Exergetic, Thermal, and Fuel Savings Analyses of a Heat-matched, Bagasse-based Cogeneration Plant in Sugar Industries

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ABSTRACT

The sugar industry employs different cogeneration schemes to satisfy process steam demand, and generates surplus power by upgrading the steam inlet parameters. A wide range of steam inlet parameters is used in Indian sugar industries, and varies from 21 bar to 110 bar in pressure and 330°C to 540°C in temperature. Most of the people understand that higher pressure (HP) steam inlet conditions result in more efficient power plant. In this article, exergy methods, in addition to more conventional energy analysis, are employed to evaluate overall and component efficiencies and to identify and assess thermodynamic losses. The analysis is carried out for a heat-matched bagasse-based cogeneration plant of a typical 2500 tcd sugar factory using a backpressure steam turbine and an extraction condensing steam turbine for a wide range of steam inlet conditions; selected around the sugar industry's export cogeneration plant for better choice of cogeneration plant configuration. The results indicate that a backpressure turbine plant achieves the highest energy and exergetic efficiency, and fuel savings; the condensing turbine plant generates maximum power per tonne of cane processed. Steam inlet conditions of 61 bar and 475°C can be considered as the optimal steam parameters that yield the best thermodynamic advantage. Exergy analysis of the components indicates that the turbine is the most efficient and the boiler is the least efficient component of the plant.

Keywords: Bagasse, cogeneration, exergy, efficiency.

Nomenclature

λ_{CG}	Heat to power ratio produced	EUF	Energy utilization factor
BPST	Backpressure steam turbine	FESR	Fuel energy savings ratio
η_{EX}	Exergetic efficiency	HP	High pressure
η_B	Heat only boiler efficiency	HT	High temperature
η_{th}	Thermal efficiency	LHV	Lower heating value
η_C	Conventional power plant efficiency	tcd	Tonnes of cane crushed per day
SG	Separate generation	tch	Tonnes of cane crushed per hour
E_f	Chemical exergy of fuel bagasse	tph	Tonnes per hour
W_{CG}	Net co-generated power	B	Boiler
PH	Process heater	rej	Rejected
CF	Centrifugal	COND	Condenser
F_{CG}	Cogeneration plant fuel consumption		

INTRODUCTION

Manufacturing of white crystal sugar using a double sulfitation process in the Indian sugar industries requires low-pressure steam (utilizing latent heat) at 2.5 bar and 120°C for juice heating and medium pressure steam at 8 bars and 210°C for sulfur melting and centrifuge [1]. In an existing system, the steam is generated in the low-pressure boilers by burning all the bagasse generated. This system was developed when the possibility of export of power to the grid was not envisaged, and storage of large quantities of combustible bagasse in the premises of the sugar factory was not an advisable option [2]. The sugar industry is now moving towards substantially improved power stations, by adopting HP/HT steam conditions and high efficiency steam turbines, so that surplus power can be exported to the grid when prices are attractive, or otherwise can save (fuel) surplus bagasse, which can be utilized for many other productive purposes.

A wide range of steam inlet parameters is used in the sugar industries and varies between 21 bar to 110 bar and 300 to 540°C in temperature [3, 4, 5]. Various combinations are possible within these limits of pressure and temperature. The maximum pressure configuration employed internationally is 105 bar in a sugar mill in Okeelanta, Florida, USA [6]. Further, most of the engineers involved in the design of bagasse-based cogeneration plants understand that higher HP steam inlet conditions result in a more efficient power plant.

The sugar industry employs different cogeneration schemes to satisfy the process steam demand and generates surplus power to export to the grid. The steam turbine based cogeneration systems in sugar mills can be considered over a large range of heat to power ratios. Although the choice of turbine depends on the boiler pressure selected, a simple backpressure type or extraction condensing type or a combination of these two could be a better choice [7, 8]. Further, the heat to power ratio is the key criterion in the selection of the steam turbines for the cogeneration plants [9].

Although, energy efficiencies are most commonly used up to now, a thermodynamically more accurate evaluation and more fair comparison between systems can be based on exergetic efficiency [10, 11, 12]. A number of thermodynamic criteria are used to evaluate and compare the cogeneration plants with each other and with separate generation plants. Criteria such as fuel energy savings ratio, heat to power ratio, exergetic efficiency and power generated per tonne of cane processed prove to be more important and relevant [13, 14, 15].

In the light of this, energy, exergy, and fuel savings analysis are investigated for a heat-matched bagasse-based cogeneration plant in the sugar industry. The analysis is carried out for a typical 2500 tcd sugar factory using backpressure steam turbine and an extraction condensing steam turbine cogeneration plants, for a wide range of optimal steam inlet conditions selected around the sugar industry's export cogeneration plants.

In the analysis, exergy methods, in addition to the more conventional energy analyses, are employed to evaluate overall and component efficiencies and to identify and assess thermodynamic losses. This analysis provides a strong thermodynamic base for the selection of cogeneration plant configuration, e.g., steam inlet condition, steam turbine, etc. and can assist in the design improvement efforts. The results should also assist in the optimization of cogeneration plant configuration, for better choice of system configuration.

DESCRIPTION AND CONFIGURATION OF A COGENERATION PLANT

The description and configurations of a cogeneration plant of a typical 2500 tcd sugar factory using backpressure steam turbine and extraction condensing steam turbine are presented in Figures 1 and 4, as explained below.

Backpressure Steam Turbine Cogeneration Plant [BPST]

This is the simplest and most energy efficient cogeneration configuration, widely practiced by the sugar mills. In this scheme, the boiler produces the quantity of steam required for the process. The medium pressure steam required for the process is directly tapped off from the boiler outlet, goes to the pressure reducing, desuperheater (PRDS) and is then sent to the consuming point. The low-pressure steam required for process heating is taken from the backpressure turbine exhaust. By upgrading the inlet steam parameters, surplus power is generated.

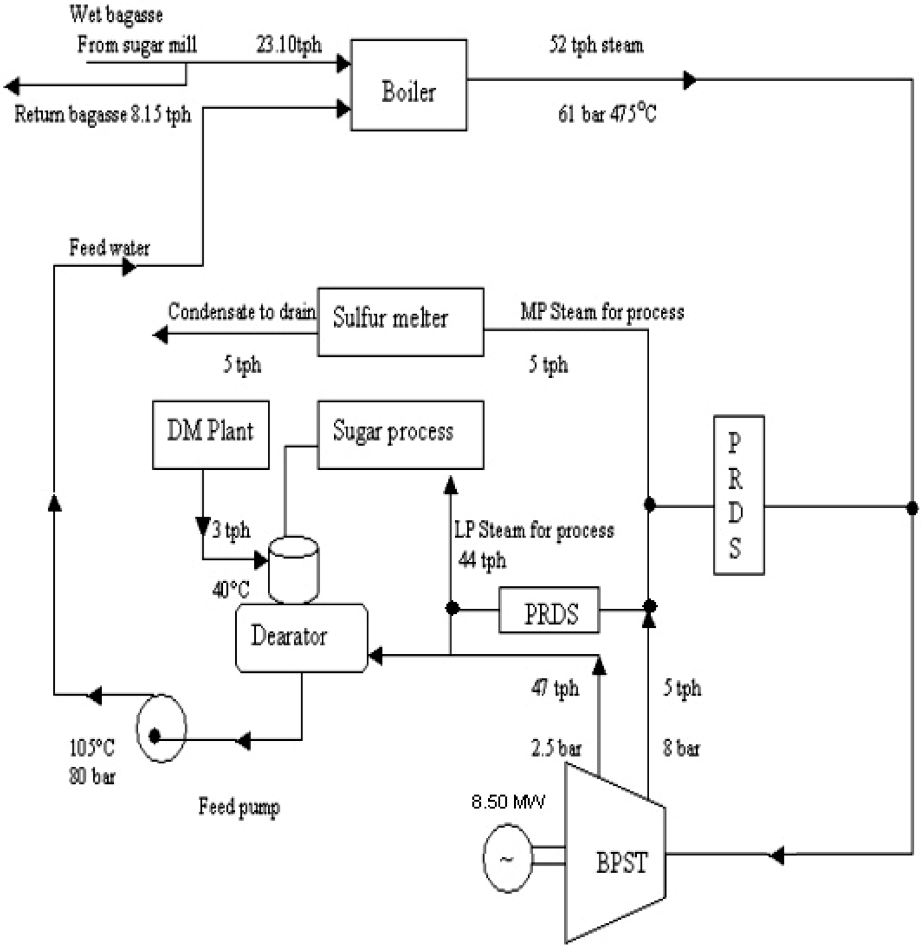

Figure 1. Cogeneration plant of a typical 2500 tcd sugar mill using backpressure steam turbine

