

Exergetic Comparison of Bagasse-based Cogeneration Plants

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ABSTRACT

Sugar industry employs different cogeneration schemes to satisfy the plant's process steam demand and generate possible surplus power by upgrading the steam inlet parameters. Though, energy efficiencies are most commonly used up to now, a thermodynamically more accurate evaluation and more fair comparison between different systems can be based on exergetic efficiency. In the light of this, in this article exergetic performance comparison of three actual heat-matched, bagasse-based cogeneration plants working in, three different sugar mills located in, Belgaum district, Karnataka State, India, namely (i) Hira Sugar Works Ltd (HWSL) (ii) Doodhaganga Krishna Sahakari Sakkare Karkhane Ltd (DKSSK), (iii) Ugar Sugar Works Ltd (USWL) is presented. In the analysis, in addition to the more conventional energy analysis, exergy analysis is employed to evaluate overall and component efficiencies and to assess the thermodynamic losses. The results indicate that the three-cogeneration plants perform with energy and exergetic efficiency of 0.702, 0.628, 0.648 and 0.187, 0.234, 0.225 respectively for HWSL, DKSSK and USWL. Boiler is the major component contributing most to the overall in-efficiency in all the three plants.

Keywords: Bagasse, cogeneration, exergy, efficiency.

INTRODUCTION

Manufacturing of white crystal sugar using 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 bar and 210°C for sulfur melting and centrifuge [1,2]. Cogeneration plants in the Indian sugar mills are primarily designed to satisfy the plant's process steam demand, as these are all heat-matched plants,

Nomenclature

α	Exergetic factor	η_{EE}	Exergetic efficiency
B	Boiler		
BPST	Backpressure steam turbine	η_{T_1}	Thermal efficiency of conventional power plant
CEST	Extraction condensing steam turbine	HP	High Pressure
CF	Centrifugal	HT	High Temperature
CG	Cogeneration	mf	Mass flow rate
Cond	Condenser	PH	Process heater
Cv	Calorific Value, kJ/kg	PRDS	Pressure reducing and de-superheating station
DM	De-mineral water plant	Q_{CG}	Useful process heat, kW
E_r	Chemical exergy of fuel bagasse kW	rej	Rejected
E_Q	Process heat exergy = a Q_{CG}	T_a	Air temperature at the exit of air pre-heater °C
EUf	Energy utilization factor	tcd	Tonnes of cane crushed per day
Fc	Conventional power plant fuel consumption, kW	T_g	Temperature of combustion gas °C
F_{CG}	Cogeneration plant fuel consumption, kW	T_o	Atmospheric air temperature °C
η_x	Overall efficiency of conventional power plant	tph	Tonnes per hour
η_{xr}	Energy efficiency of cogeneration plant	W_{CG}	Net co-generated power, kW

and surplus power is generated by up-grading the steam inlet parameters [3-5]. Sugar industry employs different cogeneration schemes to satisfy the plant's process steam demand and generate surplus power.

The configurations of the steam turbines used vary right from simple backpressure turbine to extraction condensing steam turbine or a combination of these two [6, 7]. Wide ranges of steam inlet parameters are used and these vary from 21 bar to 110 bar in pressure and 330 to 540°C in temperature [8-10]. The maximum pressure configuration employed internationally is 105 bar, in a sugar mill at Okeelanta, Florida, USA [2].

A number of thermodynamic criteria can be used to evaluate and compare different cogeneration schemes with each other [11-13]. Though, 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 [14-16]. Introducing the second law analysis has proved to be a valuable methodology for evaluation, comparison and optimization of cogeneration plants [12, 13, 17, 18].

In the light of this, the present article provides thermodynamic performance evaluation of three actual heat-matched, bagasse-based cogen-

eration power plants working in three different sugar mills, located in Belgaum, India namely (i) Hira Sugar Works Ltd, Sankeshwar (ii) Doodhaganga Krishna Sahakari Sakkare Karkhane Ltd, Chikodi, and (iii) Ugar Sugar Works Ltd, Ugar. The exergetic performance of three plants is compared with each other. This will help the plant designers and engineers for the design improvement and choice of alternative schemes, which will yield the best thermodynamic advantage.

