Exergetic efficiency is then given by:

$$\eta_{EX} = \frac{W_{CG} + E_Q}{E_f} \quad (\text{eq 2})$$

Where, E_Q is exergy equivalent of process heat and E_f is the chemical

exergy of fuel. Introducing the second law analysis has proved to be a valuable methodology for evaluation and optimization of cogeneration plants [Bejan 1988, Korobitsyn 1998, Khaliq and Choudhary 2007].

Other Measures of Efficiency

There are also partial measures of efficiency, based on electricity output and heat output per unit fuel consumption. These are defined below.

Electrical efficiency

$$\eta_e = \frac{W_{CG}}{F_{CG}} \quad (\text{eq 3})$$

Thermal efficiency

$$\eta_{th} = \frac{Q_{CG}}{F_{CG}} \quad (\text{eq 4})$$

Total energy efficiency or cogeneration plant efficiency

$$\eta_{CG} = \eta_e + \eta_{th} \quad (\text{eq 5})$$

Heat-to-power Ratio

Because heat and power have different thermodynamic qualities, heat-to-power ratio is an important technical parameter influencing the selection of cogeneration system. If the heat-to-power ratio of the industrial energy demand is similar to that of the cogeneration system being considered, the system will be matched for the application. The heat-to-power ratio provided by the cogeneration plant is

$$\lambda_{CG} = \frac{Q_{CG}}{W_{CG}} \quad (\text{eq 6})$$

Considering equations (3), (4) and (5), Equation (6) can be written as

$$\lambda_{CG} = \frac{\eta_{th}}{\eta_e} = \frac{\eta_{th}}{\eta_{CG} - \eta_{th}} \quad (\text{eq 7})$$

Further, equation (1) and equation (6) lead the expression

$$\eta_{CG} = \eta_e (1 + \lambda_{CG}) \quad (\text{eq 8})$$

Equation 7 helps us in determining the acceptable values of the heat-to-power ratio, when the thermal efficiency of the cogeneration system is known, given the fact that the total energy efficiency or cogeneration plant efficiency does not typically exceed 90%.

If $\eta_{th} = 0.50$, and $0.55 \leq \eta_{CG} \leq 0.90$. Then equation 7 indicates that η_{CG} is in the range of $10 \leq \eta_{CG} \leq 1$. Table 1 shows the heat-to-power ratios and other parameters of different cogeneration systems.

Table 1. Heat-to-power Ratios and Other Parameters of Cogeneration Systems [CoGen Manual, 2004]

<i>Cogeneration system</i>	<i>Heat to Power Ratio</i> Q_{CG}/W_{CG}	<i>Electrical Efficiency</i> η_e	<i>Total Energy Efficiency</i>
Backpressure steam turbine	4 - 14.3	14 - 28	84 - 92
Extraction condensing steam turbine	2 - 10	22 - 40	60 - 80
Gas turbine	1.3 - 2.0	24 - 35	70 - 85
Combined cycle (gas plus steam turbine)	1.0 - 1.7	34 - 40	69 - 83
Reciprocating engine	1.1 - 2.5	33 - 35	75 - 85

The total energy efficiency is relatively high (60 to 90%). However, the electrical efficiency is 15 to 20%, which results in high heat-to-power ratio. In general, the higher the temperature required for process steam, the lower the electrical efficiency. The electrical energy efficiency can be increased to a certain extent by increasing the pressure and temperature of steam at the turbine inlet.

Fuel Energy Savings Ratio

The demand for heat, Q_D , and power, W_D , at an industrial site can be satisfied either by a separate generation plants, as shown in Figure 5, or by a cogeneration plant, Figure 6. If a cogeneration plant substitutes a conventional power plant of overall efficiency η_C and separate heat only

boiler of efficiency η_B , meeting the same loads of heat Q and power W , then the fuel saved by the cogeneration plant over separate generation is the difference between the fuel consumption of the two plants.