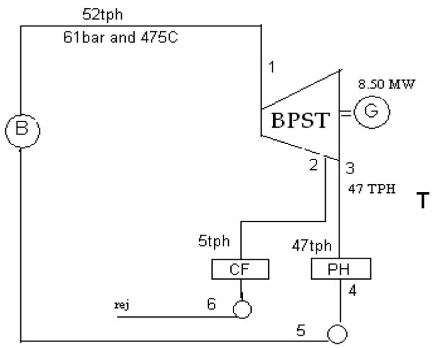

Figure 2. Steam Power Cycle Using BPST

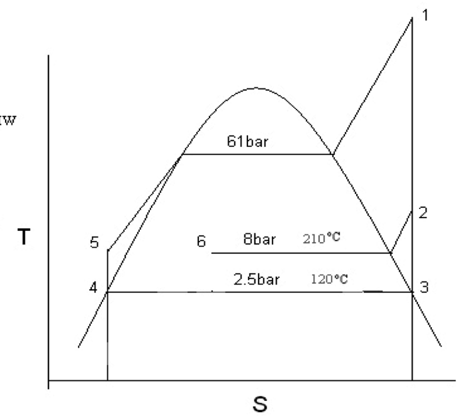

Figure 3. T-S Diagram

This scheme would cost the least. Because the turbogenerator is floating with the grid (for sending the excess power produced), it is possible to draw power from the grid whenever the turbogenerator is out of service. On such occasions, the low-pressure steam supply to the sugar mill is drawn through the second PRDS. The sugar mill operation remains unaffected by the availability of the turbogenerator.

The steam cycle for a typical 2500 tcd sugar mill cogeneration with such an arrangement is shown in Figure 2 and its representation is on T-S diagram in Figure 3. It can be seen that the sugar mill will accumulate unutilized bagasse at the rate of 8.15 tph. For a sugar mill working for 200 days in a year, this would mean 40,300 tonnes of excess bagasse generated per year. This excess bagasse can be utilized for other productive purposes. This type of scheme is not attractive for off-season operation. The only advantage of this method is extreme simplicity and low capital cost.

Extraction Condensing Steam Turbine Cogeneration Plant

This system is the most established method of cogeneration currently in use in sugar factories. This involves the use of high-pressure boilers and extraction condensing steam turbines for power generation. Steam required for the process is extracted at 8 bar and 2.5 bar, and the balance of steam goes to the condenser. The steam cycle for a typical 2500 tcd sugar mill working with such an arrangement is shown in Figure 5 and its representation is on T-S diagram in Figure 6.

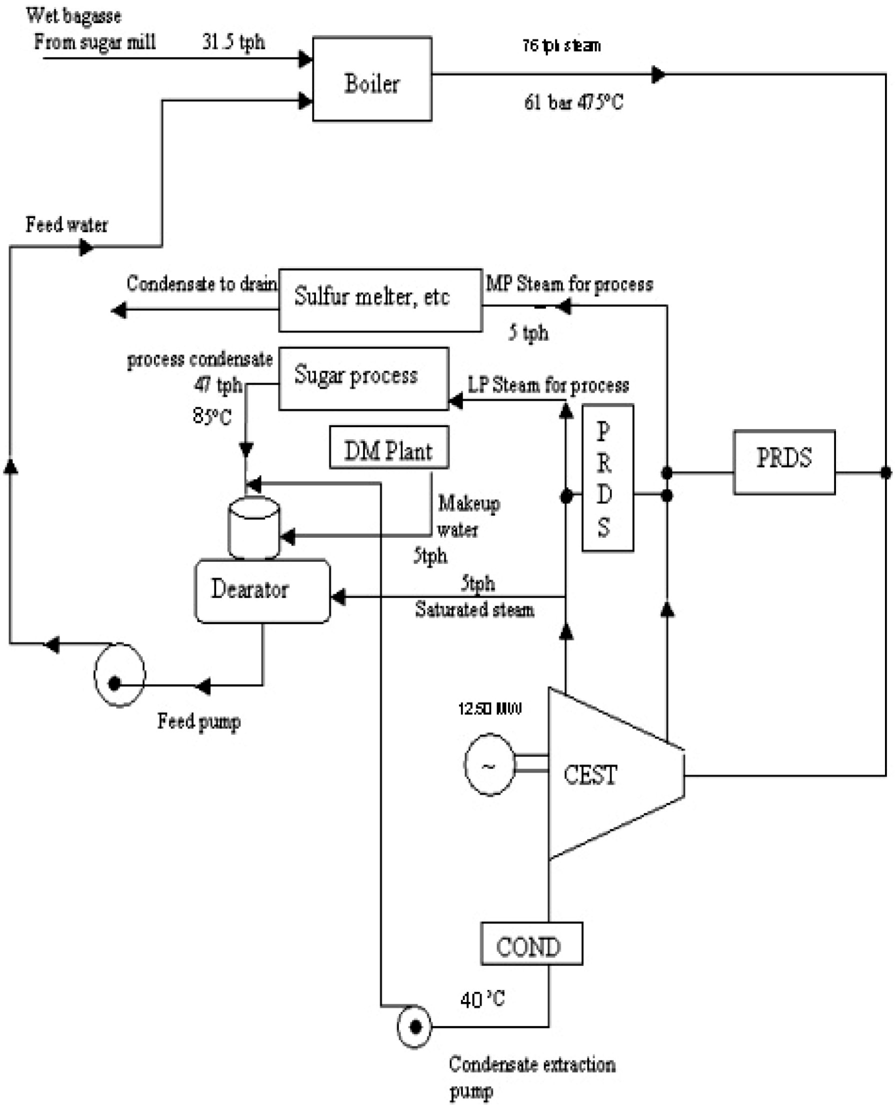

Figure 4. Cogeneration plant with off-season operating capability for a 2500 tcd sugar mill using an extraction-condensing steam turbine

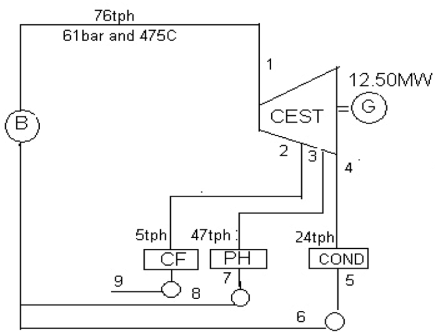

Figure 5. Steam Power Cycle Using Extraction Condensing Steam Turbine

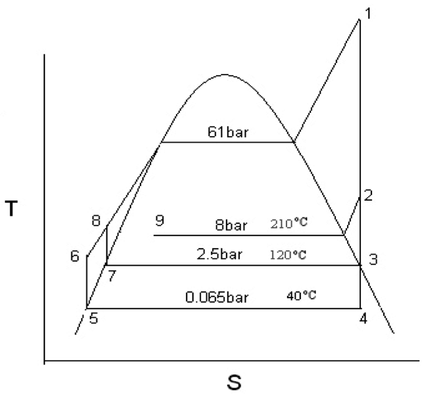

Figure 6. T-S Diagram

Such plants can generate and supply surplus power to the grid during off-season, also either by using saved bagasse, purchased from nearby factories, or any other alternative fuels. Obviously during off-season the turbogenerator will work in fully condensing mode, and therefore, the condenser sizing will have to be done accordingly.

In this technology, a fairly stable quantity of surplus power export is feasible because fluctuation in process steam demand can be off set by corresponding changes in the quantity of steam to the condenser. In addition, the effect of variation in rate of cane crushing can be offset by using bagasse silos, which can ensure a stable rate of bagasse supply to the boilers irrespective of fluctuation in cane crushing rate. During shutdown of the mill as a result of a breakdown, or general cleaning, power export can be continued through back feeding of stored bagasse from the silos.