PERFORMANCE CRITERIA

The performance criterion for conventional closed circuit power plant is usually taken as the overall efficiency, the product of the closed cycle thermal efficiency (η_{Th}) and the boiler efficiency (η_B).

$$\eta_C = \left(\frac{W}{Q_B} \right) \times \left(\frac{Q_B}{F_C} \right) = \eta_{Th} \eta_B = \frac{W}{F_C} \quad (1)$$

Where, $F_C = mf \times C_v$

This criterion of performance has less relevance to cogeneration plant, which provides process heat and generates electrical power from the same common fuel source. Cogeneration of heat and power implies production of two different kinds of energy. A common denominator should first be established to analyze the efficiency a cogeneration plant. The more logical criterion is the energy utilization factor or energy efficiency of cogeneration plant [11, 16] and is given by

$$EU\text{F or } \eta_{cg} = \frac{W_{CG} + Q_{CG}}{F_{CG}} \quad (2)$$

Where, Q_{CG} is the process heat rejected which meets a required heat load at temperature T_u . However it must be remembered that work (W) is high-grade energy and process heat (Q_{CG}) is low-grade energy [19]. Thus, energy efficiency is not entirely the satisfactory criterion of performance as it gives equal weight to both W_{CG} and Q_{CG} .

Exergy is a measure of energy quality and the exergetic or Second Law efficiency is the measure of perfectness of system [17-20]. Thermodynamic suggests the use of 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 fuel is also taken into account. The exergetic efficiency of the cogeneration plant as a whole is expressed as

$$\eta_{\text{ex}} = \frac{W_{\text{CG}} + E_{\text{Q}}}{E_{\text{f}}} \quad (3)$$

Using the exergetic factor α equation (3) can be modified and expressed as

$$\eta_{\text{ex}} = \frac{W_{\text{CG}} + \alpha Q_{\text{CG}}}{E_{\text{f}}} \quad (4)$$

$\alpha = 0.260$ for the process heat obtained at 2.5 bar and 120°C .

Introducing the second law analysis has proved to be a valuable methodology for the evaluation comparison and design optimization of cogeneration plants [14, 21-23].

COGENERATION PLANTS CONFIGURATIONS

Indian sugar industries employ different cogeneration schemes primarily to satisfy the plant's process steam demand and generate surplus power by upgrading the steam inlet parameters. Three typical plants were chosen for the analysis. The basis for the selection of these plants is (i) the conventional captive cogeneration plant using low pressure boilers and backpressure steam turbines, (ii) the ultra modern HP/HT high efficiency extraction condensing steam turbine cogeneration plant exporting power round the year, and (iii) the largest capacity cogeneration plant in the country using combined backpressure and condensing steam turbine technology emerged from the field experience. They are as shown in figure 1,2 and 3 and are located respectively at

DKSSK—Doodhaganga Krishna Sahakari Sakkare Karkhane Ltd, Chikodi
 USWL—Ugar Sugar Works Ltd, Ugar.

In all the three plant mill-wet bagasse obtained having 50% moisture is directly burnt in the specially designed boilers to generate steam at the designed pressure and temperature. Process steam is obtained either from the exhaust of the backpressure steam turbine or through suitable extractions drawn across the condensing turbine, as shown in respective figures. Table 1 shows the major configurations and operating parameters of the three plants chosen for the analysis.

Table 1. Configurations and operating parameters of the cogeneration plants

S. No	Plant	Cane crushing capacity tcd	Steam inlet conditions		No of boilers	Steam generation rate tph	Type of steam turbines used in the plant	Power plant installed capacity kW	Power Generated kW
			P bar	T °C					
1	HSWL	5500	21	340	06	135	BPST	5750	5750
2	DKSSK	5500	65	495	01	117	CEST	20700	20700
3	USWL	10000	65	495	04	270	COMBINED BPST CEST	22800 30000	17000 27000

PERFORMANCE ANALYSIS

The cogeneration plant is complex and includes numerous pumps, fans, and blowers that are not monitored for energy consumption. Therefore the boundary of the system is the entire plant. Applying steady flow energy equations and mass balance to each of the processes in Figures 1, 2 and 3, neglecting the changes in kinetic energy and potential energy, the energy flow rates and first law efficiencies are calculated.