The general expression for the fuel consumption of separate generation plants is

$$F_{SG} = F_C + F_B = \frac{W_D}{\eta_C} + \frac{Q_D}{\eta_B} \tag{eq 9}$$

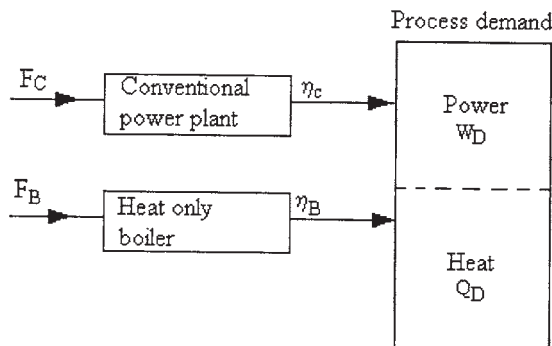


Figure 5. Separate Generation

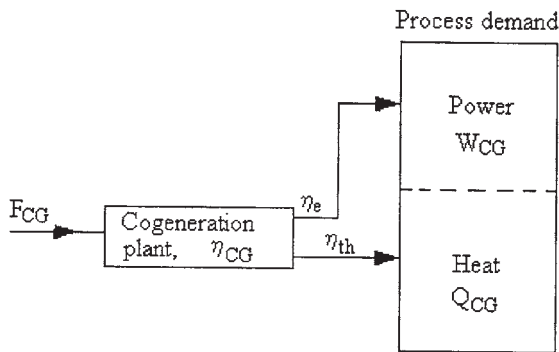


Figure 6. Cogeneration

The fuel consumption of a cogeneration plant is

$$F_{CG} = \frac{W_{CG} + Q_{CG}}{\eta_{CG}} \quad (\text{eq 10})$$

The relative fuel consumption factor (Φ) of the two plants is expressed as

$$\Phi = \frac{F_{CG}}{F_{SG}} \quad (\text{eq 11})$$

The fuel energy savings of a cogeneration plant over separate generation plants is

$$\Delta F = F_{SG} - F_{CG} \quad (\text{eq 12})$$

The fuel energy savings ratio (FESR) of a cogeneration plant is

$$\text{FESR} = \frac{\Delta F}{F_{SG}} = \frac{F_{SG} - F_{CG}}{F_{SG}} \quad (\text{eq 13})$$

$$= 1 - \frac{F_{CG}}{F_{SG}} \quad (\text{eq 14})$$

$$\text{FESR} = 1 - \Phi \quad (\text{eq 15})$$

Introducing the two heat-to-power ratios, for the demand, λ_D and for the cogeneration plant, λ_{CG} . Equations 9 and 10 can be expressed as:

$$F_{SG} = \frac{Q_D (\eta_B + \lambda_D \eta_C)}{\lambda_D \eta_B \eta_C} \quad (\text{eq 16})$$

$$F_{CG} = \frac{Q_{CG} (1 + \lambda_{CG})}{\lambda_{CG} \eta_{CG}} \quad (\text{eq 17})$$

Using equations 16 and 17 in equation 11, the relative fuel consumption

factor is expressed as

$$\Phi = \frac{\frac{Q_{CG} (1 + \lambda_{CG})}{\lambda_{CG} \eta_{CG}}}{\frac{Q_D (\eta_B + \lambda_D \eta_C)}{\lambda_D \eta_B \eta_C}} \quad (\text{eq 18})$$

In the sugar industries, process heat is the basic need to be satisfied fully, and power is produced as a by-product, therefore $Q_{CG} = Q_D$ is a must.