THERMODYNAMIC PERFORMANCE CRITERIA

Cogeneration of heat and power implies production of two different kinds of energy. A common denominator should first be established to determine the efficiency of a cogeneration plant. A number of criteria can be used to assess the plant's performance [9, 10, 13]. The most important, frequently used of those parameters are (1) energy utilization factor, or first law efficiency or energy efficiency; (2) heat to power ratio; (3) relative fuel consumption factor; (4) fuel energy savings ratio or the avoided fuel costs; (5) power generated per tonne of cane processed; (6) turbine specific steam consumption; and (7) exergetic efficiency.

Energy Utilization Factor (EUF)

The first, most straightforward criterion is based on the First Law analysis, which deals only with the quantitative side of energy. It is the thermal efficiency of conventional plant $(\eta_{th})_C$ and energy utilization factor for cogeneration plant

$$(\eta_{th})\ c = \frac{W_{net}}{F_{CG}} \tag{1}$$

$$EUF = \frac{W_{CG} + Q_{CG}}{F_{CG}} \tag{2}$$

Introducing the two efficiencies, thermal efficiency (η_{th}) and electrical efficiency (η_e) for the cogeneration plant

$$\eta_{th} = \frac{Q_{CG}}{F_{CG}}, \quad \text{and } \eta_e = \frac{W_{CG}}{F_{CG}} \tag{3}$$

Energy utilization factor can be expressed as

$$EUF = \eta^{th} + \eta_e \tag{4}$$

Where, Q_{CG} is the process heat obtained at useful temperature TU, and WCG is the net electrical energy or power generated. Here, the process heat is the low-grade energy and WCG is high-grade energy [16]. Therefore, energy utilization factor cannot be an entirely satisfactory criterion of performance because it adds both heat and electricity.

Fuel Energy Savings Ratio and Relative Fuel Consumption Factor

The fuel savings deals with the fuel consumption of the cogeneration plant and separate generation plants. If a cogeneration plant substitutes a separate conventional power plant of overall efficiency η_C and heat only boiler of efficiency η_B, meeting the same loads of electricity W and process heat/steam Q. The general expressions for the fuel consumption of separate generation and cogeneration plants are shown in equations 5 and 6.

$$F_{SG} = \frac{W}{\eta_C} + \frac{Q}{\eta_B} \tag{5}$$

$$F_{SG} = \frac{W_{CG} + Q_{CG}}{\eta_{CG}} \tag{6}$$

Then the relative fuel consumption factor (Φ) and fuel energy savings (ΔF) are

$$\Phi = \frac{F_{CG}}{F_{SG}} \tag{7}$$

$$\Delta F = F_{SG} - F_{CG} \tag{8}$$

The fuel energy savings ratio (FESR) is expressed as

$$FESR = \frac{\Delta F}{F_{SG}} = 1 - \frac{F_{CG}}{F_{SG}} \tag{9}$$

$$FESR = 1 - \frac{1 + \lambda_{CG}}{EUF\left[\frac{1}{\eta_C} + \frac{\lambda_{CG}}{\eta_B}\right]} \tag{10}$$

However, it is important to remember that the FESR calculated by using equation 10 is meaningful, when both, separate generation and cogeneration plant are consuming the same fuel, where as the cogeneration plants in sugar industries are burning the (waste) fuel bagasse. Therefore, to quantify the fuel savings, it is necessary to calculate the fuel equivalent values when comparing separate generation plants consuming fossil fuels like coal, oil and gas etc. FESR is the most relevant criterion, yet described, in the evaluation of cogeneration plant because it can be used directly in the economic assessment of the plant.

Exergetic Efficiency

Exergy is a measure of the energy quality, and exergetic or second law efficiency is the measure of the perfectness of system [17, 18]. Thermodynamics suggest the use of the exergetic factor, which exactly indicates 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 [15, 19, 20].

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

$$\eta_{EX} = \frac{W_{CG} + E_Q}{E_f} \tag{11}$$

Using the exegetic factor, equation 11 can be expressed as

$$\eta_{EX} = \frac{W_{CG} + \alpha\ Q_{CG}}{E_f} \tag{12}$$

α = 0.260 for process heat obtained at 2.5 bar and 120°C.

Introducing the Second Law analysis has proven to be valuable for evaluation and optimization of cogeneration plants [17, 21]. After first being used as an academic criterion, exergetic efficiency is now becoming more often used by engineering companies and industries.

PERFORMANCE ANALYSIS

The performance analysis of the cogeneration plant of typical 2500 tcd sugar factory considered is based on a constant steam supply of 52 tph, for process heating, and power generated is a by-product. Because these plants are heat-matched cogeneration plants, satisfying process steam demand is a must, and upgrading the steam inlet parameters generates the surplus power. Therefore, it is essential to understand by what amount the steam inlet parameter is to be upgraded, to get optimum thermodynamic advantage.

There is no theoretical limit to the amount of superheat if the boiler can create it at any working pressure; however, the practical limit of superheat temperature obtainable in the boiler using fuel, such as mill-wet bagasse, is around 520°C [6]. For the exhaust conditions of 2.5 bar and 120°C selected and 85% barrel efficiency assumed, the optimal HP/HT steam conditions and corresponding steam to bagasse ratio, around the sugar industry's export cogeneration plant are selected for the analysis [4, 6, 22]. Table 1 shows the optimal HP/HT steam inlet conditions selected, and corresponding values of steam to bagasse ratio and steam generation rate of a 2500 tcd sugar mill.

The results are determined for the optimal conditions selected, and a summary of the results obtained is given in Table 2 and Table 3 for backpressure and extraction condensing steam turbine cogeneration plants, respectively. In each of these steam inlet conditions, 47 tph of steam at 2.5 bar and 120°C and 5 tph of steam at 8 bar and 210°C

Table 1. Steam to bagasse ratio and steam generation rate at selected optimal steam inlet conditions

Pressure, bar	*21*	*31*	*41*	*61*	*81*	*110*
Temperature, °C	340	388	423	475	513	545
Steam to bagasse ratio	2.11	2.25	2.36	2.43	2.45	2.56
Steam generation rate, tph	66	71	74	76	77	81

Table 2. Energy and Exergy flow rates and efficiencies for a heat-matched backpressure steam turbine cogeneration plant of a 2500 tcd sugar factory

Steam Pressure, bar		**21**	**31**	**41**	**61**	**81**	**110**
Temperature, °C		**340**	**388**	**423**	**475**	**513**	**545**
Heat	kW_{th}	31596	31596	31596	31596	31596	31596
	kW_{ex}	8239	8239	8239	8239	8239	8239
Power W_{CG}	kW_e	4440	5502	6621	7649	7389	8553
Fuel	kW_{th}	52360	49109	46814	45475	45092	43159
	kW_{ex}	67691	63488	60521	58790	58296	55796
Heat to power ratio	λ_D	9.0	9.0	9.0	9.0	9.0	9.0
	λ_{CG}	7.11	5.75	4.78	4.13	4.28	3.69
η_{th}		0.603	0.643	0.675	0.695	0.700	0.732
η_e		0.085	0.112	0.141	0.168	0.164	0.198
EUF		0.688	0.755	0.816	0.863	0.864	0.930
$\eta_{th\ ex}$		0.122	0.129	0.136	0.140	0.141	0.148
$\eta_{e\ ex}$		0.084	0.110	0.140	0.167	0.162	0.196
η_{EX}		0.206	0.239	0.276	0.307	0.303	0.344
FESR at η_C	0.30	-0.046	0.081	0.181	0.247	0.245	0.322
	0.40	-0.133	-0.005	0.093	0.161	0.158	0.236
	0.50	-0.190	-0.006	0.031	0.098	0.096	0.173
ϕ, λ_D=9.00	0.30	1.046	0.919	0.819	0.753	0.755	0.678
at η_C	0.40	1.133	1.005	0.907	0.839	0.842	0.764
	0.50	1.190	1.006	0.969	0.902	0.904	0.826
Power generated	kWh/tc	43	53	64	74	71	82
Turbine specific steam consumption	kg/kWh	11.71	9.45	7.85	6.80	7.04	6.08

Table 3. Energy and Exergy flow rates and efficiencies for a heat-matched extraction condensing steam turbine cogeneration plant of a 2500 tcd sugar factory