Each of these plants delivers process steam at 2.5 bar and 120°C for juice heating and 8 bar and 210°C for sulfur melting and centrifuge. The steam turbine has an isentropic efficiency of 85% and expands steam from inlet conditions to 2.5bar and 120°C in backpressure turbine and to 0.065bar and 40°C in condensing turbine, and turbo-generator efficiency is 92%. All systems comprise a de-aerator and it was also assumed neither boiler blow down nor de-aerator vent flows, and that the return

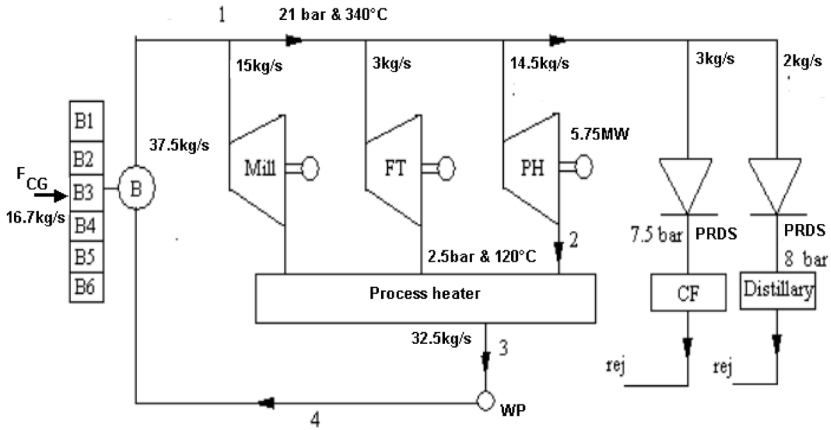


Figure 1. Captive or isolated cogeneration power plant of HSWL

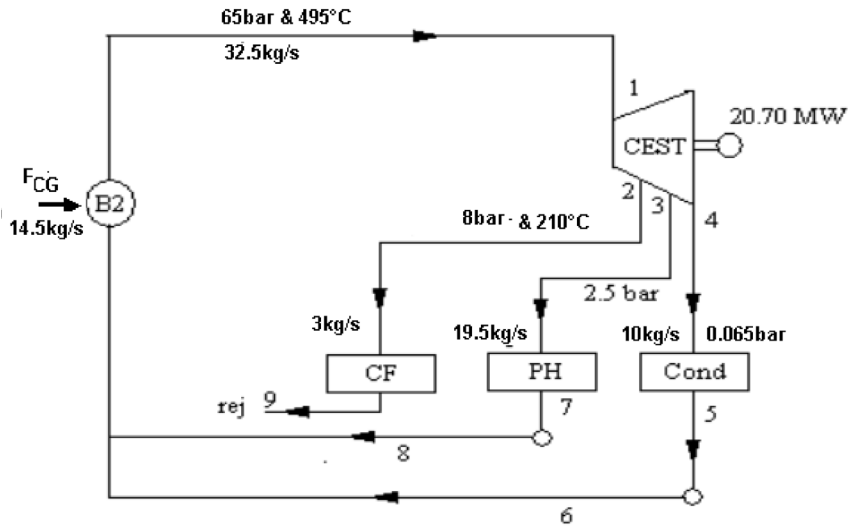


Figure 2. DKSSK cogeneration power plant

flow constituted a 100% of process flow. The mass flow rates of steam rejected in centrifugal and distillery are balanced by make up water supplied by De-mineral water plant.

Using the exergetic factor and chemical exergy of fuel bagasse, the exergy flow rates are calculated assuming steady flow conditions. Exergetic efficiency of cogeneration plant as a whole is determined. For the