For a heat-matched plant $Q_{CG} = Q_D$, and

$$\Phi = \frac{\lambda_D (1 + \lambda_{CG}) \eta_B \eta_C}{\lambda_{CG} \eta_{CG} [\eta_B + \lambda_D \eta_C]} \quad (\text{eq 19})$$

If $y = \frac{\lambda_D}{\lambda_{CG}}$, the ratio of two heat-to-power ratios, then from equation 19 the following remarks can be made:

- (i) If $\lambda_{CG} = \lambda_D$, $y = 1$, then it is a matched plant
- (ii) If $\lambda_{CG} < \lambda_D$, $y > 1$, then the plant is generating surplus power that can be exported to grid.
- (iii) If $\lambda_{CG} > \lambda_D$, $y < 1$, then it is unmatched plant, and imports power from the grid.

Equation 19 can be written as:

$$\Phi = y \frac{(1 + \lambda_{CG}) \eta_B \eta_C}{\eta_{CG} [\eta_B + \lambda_{CG} \eta_C]} \quad (\text{eq 20})$$

Equation 20 estimates the relative fuel consumption of heat-matched plants, not the power matched, ($\lambda_{CG} \neq \lambda_D$). If the plant is matched for both heat and power, ($\lambda_{CG} = \lambda_D$), $y = 1$, and the relative fuel consumption factor is expressed as

$$\Phi = \frac{(1 + \lambda_{CG}) \eta_B \eta_C}{\eta_{CG} [\eta_B + \lambda_{CG} \eta_C]} \quad (\text{eq 21})$$

In reality, it is not possible to design a cogeneration plant matched for both heat and power. Normally, cogeneration plants are designed to generate possible surplus power, satisfying the process steam demand.

Equation 21 can be modified and expressed as

$$\Phi = \frac{(1 + \lambda_{CG})}{\eta_{CG} \left[\frac{1}{\eta_C} + \frac{\lambda_{CG}}{\eta_B} \right]} \quad (\text{eq 22})$$

For a matched plant $\lambda_{CG} = \lambda_{D'}$, equation 21 be further modified by substituting the value of λ_{CG} from equation (7) and $\eta_{CG'}$ from equation 5, and can be expressed as equation 23.

$$\Phi = \frac{\eta_B \eta_C}{\eta_B \eta_e + \eta_C \eta_{th}} \quad (\text{eq 23})$$

$$\text{FESR} = 1 - \frac{\eta_B \eta_C}{\eta_B \eta_e + \eta_C \eta_{th}} \quad (\text{eq 24})$$

A critical condition, when fuel savings is zero, can be obtained from the equation 24.

$$\frac{\eta_e}{\eta_C} + \frac{\eta_{th}}{\eta_B} = 1 \quad (\text{eq 25})$$

Considering the efficiencies of the separate generation plant as constant, the critical cogeneration efficiency can be derived [Korobitsyn 1998], and a zero fuel savings line can be plotted for the cogeneration plant. This thermodynamic criterion of performance is perhaps the most useful one, because it can be used directly in the economic assessment of the cogeneration plant [Horlock 1987]. For a cogeneration system to be a rational choice from the primary fuel energy savings point of view, FESR must be positive [El-Wakil 1984; www.educogen.com 2001].

For example, if a cogeneration system with total energy efficiency of $\eta_{CG} = 0.80$ and heat-to-power ratio $\lambda_{CG} = 3.0$ substitutes a conventional power plant of efficiency $\eta_C = 0.30$ and a heat only boiler of efficiency $\eta_B = 0.70$, then equation 22 and equation 15 gives $\text{FESR} = 0.20$, i.e., cogeneration reduces the energy consumption by 20%. If a cogeneration plant

saves at least 5% primary fuel energy over separate generation, then it is classified as high quality cogeneration [www.electrabel.com].

Combined Efficiency for Separate Generation

From an energy resource point of view, cogeneration is beneficial only if it saves primary energy (fuel) when compared with separate generation of electricity and steam [El-Wakil 1984]. For separate generation of electricity and steam, the heat added per unit of total energy output is

$$\frac{e}{\eta_C} + \frac{1-e}{\eta_B} \quad (\text{eq 26})$$

where,

$$e = \text{electricity fraction of total energy output} = \frac{W_{CG}}{W_{CG} + Q_{CG}} \quad (\text{eq 27})$$

The combined efficiency for separate generation is therefore given by

$$\eta_{CSG} = \frac{1}{\frac{e}{\eta_C} + \frac{1-e}{\eta_B}} \quad (\text{eq 28})$$

and cogeneration is beneficial only when the cogeneration plant efficiency given by equation 1 is greater than that of combined efficiency for separate generation, equation 28.