Steam Pressure, bar		21	31	41	61	81	110
Temperature, °C		340	388	423	475	513	545
Heat	kW_{th}	31596	31596	31596	31596	31596	31596
	kW_{ex}	8239	8239	8239	8239	8239	8239
Power W_{CG}	kW_e	7298	9472	11935	14069	14114	16917
Fuel	kW_{th}	66938	66938	66938	66938	66938	66938
	kW_{ex}	85680	85680	85680	85680	85680	85680
Heat to power ratio	λ_D	9.00	9.00	9.00	9.00	9.00	9.00
	λ_{CG}	4.33	3.33	2.65	2.25	2.24	1.87
η_{th}		0.472	0.472	0.472	0.472	0.472	0.472
η_e		0.109	0.141	0.178	0.210	0.210	0.253
EUF		0.581	0.613	0.650	0.682	0.682	0.725
$\eta_{th\ ex}$		0.096	0.096	0.096	0.096	0.096	0.096
$\eta_{e\ ex}$		0.085	0.110	0.139	0.164	0.165	0.197
η_{EX}		0.181	0.206	0.235	0.260	0.261	0.293
FESR at η_C	0.30	-0.126	-0.004	0.105	0.183	0.184	0.269
	0.40	-0.254	-0.139	-0.031	0.047	0.048	0.135
	0.50	-0.347	-0.239	-0.136	-0.059	-0.058	0.030
ϕ, λ_D=9.00 at η_C	0.30	1.126	1.004	0.895	0.817	0.816	0.731
	0.40	1.254	1.139	1.031	0.953	0.952	0.865
	0.50	1.347	1.239	1.136	1.059	1.058	0.970
Power generated	kWh/tc	70	91	115	135	136	163
Turbine specific steam consumption	kg/kWh	9.04	7.50	6.20	5.40	5.45	4.78

superheat is delivered. Only the amount of steam required for satisfying the process steam demand (i.e., 52 tph steam) is generated in the backpressure steam turbine cogeneration plant, and surplus bagasse is saved. Where as, all the bagasse generated during crushing is utilized to generate steam. The surplus steam, leftover after meeting the process steam demand through suitable extractions, goes to the condenser in the extraction condensing steam turbine cogeneration plant.

The steam turbine has an isentropic efficiency of 85% and expands steam from the inlet conditions selected to 2.5 bar and 120°C in the back-pressure turbine and to 0.065 bar and 40°C in the condensing turbine. The thermal efficiency of the heat only boiler is assumed to be 90%, and the generator efficiency is assumed to be 92%. The heat-to-power ratio demand of the plant (η_D=9.0) and the heat-to-power ratio the cogeneration plant can provide power generated per tonne of cane processed. The turbine-specific steam consumption is also determined for both configurations at different steam inlet conditions. There are continuous efforts to improve the overall efficiency of a conventional power plant by introducing new and advanced energy technologies. Therefore, it is necessary to study the influence of improvement in conventional power plant efficiency on the fuel savings of cogeneration plant. Hence, the relative fuel consumption factor and fuel energy savings ratio of the cogeneration plants are calculated for three levels of conventional power plant efficiency (0.3, 0.4 and 0.5).

The exergetic efficiency of the cogeneration plant as a whole is determined. The energy efficiency and exergy efficiency of the plant are compared. For the analysis presented in this research, the average calorific value (LHV) and fuel exergy of mill-wet bagasse are assumed as 7650 kJ/kg and 9890 kJ/kg, respectively [3, 23, 24]. In the proceeding section, the distribution of loss of exergy in the plant's components is estimated. Variation of loss exergy in the various components at different steam inlet conditions selected is also determined. The exergetic efficiency of each component in the plant is calculated.

EXERGY ANALYSIS

Exregy analysis, applied to a cogeneration plant as a whole, is also used to analyze performance of separate components of the power plant. The plant is divided into its subcomponents such as boiler, turbine, condenser, process heater, etc.

The following assumptions were made:

1. Only chemical exergy was used for fuel
2. Only physical exergy was used for flue gas and steam/water flows.

The distribution of physical exergy in the various components of the plant is determined by applying exergy balance for each component, for a steady flow process.

$$E_j + \left(1 - \frac{T_o}{T_i}\right)Q_j + W_{CV} + m(ef_1 - ef_2) + E_{destroyed} = 0 \tag{13}$$

where,

$$ef_1 - ef_2 = (h_1 - h_2) - To\ (s_1 - s_2) + \frac{V_1^{\,2} - V_2^{\,2}}{2} + g(Z_1 - Z_2) \tag{14}$$

is the specific exergy flow through components, and suffix 1 and 2 in equation 14 refer to the inlet and exit conditions.

The exergy destroyed in the plant's components is a function of entropy generation and ambient air temperature surrounding the component. It is important to note here that the temperature surrounding the component in a cogeneration plant changes substantially from place to place, for example, the temperature of air surrounding the boiler and condenser. The physical exergy associated with the flow of combustion/ flue gas is determined as

$$af = m_g\, T_o \left[\frac{T_g}{T_o} - 1 - \ln \frac{T_g}{T_o}\right] \tag{15}$$

where, Tg is the flue gas temperature.

The physical exergy of flue gas produced by burning bagasse in the furnace and its utilization in the boiler for steam generation is determined the following section.

The stiochiometric air fuel ratio required for combustion of bagasse is 5.76. But it is not possible in practice to burn bagasse in industrial conditions by supplying only the quantity of air theoretically necessary; combustion will be poor and incomplete [1]. To obtain complete combustion, it is necessary to supply excess air. Let the flow rate of combustion gas be 1 kg/s and that of bagasse of "f" kg/s, therefore the flow rate of air (1-f) kg/s.

$$f_x\ Cv = m_g\ C_{pg}\ (T_g - T_o) - (C_{pa}\ (T_a - T_o) \tag{16}$$

Substituting the numerical values, equation 16 yields, f =0.1192 kg/s, and 1-f =0.8808 kg/s.

$$\text{Air fuel ratio} = \frac{1 - f}{f} = \frac{0.8808}{0.1192} = 7.40$$

and

$$\text{Excess air} = \frac{7.40 - 5.76}{5.76} = 0.285 \text{ or } 28.5\%$$

The existing practice in sugar factories confirms that around 25 to 30% excess air is supplied to the boilers.

The exergy flow rates destroyed in the plant's components are determined at optimal steam inlet conditions selected, and are given in Tables 4 and 5, respectively, for backpressure and condensing steam turbine cogeneration plants. The variation of loss of exergy in the plant's components and improvement in exergy utilization at different HP/HT steam inlet conditions are examined.

The exergy concept is further extended to determine the exergetic or Second Law efficiency of major components like boiler and turbine of the plant. This efficiency compares the actual work produced by a device to the work interactions associated with a reversible device. The general expression for exergetic efficiency of power producing/consuming device is

$$\eta_2 = \frac{w_{act}}{W_{rev}} = \frac{\eta_{act}}{\eta_{rev}} \tag{17}$$

While equations 18 and 19 are the expressions for the Second Law efficiency of turbine (η_2 turbine) and boiler (η_2 boiler), respectively

$$\eta_{2\ turbine} = \frac{(W_{net})_{ST}}{w_s(ef_1 - ef_2)} \tag{18}$$

$$h_{2\ boiler} = \frac{w_s[(h_1 - h_8) - T_o\,(s_1 - s_8)]}{E_f} \tag{19}$$

The cycle overall exergetic efficiency (η_{rev} cycle) is determined as

$$\eta_{2\ cycle} = \frac{(\eta^{th})c}{\eta_{rev}} \tag{20}$$

Where $(\eta_{th})_C$ is based on the results of First Law analysis and η_{rev} is based on the reversible heat engine operating between reservoirs at T_L and T_H (298 K and 1273 K), respectively.

RESULTS AND DISCUSSIONS

The results presented in this article, Tables 2, 3, 4, and 5 are for heat-matched bagasse based cogeneration plants of typical 2500 tcd sugar factory using an extraction backpressure steam turbine and an extraction condensing steam turbine, respectively. Table 2 and Table 3 show the energy and exergy flow rates, while Table 4 and Table 5 show the physical exergy distribution in the plant's components.