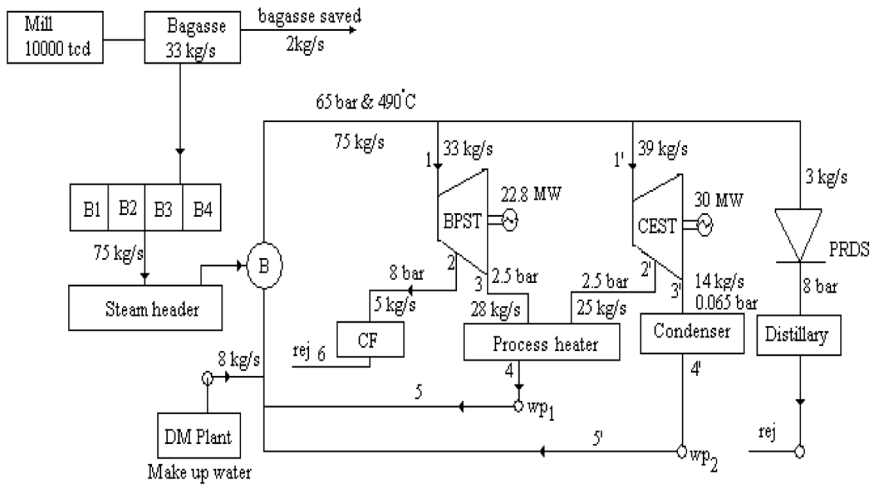


Figure 3. USWL combined cogeneration power plant

analysis reported within this article, the calorific value (LHV) and chemical exergy of mill-wet bagasse are assumed to have an average value of 7650 kJ/kg and 9890 kJ/kg respectively [9-10, 24-25]. The average steam to bagasse ratio at this pressure and temperature conditions is 2.25 [1, 2, 9].

EXERGY ANALYSIS

Exergy analysis applied to a cogeneration plant as a whole was also used to analyze performance of separate components of a power plant. The plant was divided into its subcomponents such as; boiler, turbine, condenser, process heater etc, and the following assumptions were made:

- [i] Only chemical exergy was used for fuel
- [ii] Only physical exergy was used for flue gas and steam/water

The distribution of physical exergy in the various components of plant is determined, by applying exergy balance to each component. For a

$$E_j + \left(1 - \frac{T_o}{T_i}\right) Q_j + W_{CV} + m(e_{f1} - e_{f2}) + E_{destroyed} = 0 \tag{5}$$

$$\text{Where, } e_{f1} - e_{f2} = (h_1 - h_2) - T_o(S_1 - S_2) + \frac{V_1^2 - V_2^2}{2} + g(Z_1 - Z_2) \quad (6)$$

is the specific exergy flow through components, and suffix 1 and 2 in Eqn. (6) 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 is that, the temperature surrounding the component in a cogeneration plant change substantially from place to place. For e.g. the temperature of air surrounding the boiler and condenser.

The physical exergy associated with the flow of combustion/flue gas is determined as

$$af = m_g C_{pg} T_o \left[\frac{T_g}{T_o} - 1 - \ln \frac{T_g}{T_o} \right] \quad (7)$$

Where, T_g 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 as here under.

The boiler operate between 950°C to 1000°C furnace temperature and the exhaust gas temperature is limited to 150°C. The spreader stoker furnace permits of reducing the normal excess air to 30% (instead 40-70%) and consequently of improving efficiency substantially [1]. 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 condition by supplying only the quantity of air theoretically necessary; combustion will be poor and incomplete. In order to obtain complete combustion it is necessary to supply certain excess air. Let the flow rate of combustion gas be 1 kg/s and that of bagasse be f kg/s, therefore the flow rate of air is $(1-f)$ kg/s.

$$f \times C_v = m_g C_{pg} (T_g - T_o) (C_{pa})(T_a - T_o) \quad (8)$$

On substituting the numerical values eqn (8) yields, $f = 0.1192$ kg/s, and

$1-f = 0.8808 \text{ kg/s}$.

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

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

The existing practice in sugar factories confirms the fact that about 25-30% of excess air is supplied to the boilers.

The exergy flow rates destroyed in the plant's components are determined. 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 reversible device. The general expression for exergetic efficiency of power producing/consuming device is

$$\eta_2 = \frac{W_{\text{act}}}{W_{\text{rev}}} = \frac{\eta_{\text{act}}}{\eta_{\text{rev}}} \quad (9)$$

While, equations (10) and (11) are the expressions for the second law efficiency of turbine (η_2 turbine) and boiler (η_2 boiler), respectively

$$\eta_{2 \text{ turbine}} = \frac{(W_{\text{net}})_{\text{ST}}}{w_s (ef_1 - ef_2)} \quad (10)$$

$$\eta_{2 \text{ boiler}} = \frac{w_s [(h_1 - h_8) - T_o (s_1 - s_8)]}{E_f} \quad (11)$$

However, Eqn (11) can be modified suitably for HSWL and USWL plants also.