Value Weighted Energy Utilization Factor

Another approach involves an attempt to account for the different pricing of electrical power and heat load. If the sale of electrical energy, x (Rs/kWh), and that of heat load, y (Rs/kWh), and price of fuel, z (Rs/kWh), then this value weighted energy utilization factor or energy efficiency is

$$(\eta_{CG})_{vw} = \frac{x \times W_{CG} + y \times Q_{CG}}{F_{CG} \times z} \quad (\text{eq 29})$$

Annual Total Energy Efficiency

In the previous definitions, electrical, thermal and fuel power used is (energy per unit time), which results in values of indices valid in a certain instant of time or at a certain load. All the previous equations are also valid if power is replaced by energy in a certain period of time; when integral values of indices are obtained, which reveal the performance of the system over this period. Hence, equation 1 can be written as

$$\eta_a = \frac{W_{CGa} + Q_{CGa}}{F_{CGa}} \quad (\text{eq 30})$$

where,

η_a = annual total energy efficiency

W_{CGa} = electric energy produced by the cogeneration plant during a year

Q_{CGa} = thermal energy produced during a year

F_{CGa} = fuel energy consumed during a year.

Thus, equation 30 gives the annual total energy efficiency of the cogeneration system. The performance of the system depends on the load and the environmental conditions. On the other hand, the degree of utilization of the energy forms produced is affected by the initial design of the system, the cogeneration plant operational strategy and the matching between the production and use of the useful energy forms. For these reasons integral indices over a period of time, e.g., annual indices, are often more important than the instantaneous or nominal indices, because they are more revealing of the real performance of the system.

In addition to the general performance indices defined earlier there are some performance indices that are specific to sugar mill cogeneration plants because the sugar industry not only generates power and process steam, it also generates the fuel required for it [Gollakota and Sobhanbabu 2002]. Among these, some are broader in scope and other indices are narrower in scope, focusing on individual processing stations [Kinoshita 2002]

Overall Energy Efficiency of Raw Sugar Factory

The processing unit that is the focus of this energy analysis is the raw sugar factory, and the common input is sugar cane. The index most

often used to describe the overall energy efficiency of a raw sugar factory is the gross amount of electric power generated per unit of cane processed (the gross kWh/tc). This provides an indication of the overall energy efficiency of a sugar factory. However, a more meaningful overall efficiency index than gross power generated would be the net amount of electricity generated per unit cane.

Bagasse Equivalence of Replacement Fuel

Any fuel used to replace or augment bagasse is assigned a bagasse equivalence that would generate the same quantity of steam at full load. The bagasse equivalence of the replacement fuel is calculated as

$$m_b = m_f (\text{NCV})_f / (\text{NCV})_b \eta_b \quad (\text{eq 31})$$

where

- f = replacing fuel
- η = boiler efficiency
- b = bagasse

Bagasse to Electricity Ratio (kWh/tonne)

The bagasse to electricity conversion efficiency (kWh/tonne), used for determining the electric energy equivalence, of all fuels is the full load bagasse to electricity ratio for the factory. Here, the electric power generation rate at full load (kW) is divided by the bagasse combustion rate (tonnes/hr) used for the calculation of this index.

Percent Cane Fiber

The fiber content in the cane varies substantially throughout the world, from 12 to 15%, depending on cane variety, extent of field burning, and method of harvesting, cane cleaning practices, and other factors. It is the fundamental index in assessing the energy balance of a sugar factory. Usually, higher the fiber content, the more bagasse produced and the greater the amount of electricity generation.