Although a 2500 tcd sugar factory generates 31.5 tph of bagasse, and has the potential to generate 70 tph of steam for an average value of steam to bagasse ratio of 2.25, only 52 tph of steam (what is required for process heating) is generated by consuming 23 tph of bagasse in

Table 4. Physical exergy distribution in the plant's components [BPST]

Inlet steam condition	**P, bar** **T, °C**	**21** **340**	**31** **388**	**41** **423**	**61** **475**	**81** **513**	**110** **545**
Chemical exergy of fuel	kW_{ex}	67691	63488	60521	58790	58296	55796
Power, W_{CG}	kW_e	4440	5502	6621	7649	7389	8553
Process heat, E_Q	kW_{ex}	8239	8239	8239	8239	8239	8239
Exergetic efficiency plant	η_{ex}	0.206	0.239	0.276	0.307	0.303	0.344
Physical exergy of flue gases	kW_{ex}	31170	31170	31170	31170	31170	31170
Exergy losses							
Boiler, I_b	kW_{ex} %	16678 53.50	15169 48.70	13803 44.30	12247 39.30	11906 38.20	10556 33.90
Exhaust gas I_{Exg}	kW_{ex} %	1185 3.80	1185 3.80	1185 3.80	1185 3.80	1185 3.80	1185 3.80
Steam turbine I_{ST}	kW_{ex} %	913 2.90	1064 3.40	1001 3.20	1241 3.90	1914 6.14	1776 5.70
Condenser I_{cond}	kW_{ex} %	- -	- -	- -	- -	- -	- -
Others I_{other}	kW_{ex} %	285 0.009	11 -	321 1.30	554 1.78	537 1.70	861 2.80
Total Irreversibilities I_{total}	kW_{ex} %	19061 61.20	17418 55.90	16310 52.60	15281 49.00	15542 49.84	14378 46.13
Exergtic efficiency of boiler	$\eta_{2\ b}$	0.214	0.252	0.287	0.322	0.330	0.37
Turbine	$\eta_{2\ t}$	0.86	0.87	0.89	0.89	0.83	0.86
Cycle	$\eta_{2\ cycle}$	0.211	0.249	0.287	0.318	0.310	0.346

Table 5. Physical exergy distribution in the plant's components [CEST]

Inlet steam condition	P, bar	21	31	41	61	81	110
	T, °C	340	388	423	475	513	545
Chemical exergy of fuel	kW_{ex}	85680	85680	85680	85680	85680	85680
Power, W_{CG}	kW_e	7298	9472	11935	14069	14114	16917
Process heat, E_Q	kW_{ex}	8239	8239	8239	8239	8239	8239
Exergetic efficiency plant	η_{ex}	0.181	0.206	0.235	0.260	0.261	0.293
Physical exergy of flue gases	kW_{ex}	45920	45920	45920	45920	45920	45920
Exergy losses		-	-	-	-	-	-
Boiler, I_b	kW_{ex} %	24552 53.46	21221 46.21	18276 39.80	14991 32.65	14409 31.38	10776 23.47
Exhaust gas I_{Exg}	kW_{ex} %	1746 3.80	1746 3.80	1746 3.80	1746 3.80	1746 3.80	1746 3.80
Steam turbine I_{ST}	kW_{ex} %	1714 3.74	2038 4.44	2277 4.95	2510 5.55	2650 5.78	2795 6.09
Condenser I_{cond}	kW_{ex} %	395 0.86	515 1.12	511 1.11	635 1.40	653 1.42	759 1.65
Others I_{other}	kW_{ex} %	- -	- -	- -	- -	- -	- -
Total Irreversibilities I_{total}	kW_{ex} %	28407 61.86	25520 55.58	22810 49.68	19882 43.29	19462 42.38	16076 35.00
Exergtic efficiency of boiler	$\eta_{2\ b}$	0.210	0.240	0.272	0.306	0.316	0.357
Turbine	$\eta_{2\ t}$	0.764	0.717	0.733	0.723	0.690	0.689
Cycle	$\eta_{2\ cycle}$	0.427	0.458	0.483	0.514	0.527	0.551

backpressure steam turbine cogeneration plant. By doing so, the plant saves 8.5 tph (30%) of bagasse. Thus, a sugar factory working for 200 days season can save 40,300 tonnes of bagasse, which can be utilized for other productive purposes, if the electricity sale prices are not attractive. The reader should not confuse this bagasse savings with that of FESR of cogeneration plant with separate generation plants.

It is seen from the results that there is substantial improvement in both energy and exergy efficiency of the plant with increases in steam inlet pressure and temperature in both systems. The highest energy and exergetic efficiency are 0.93 and 0.344, respectively, at 110 bars and 545°C steam inlet conditions. Thus the backpressure steam turbine cogeneration system is the most energy efficient configuration. Figures 7 and 8 show the efficiency comparison of backpressure and condensing steam turbine cogeneration plants, respectively, at different optimal steam inlet conditions.

The heat-to-power ratio (λ_{CG}) provided by the cogeneration plant

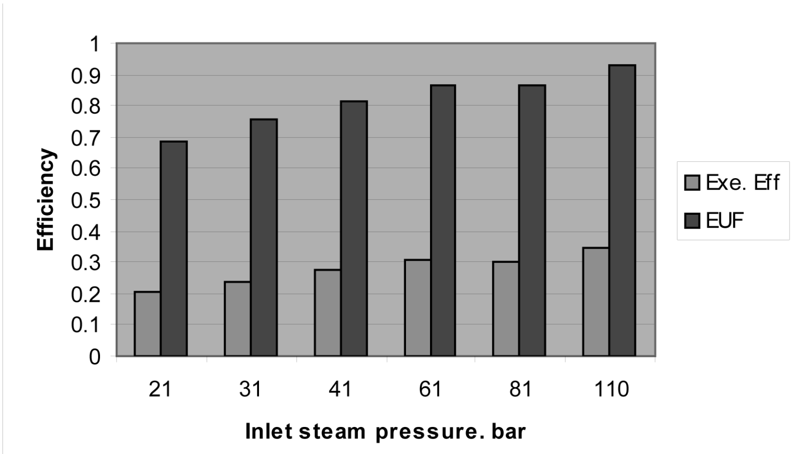

Figure 7. Efficiency comparison of backpressure steam turbine cogeneration plant

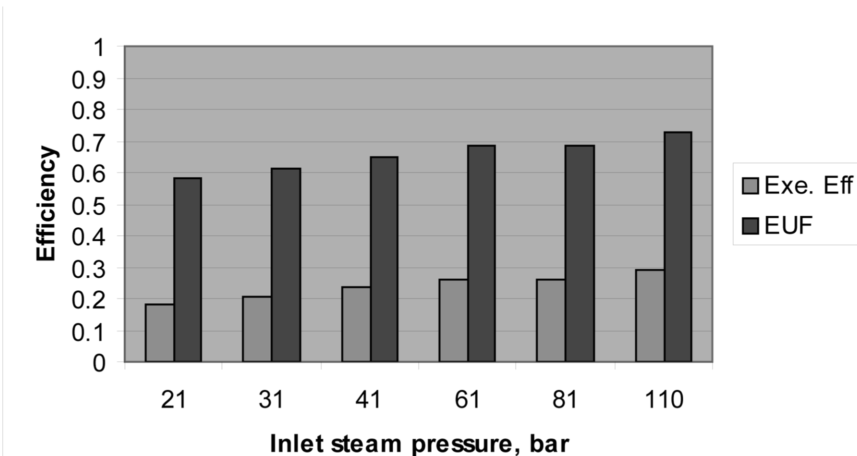

Figure 8. Efficiency comparison of condensing steam turbine cogeneration plant

is less than the heat to power ratio demand of the plant, and decreases with increases in steam inlet pressure and temperature, indicating production of more surplus power. The heat to power ratio demand of the plant remains constant at all values of steam inlet conditions. Thus, these are heat-matched plants, and not, both heat- and power-matched cogeneration plants.

The fuel energy savings ratio of the plant improves substantially with increasing steam inlet pressure and temperature in both configurations. The results obtained indicate values of FESR at steam inlet pressure and temperature less than 31 bar and 388°C for the backpressure steam turbine plant and 41 bar and 423°C for the extraction condensing steam turbine plant, respectively, at all the three levels of conventional power plant efficiency assumed. Thus, these plants are not thermodynamically attractive from the primary fuel energy savings point of view at steam inlet conditions below 31 bar and 388°C using the backpressure steam turbine and 41 bar and 423°C using the extraction condensing steam turbines for cogeneration plants, respectively. Figures 9 and 10 show the variation of relative fuel consumption factor, and Figures 11 and 12 show the variation of fuel energy savings ratio of backpressure and extraction condensing steam turbine cogeneration plants, respectively, at the optimal steam inlet conditions selected.