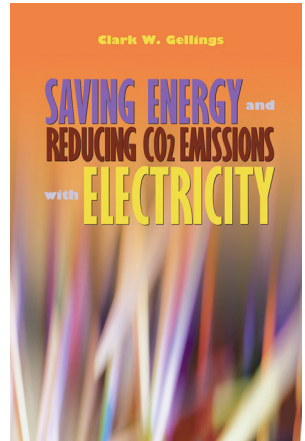
The cycle overall exergetic efficiency (η_2 cycle) is determined as

$$\eta_{2 \text{ cycle}} = \frac{\eta_{\text{TH}}}{\eta_{\text{rev}}} \quad (12)$$

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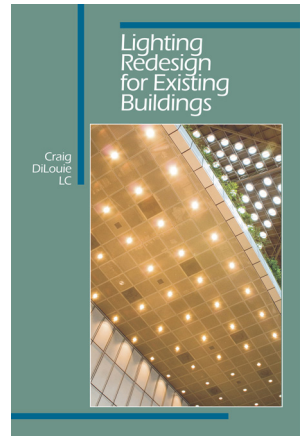
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Where, η_{TH} is based on the results of first law analysis and η_{rev} is based on the reversible Carnot cycle heat engine operating between reservoirs at T_L and T_H (298 K and 1273 K) respectively. The summary of the results obtained is given in Table 2.

Table 2. Energy and exergy flow rates, and efficiencies of bagasse-based cogeneration plants.

Cogeneration Plant			HSWL	DKSSK	USWL
Inlet steam condition		P, bar	21	65	65
		T °C	340	495	495
Process heat,	Q_{CG}	kW_{th}	89859	48933	127918
	E_Q	kW_{ex}	27063	12833	33207
Power,	W_{CG}	KW_e	5750	20700	44000
Fuel		kW_{th}	136017	110925	265838
		kW_{ex}	175845	143405	343678
EUF or η_{CG}			0.702	0.628	0.648
Exergetic efficiency plant, η_{EX}			0.187	0.234	0.225
Physical exergy of flue gases		kW_{ex}	93362	75802	182370
Exergy losses			--	--	--
Boiler, I_b		kW_{ex}	56034	33212	82103
		%	60.00	43.81	45.00
Exhaust gas I_{EXg}		kW_{ex}	3540	2882	6915
		%	3.80	3.66	3.79
Steam turbine I_{ST}		kW_{ex}	1169	5800	9019
		%	1.25	7.65	4.95
Condenser I_{cond}		kW_{ex}	--	1021	1455
		%		1.35	0.797
Others I_{other}		kW_{ex}	975	--	5671
		%	1.04	--	3.11
Total Irreversibilities I_{total}		kW_{ex}	61718	42915	105163
		%	66.10	56.48	57.67
Exergetic efficiency of boiler		η_{2b}	0.21	0.30	0.28
Turbine		η_{2t}	0.90	0.67	0.87 BPST 0.71 CEST
Cycle		η_{2cycle}	0.21	0.51	0.31 BPST 0.51 CEST

RESULTS AND DISCUSSIONS

The results reported in this article, present the exergetic performance comparison of three actual heat-matched, bagasse-based cogeneration plants, working in Belgaum, Karnataka state, India. The exergetic performances of these plants are compared with each other. These results will help the plant designers and engineers in the design improvement and thermodynamic optimization of plant configurations.

A remarkable difference is seen between energy and exergetic efficiency of the three plants considered. HSWL plant performs with highest energy efficiency and least exergetic efficiency. Whereas DKSSK plant perform with highest exergetic efficiency and least energy efficiency. Figure 4 shows the efficiency comparison of three plants.

The second law efficiency of cogeneration plant and cycle determined compare how close, thermodynamically the plant approaches the value of reversible Carnot cycle efficiency. Figure 5 shows the exergetic efficiency comparison of plant and cycle.

It can be seen from the results that, substantial exergy losses are noticed in the bagasse fired boilers in all the three plants. Therefore boiler is the major component contributing most to the plant's overall inefficiency. Depending on the steam generation pressure, the losses vary from 60 to 44%, and total exergy losses vary from 66 to 56.50%. Figure 6 shows the comparison of total exergy losses and boiler losses.