Percent Bagasse Moisture

Bagasse moisture content varies with different cane preparation and juice extraction equipment and practices, from 45 to 50%. Usually, the lower the moisture content, the higher the boiler efficiency. Also, because the amount of excess air needed for complete combustion nor-

mally decreases with decreasing bagasse moisture content, lower moisture content also improves boiler efficiency by reducing the amount of excess air required.

Steam Consumption (kg/tc)

The process steam consumption by a sugar factory is defined as kg of steam required to process 1 tonne of cane (kg/tc). Although many sugar factories throughout the world consume more than 600 kg/tc, some experts feel that the most efficient factories should be able to operate with less than 300 kg/tc. Inefficient factories consume > 550 kg/tc; average factories, 450-500 kg/tc; and efficient factories < 400 kg/tc.

Boiler Efficiency

Boiler efficiency is defined as the amount of heat transferred to boiler feed water to generate steam, divided by the gross heating value of the fuel. As with most efficiency parameters, the higher is the index, the more efficient the process. This index is useful because it isolates the steam generation unit from other components in the cogeneration system. Boiler efficiency depends on many parameters like properties of fuel (in particular moisture content of bagasse), excess air supply, etc. Boiler efficiency varies substantially throughout the world. Inefficient low-pressure steam generation plants, that burn bagasse have efficiencies < 60%; average plants 60-65% and efficient plants > 65%.

Steam to Bagasse Ratio, (kg/kg)

Steam to bagasse ratio equals steam generation rate (kg/s), divided by bagasse combustion rate (kg/s). Although not as precise an indication of the efficiency at which steam is generated from bagasse, it is nevertheless useful as a preliminary indication of steam generation efficiency, and useful for computational and design purposes.

Heat Rate: Processing (kJ/kWh)

The most commonly used index for describing the efficiency of electric power generation system is the heat rate, i.e., the gross heating value of fuel consumed in generating a unit of electricity, normally expressed as kJ/kWh. An efficient raw sugar factory/cogeneration plant should be able attain a heat rate of < 36,000 kJ/kWh during processing while consuming only bagasse, i.e., should have an electrical efficiency, $\eta_e > 10\%$.

Heat Rate: Generation-only (kJ/kWh)

The heat rate (i.e., gross heating value of fuel consumed in generating a unit of electricity, normally expressed as, kJ/kWh), of the power plant while the sugar factory is not operating or using steam or electricity, gauges the efficiency of the cogeneration system, while generating electricity only. Efficient bagasse-based power plants attain a heat rate of 18,000 kJ/kWh, i.e., has a net electrical efficiency of approximately 20%.

Power Generation: Cane (kWh/tc)

The gross amount of electric power generated per unit of cane processed is a useful index for gauging the overall energy efficiency of a sugar factory / cogeneration plant. Factories that do not export power normally are designed to generate only to meet the captive requirements of the plant, ~10 to 20 kWh/tc, where as highly efficient sugar factories can generate ≥ 100 kWh/tc.

Many more indices are available in the literature; however, these are the most important, often used in the energy analysis of cogeneration power plants in sugar industries. Cane processing comprises many different operational periods, e.g., peak crushing, equipment malfunction, delay, etc. For the analysis of energy consumption and conversion in a raw sugar factory, the data collection period should consider the weighted contribution of the factory over the duration of the season. The overall energy consumption and conversion are determined for the entire season.

CONCLUSIONS

Steam turbines are indispensable for cogeneration plants in sugar industries, when burning fuels such as bagasse, because the technology is well matured and established. Bagasse gasification technology has not been fully developed, and it is considered to be a technology of the long-term future. Thus, BIG-GT and BIG-STIG are considered to be cogeneration technologies of the future. Further, complete integration of BIG-GT and BIG-STIG to sugar mills is quite difficult because this system alone cannot generate required quantity of steam for process heating using waste-heat recovery boilers. However, BIG-GT and BIG-STIG are potentially attractive because these technology options can

generate almost more than twice the power generated by conventional CEST technology. These thermodynamic performance parameters help in designing, developing, determining the better choice of system configuration and comparing the alternative cogeneration systems.