To examine the influence of improvement in conventional power plant efficiency on the fuel savings of the cogeneration plant, a graph of relative fuel consumption factor versus conventional power plant efficiency and FESR versus conventional power efficiency are plotted. Figures 13 and 14 depict the variation of relative fuel consumption factor, and Figures 15 and 16 show the variation of FESR with improvement in conventional power plant efficiency for backpressure and condensing steam turbine cogeneration plants, respectively. FESR is highly sensitive to improvement in conventional plant efficiency at low heat-to-power ratios.

The power generated per tonne of cane processed improves substantially and turbine specific steam consumption decreases drastically with increases in steam inlet pressure and temperature in both the configurations. The highest power generation is 163 kWh/tc and 82 kWh/tc, and the lowest specific steam consumption is 4.78 kg/kWh and 6.08 kg/kWh at 110 bar and 545°C steam inlet conditions for extraction condensing steam turbine and for backpressure steam turbine, respectively. Figures 17 and 18 show the comparison of power generation and turbine-specific steam consumption of the both turbines at different steam inlet conditions.

The loss of exergy in the components of a cogeneration plant and the total irreversibility decrease with increases in steam inlet pressure and temperature. Further, boilers are the major components contributing most to the plant's total inefficiency. The total irreversibilities and boiler irreversibility vary from 61.20 to 46.13% and 53 to 34% for backpressure

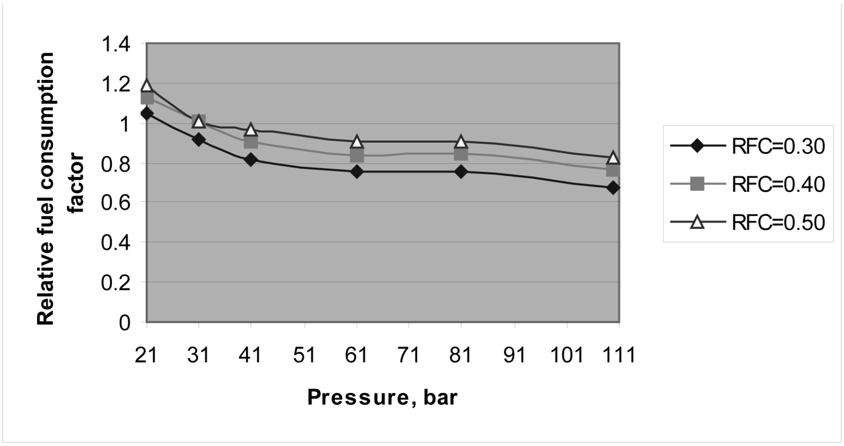

Figure 9. Variation of relative fuel consumption factor for backpressure turbine plant

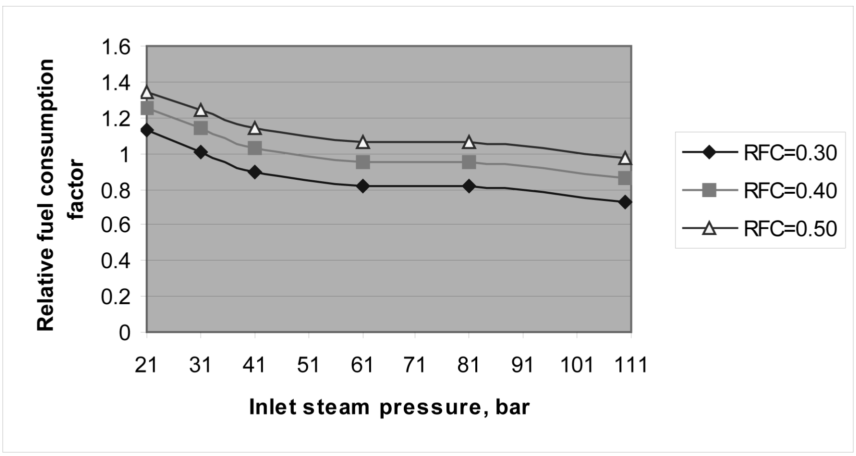

Figure 10. Variation of relative fuel consumption factor for extraction condensing turbine plant

steam turbines, and 61.86 to 35% and 53.46 to 23.47% for extraction condensing steam turbines, respectively, depending on the steam inlet conditions. Figures 19 and 20 show the exergy loss in the plants' components and total irreversibility at different optimal steam inlet conditions for both systems.

The exergetic efficiency of the boiler, cogeneration plant, and cycle

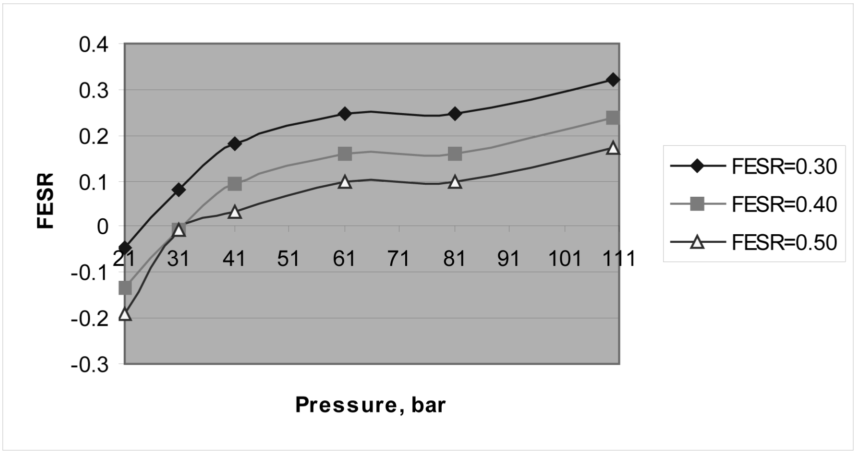

Figure 11. Variation of fuel energy savings ratio for backpressure turbine plant

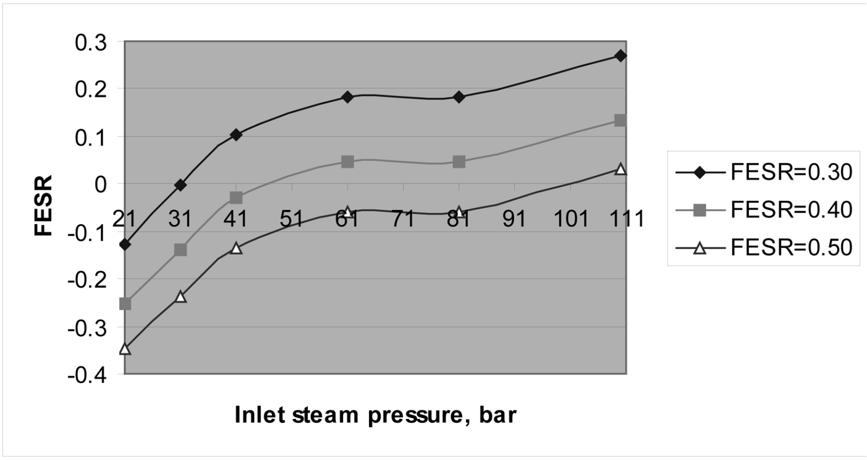

Figure 12. Variation of fuel energy savings ratio for extraction condensing turbine plant

improve with increases in steam pressure and temperature inlet conditions in both configurations. The highest plant exergetic efficiency is 0.344 for the backpressure steam turbine and cycle efficiency of 0.551 for a condensing steam turbine plant, at steam inlet conditions of 110 bar and 545°C. Thus, although the backpressure steam turbine plant attains higher exergetic efficiency, a condensing steam turbine cycle is the more efficient