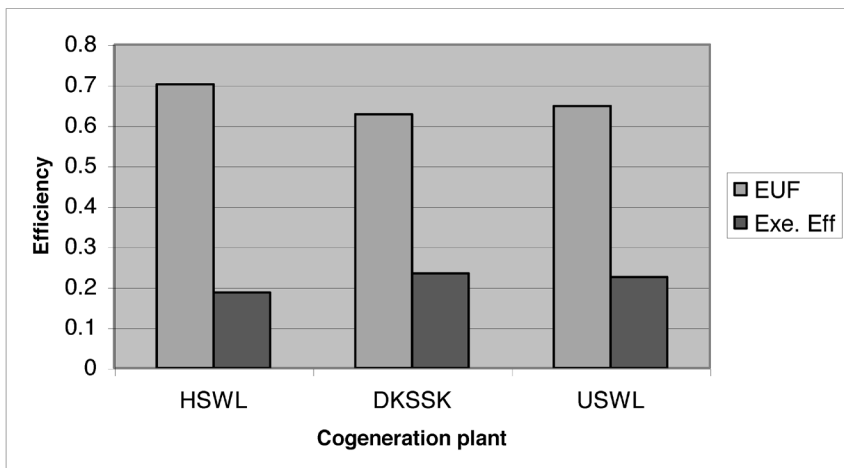


Figure 4. Efficiency comparison of plants

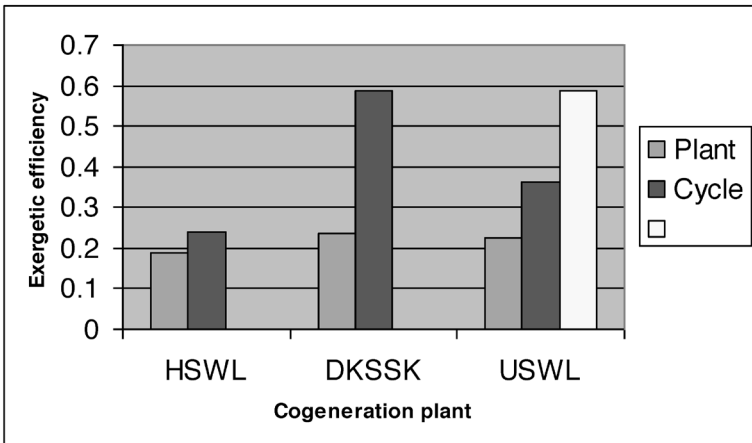


Figure 5. Exergetic efficiency comparison of plant and cycle

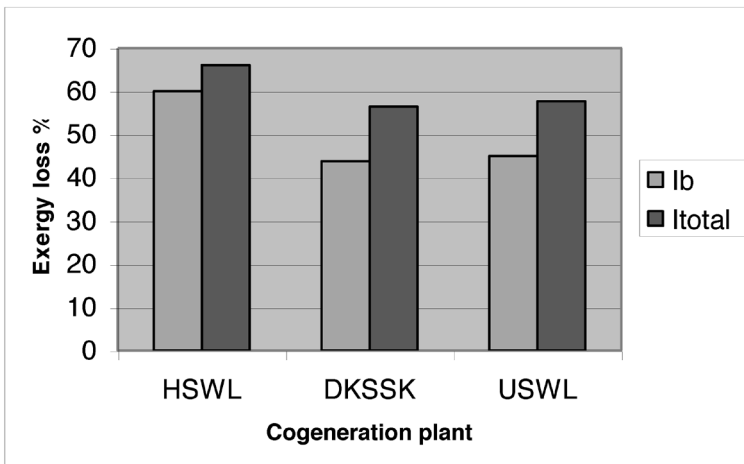


Figure 6. Comparison of total exergy losses and boiler losses.

CONCLUSIONS

The exergetic efficiency of all the three cogeneration plants considered (0.187, 0.234 and 0.225) is much lower than the normal value of overall efficiency of conventional power plant (0.35). Hence, in terms of technology development only cogeneration plants with exergetic efficiency close to that of overall efficiency of conventional power plant

should be used. However, in spite of all these considerations bagasse based cogeneration plants in the Indian sugar mills are considered as environmentally and economically attractive as they burn (waste) fuel bagasse. HSWL plant using low-pressure boilers and backpressure steam turbines was found not attractive in exergetic terms, though it attains high value of EUF. Both DKSSK and USWL plants were found moderate in terms of exergetic performance value, though both attain high value of EUF.