References

1. Bejan. A., 1988, *Advanced Engineering Thermodynamics*, John Wiley and Sons, New York.
2. Bureau of Energy Efficiency (BEE), 2004, *Best Cogeneration Practice Manual*, India, (www.bee-india.nic.in)
3. Mbohwa, Charles and Suichi Fukuda., 2003, *Electricity from Bagasse in Zimbabwe, Biomass and Bioenergy*, Vol. 25, Issue. 2, pp 197-207.
4. Mbohwa, Charles, 2003, *Bagasse Energy Cogeneration Potential in the Zimbabwean Sugar Industry*, *Renewable Energy*, Vol. 28, pp 191-204.
5. Kinoshita, Charles M., 2002, *Sugar Factory Energy Data Protocol*, "Handbook on Sugar Mill Cogeneration in India," Winrock International India, pp 189-202.
6. El-Wakil, 1984, *Power Plant Technology*, Tata McGraw Hill, Singapore, pp 72-76.
7. Larson, Eric D., Robert. H. Williams, M Regis, and L.V. Leal., 2001, *A Review of Biomass Integrated-Gasifier/Gas Turbine Combined Cycle Technology and its Application in Sugar Cane Industries, with an Analysis for Cuba*, *Energy for Sustainable Development*, Vol. 5, Issue 1, March, pp 54-76.
8. Goel. D.K., 1994, *Technical Options for Cogeneration Configurations in Sugar Industry*, *Proceedings of Western Regional Workshop on Bagasse-based Cogeneration*, pp 37-41.
9. Gollakota, Sai.V. and Sobhanbabu. P.R.K., 2002, *Handbook on Sugar Mill Cogeneration in India*, Winrock International India.
10. Gwang'Ombe F.R.D. et al., 2004, *Renewable Energy Technologies in Tanzania-Biomass Based Cogeneration*, draft report.
11. Hollomon, Brad., 1993, *Advancing Cogeneration in the Indian Sugar Industry*, New Delhi, Winrock International.
12. Horolock, J.H., 1987, *Cogeneration-Combined Heat and Power-Thermodynamics and Economics*, Pergamon Press, Oxford.
13. Hugot, H.E., 1986, *Handbook of Cane Sugar Engineering*, Elsevier, 3rd Edition.
14. Ertesvag, Ivar S., 2007, *Exergetic Comparison of Efficiency Indicators for combined Heat and Power (CHP)*, *Energy*, Vol. 32, pp 2038-2050.
15. Kamate, S.C. and P.B. Ganagavati, 2008, *Exergy Analysis of Cogeneration Power Plants in Sugar Industries*, *International Journal of Applied Thermal Engineering*.
16. Khaliq, A and K. Choudhary, 2007, *Combined First and Second Law Analysis of Gas-Turbine Cogeneration System with Inlet Air Cooling and Evaporative After Cooling of the Compressor Discharge*. *International Journal of Engineering for Gas-Turbine and Power*, Vol. 129, pp 1004-1011.
17. KongWin, Chang KTKF, et al., 1999, *Bagasse Gasification Technologies for Electricity Production in the Sugar Industry*, 1999 Congress, *Factory Abstracts Index*.
18. Korobitsyn, M.A., 1998, *Industrial Cogeneration*, Twente University, pp 65-82.
19. Kotas, T.J., 1985, *The Exergy Method Analysis of Thermal Power Plants*, Butterworths, London.
20. Sanjay, Mande and V.N. Kishore, 1996, *Technological Options for Combined Heat and Power Systems*, *Proceedings of Cogeneration India 96*, New Delhi, TERI, pp 163-170.