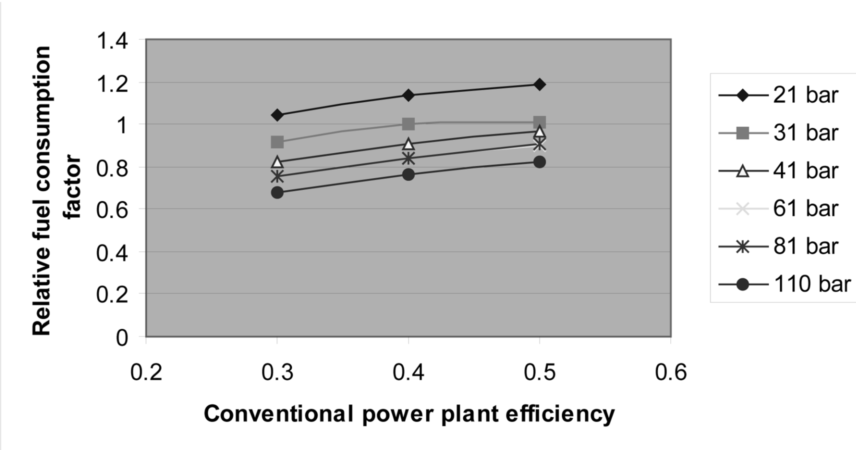

Figure 13. Variation of relative fuel consumption factor for backpressure turbine plant

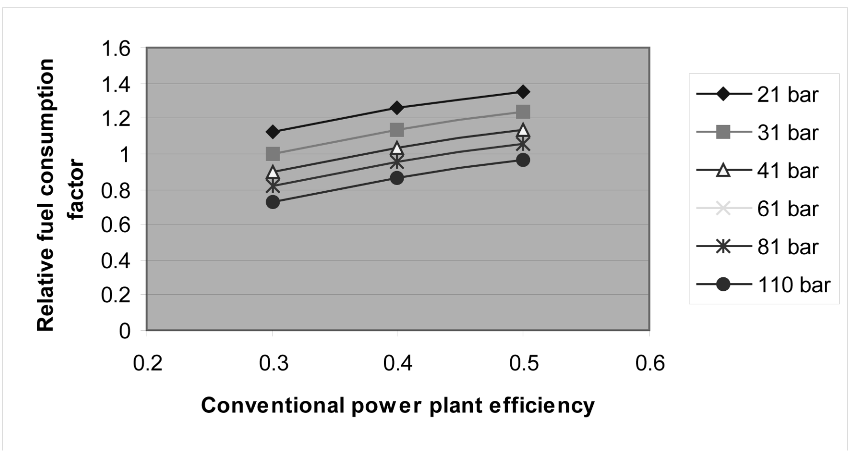

Figure 14. Variation of relative fuel consumption factor for extraction condensing turbine plant

power cycle. Figures 21 and 22 show the exergetic efficiency comparison of the cogeneration plant and cycle for backpressure and condensing steam turbine cogeneration system at different steam inlet conditions.

The exergetic efficiency comparison of plant and cycle depicts how closely the plant thermodynamically approaches the value of a reversible Carnot cycle efficiency, after allowing for process heat rejection. These

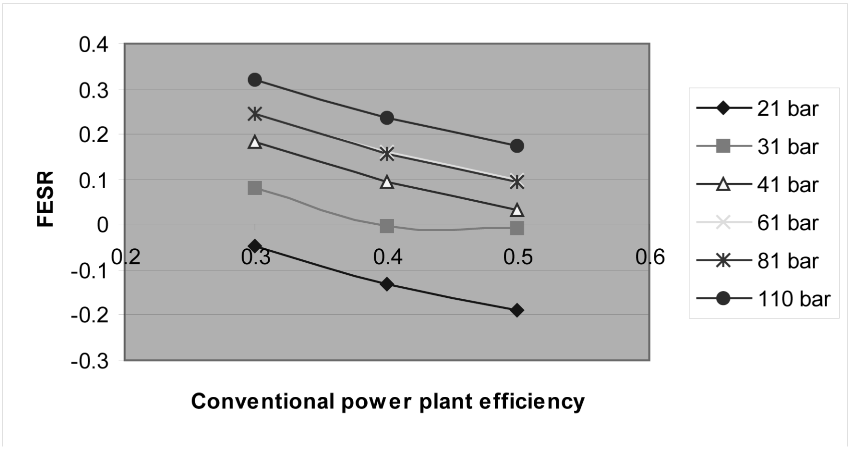

Figure 15. Variation of FESR for backpressure turbine cogeneration plant

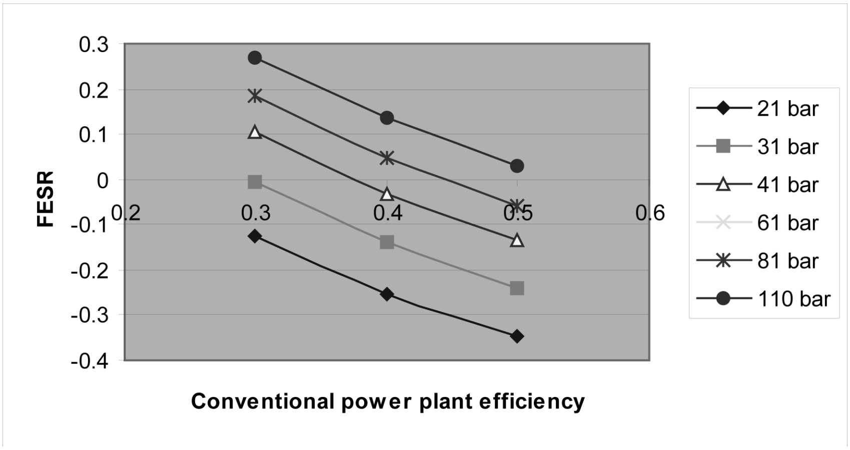

Figure 16. Variation of FESR for extraction condensing turbine cogeneration plant

are thermodynamic conclusions; whether it is worth choosing such higher HP steam condition will be subject to economic considerations.

CONCLUSIONS

A remarkable difference is seen between energy and exergy efficiency of the same system at all the steam inlet conditions. The improve-

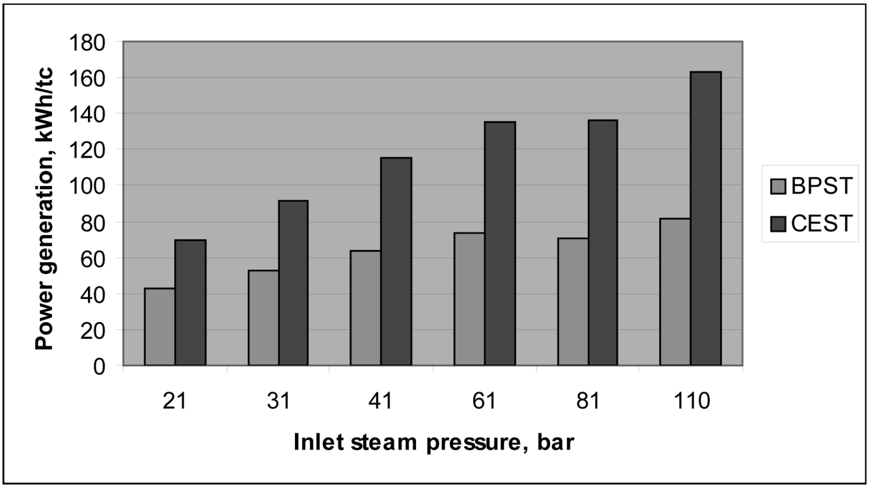

Figure 17. Power generation comparison of turbines

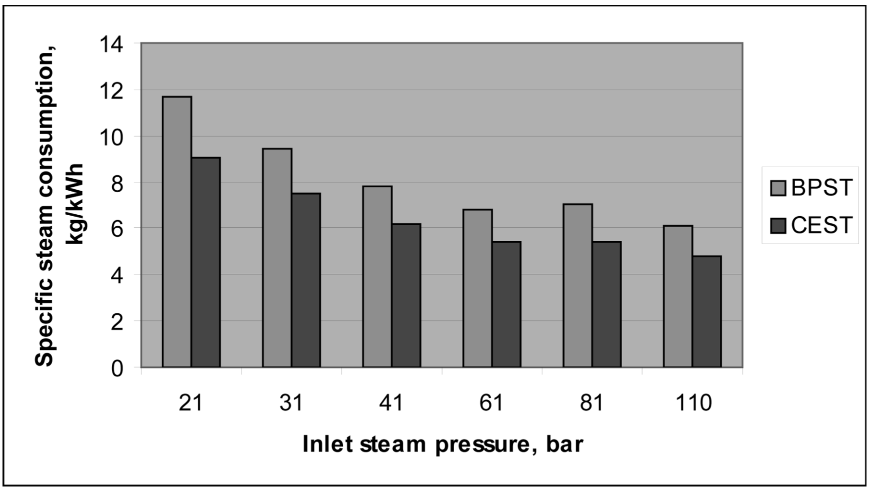

Figure 18. Specific steam consumption comparison of turbines

ment in energy and exergy efficiency of the plant, power generated per tonne of cane processed is substantial over range of higher HP/HT steam inlet conditions selected. Cogeneration plants are thermodynamically attractive only when these plants save a substantial amount of primary fuel energy over separate generation. From this point of consideration, cogeneration plants should only be considered when using steam inlet