21. Inkson, Mike and B. Misplon, 2005, Cogeneration Thermodynamics Revisited, *International Sugar Journal*, Vol. 107, Issue 1279, pp 390-403.
22. Nag, P.K., 2001, *Power Plant Engineering*, Tata McGraw Hill, 2nd Edition, New Delhi, pp 38-117.
23. Naidu, B.S.K., 1996, Cogeneration in Sugar Industries: Potential and Prospects in India, *Proceedings of Cogeneration India 96*, New Delhi, TERI, pp 45-58.
24. Nath, C. N., 1996, Steam Turbine Options for Optimizing Cogeneration Applications, *Proceedings of Cogeneration India 96*, New Delhi, TERI, pp 117-126.
25. Natu, S.C. and Deepak Zade, 2002, *Handbook on Sugar Mill Cogeneration in India*, New Delhi, Winrock International India, 1st Edition, pp 3-37.
26. Pellegrini, Luiz Felipe and Silviode Oliveira Jr., 2007, Exergy Analysis of Sugar Cane Bagasse Gasification, *Energy*, Vol 32, pp 314-327.
27. Porter, R.W. and Mastaniah K.M., 1982, Thermal-Economic Analysis of Heat Matched Cogeneration System, *Energy*, Vol.7, Issue 2, pp 171-187.
28. Pallav, Purohit and Axel Michelowa, 2007, CDM Potential of Bagasse Cogeneration in India, *Energy Policy*, Vol 35, pp 4779-4798.
29. Ramjatun, S., J. Gukhool and Seebaluck, 1999, Optimization of Power Generation in the Local Cane Sugar Factories, *Science and Technology*, Vol. 3, pp 79-86.
30. Robert, H.M. and J.H. Collins, 2007, *Handbook of Energy Conservation*, Vol. 1, New Delhi, CBS Publishers, 1st Edition.
31. Smouse, Scott. M. et al., 1998, Promotion of Biomass Cogeneration with Power Export in the Indian Sugar Industry, *Fuel Processing Technology*, Vol. 54, pp 227-247.
32. Sharma, M.P. and J.D. Sharma, 1999, Bagasse Based Cogeneration System for Indian Sugar Mills, *Renewable Energy*, Vol. 16, pp 1011-1014.
33. Siddharth, Bhat M. and N. Rajkumar, 2001, Mapping of Combined Heat and Power Systems in Cane Sugar Industry, *Applied Thermal Engineering*, Vol. 21, pp 1707-1719.
34. Prasad, Surendra, 2004, Energy Aspects of Fiji's Sugar Industry: A Case for More Efficient Generation from Bagasse, *Fijian studies*, Vol. 1, No. 2, Fiji Institute of Applied Studies, pp 243-264.
35. Svein, J. Nesheim and Ivar S. Ertesvag, 2007, Efficiencies and Indicators Defined to Promote Combined Heat and Power, *Energy Conversion and Management*, Vol. 48, pp 1004-1015.
36. www.educogen.com, 2001, *The European Educational Tool on Cogeneration*, pp 9-12.
37. Electrabel, www.electrabel.com

ABOUT THE AUTHORS

S.C. Kamate obtained his M.Tech in energy systems engineering specialization in 2002. Professor Kamate presently serves at VTU (Visweshwariah Technological University) as a research scholar and as a principal of K.L.E. Polytechnic, Hubli, India. Formerly, he was managing director of the Basaveshwar Sugar and Allied Products Ltd. His areas of research interest are bagasse-based cogeneration, energy conservation in sugar industries and thermodynamics. Professor Kamate may be contacted via e-mail at kamateksk@rediffmail.com.

P.B. Gangavati, Ph.D., 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. Dr. Gangavati has been a faculty of mechanical engineering at the Basaveshwar Engineering College, Bagalkot (India) since 1982, where he currently serves as a professor. His areas of interest include renewable energy, cogeneration and combustion / gasification. Professor Gangavati may be contacted at pbgangavati123@rediffmail.com.