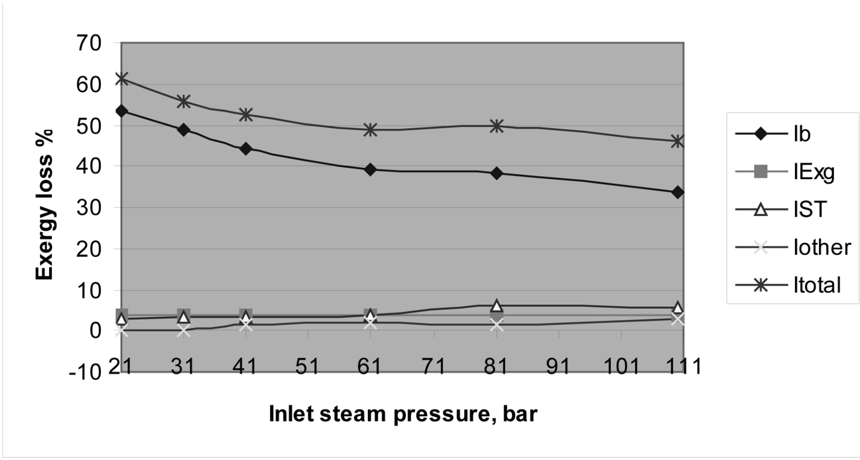

Figure 19. Variation of exergy loss in the components of backpressure steam turbine cogeneration plant

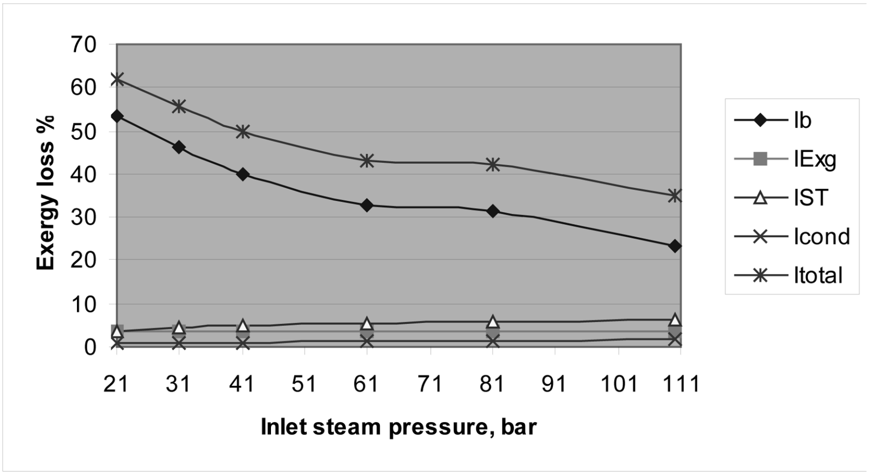

Figure 20. Variation of exergy loss in the components of extraction condensing steam turbine cogeneration plant

conditions above 31 bar and 388°C using backpressure turbines and 41 bars and 423°C using condensing turbines. The fuel savings of the cogeneration plant is highly sensitive to the improvement in conventional power plant efficiency at low heat-to-power ratios. Cogeneration plants are thermodynamically acceptable only if at least the exergetic efficiency of the plant is equal to the thermal efficiency of the conventional power

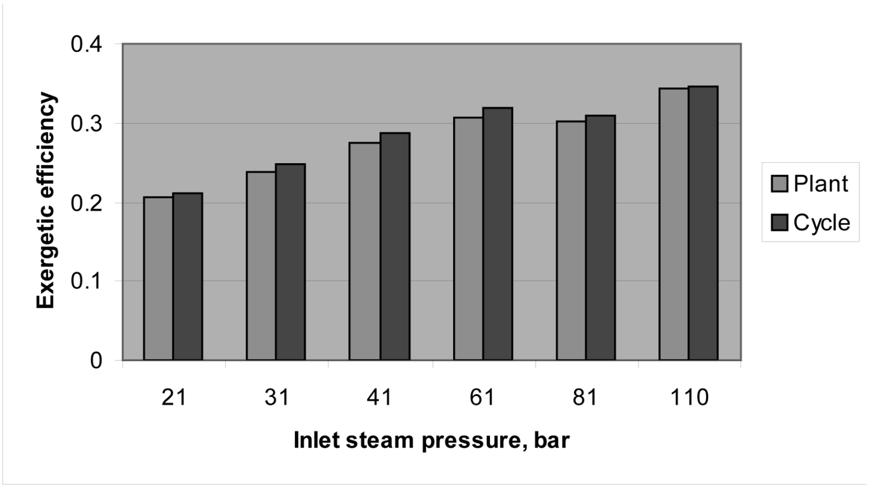

Figure 21. Exergetic efficiency comparison for backpressure steam turbine cogeneration plant

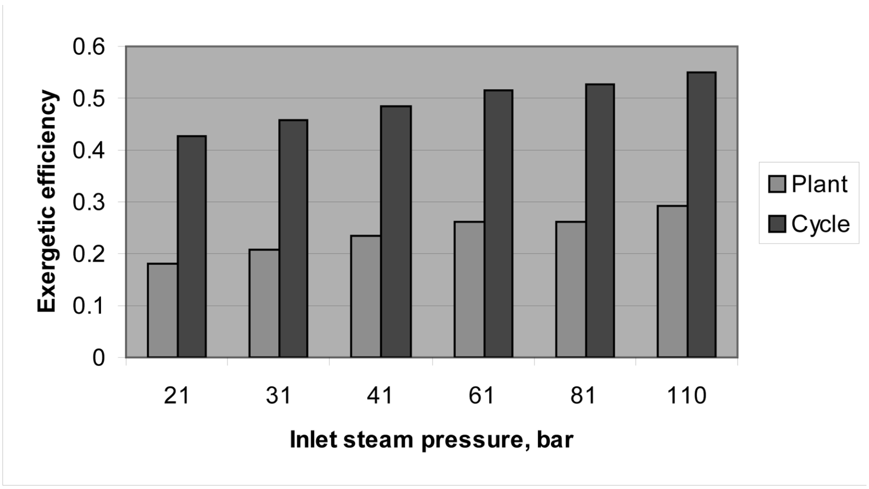

Figure 22. Exergetic efficiency comparison for extraction condensing steam turbine cogeneration plant

plant. The exergetic efficiency obtained for both the configurations in the analysis at all the steam inlet conditions selected is much lower than the thermal efficiency of the conventional power plant. However, the bagasse-based cogeneration plants in the Indian sugar industries are economically and environmentally attractive because they burn bagasse (waste) fuel.

No doubt, the introduction of higher HP/HT steam conditions has more thermodynamic advantage because these steam inlet conditions yield better performance results. However, it is seen from the results that improvements in performance values of the plant at steam inlet conditions above 61 bar and 475°C are marginal in both the configurations, although there are substantial increases in steam inlet pressure and temperature. Therefore, for little gains, adopting very high HP/HT steam conditions is meaningless, unless its economic returns are justified. Thus, steam inlet conditions of 61 bars and 475°C can be considered as optimal steam inlet conditions for bagasse-based cogeneration plants. Boilers are the major component contributing most to the plant's overall inefficiency in both the cases.

Backpressure steam turbines are the best choice for low-pressure steam turbine cogeneration plants from the point of integrating process steam demand and incidental power generation. This system yields the highest energy, exergetic and fuel savings results. If the sale price of electricity is attractive over fuel savings, then an extraction condensing steam turbine could be the better choice because the power generated by the turbine per tonne of cane processed is substantially higher, although energy and exergy efficiency of the plant is comparatively low, as that of backpressure steam turbine. Thus, the choice of the turbine has to be done very judiciously.

The high values of First Law system efficiency reflect only the quantitative, and not the qualitative side of the process, and only exergy criterion can demonstrate the imperfection of these configurations. These are the thermodynamic conclusions; whether it is worth making such conclusions is subject to economic considerations.

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