It was shown that the energy utilization factor or energy efficiency based on the First Law failed as a means for comparing different cogeneration schemes. The high values of energy efficiency reflects only the quantitative measure of energy flows associated with system and not the quality of energy, and only the exergy criterion can demonstrate the imperfections of these configurations.

References:

- [1] H.E. Hugot, *Handbook of Cane Sugar Engineering*, Elsevier, 3rd edition, 1986.
- [2] Sai V. Gollakota and P.R.K. Sobhanbabu, *Handbook on Sugar Mill Cogeneration in India*, New Delhi, Winrock international, 1st edition, 2002.
- [3] Sanjay Mande and V.N. Kishore, Technological options for combined heat and power systems, *Procee of Cogen India 96*, New Delhi, TERI, 1996, pp 163-170.
- [4] J. Raghuram and Rangan Banerjee, Energy and cogeneration targeting for a sugar factory, *Applied Thermal Engineering*, Vol. 23, 2003, pp 1567-1575.
- [5] Mike Inkson and Misplon, B., *Cogeneration thermodynamics revisited*, *International Sugar Journal*, Vol.107, issue 1279, 2005, pp 390-403.
- [6] C.N. Nath, Steam turbine options for optimizing cogeneration applications, *Procee of Cogen India 96*, New Delhi, TERI, 1996, pp 117-126.
- [7] M. Siddharth Bhat and N. Rajkumar, Mapping of combined heat and power systems in cane sugar industry, *Applied Thermal Engineering*, Vol.21, 2001, pp 1707-1719.
- [8] A.K. Srivatsav, Selection of steam parameters for cogeneration, *Procee of Cogen - India 96*, New Delhi, TERI, 1996, pp 158-162.
- [9] Charles Mbohwa and Suichi Fukuda, Electricity from bagasse in Zimbabwe, *Bio-mass and Bioenergy*, Vol.25, issue.2, 2003, pp 197-207.
- [10] Charles Mbohwa, Bagasse energy cogeneration potential in the Zimbabwean Sugar Industry, *Renewable Energy*, Vol.28, 2003, pp 191-204.
- [11] J.H. Horlock, *Cogeneration-Combined heat and Power-Thermodynamics and Economics*, Malabar, Florida, Krieger Publishing Company, 12th edition, 1997.
- [12] M.A. Korobitsyn, *Industrial Cogeneration*, University of Twente, Netherland, 1998, pp 65-82.
- [13] Ivar S. Ertesvag, Exergetic comparison of efficiency indicators for combined heat and power (CHP), *Energy* 2007, Vol. 32, pp 2038-2050.
- [14] T.J. Kotas, *The Exergy Method of Thermal Plant Analysis*, London, Butterworths, 1st edition, 1985.
- [15] A. Bejan, *Advanced Engineering Thermodynamics*, New York, John Wiley and Sons, 1st edition, 1988.

- [16] www.educogen.com, *The European Educational Tool On Cogeneration*, 2nd edition, Dec 2001.
- [17] Marc A. Rosen, M.N. Le and Ibrahim Dincer, Efficiency analysis of a cogeneration and district energy system, *Applied Thermal Engineering*, Vol. 25, 2005, pp 147-159.
- [18] A. Khaliq and K. Choudhary, 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, 2007, pp 1004-1011.
- [19] P.K. Nag, *Basic and Applied Thermodynamics*, New Delhi, TMG, 1st edition, 2002.
- [20] Margaret B. Bailey, et al, Exergetic, thermal and externalities analysis of a cogeneration plant, *Solar Energy Engineering*, Vol. 128, 2006, pp 98-103.
- [21] M.A. Habib, Thermodynamic analysis of the performance of cogeneration plants, *Energy*, Vol. 17, issue 5, 1992, pp 485-491.
- [22] Tamer Yilmaz, Optimization of cogeneration systems under alternative performance criteria, *Energy Conversion and Management*, Vol. 45, 2004, pp 939-945.
- [23] Yasin Ust, Bahri Sahin and Ali Kodal, Optimization of a dual cycle cogeneration system based on a new exergetic performance criterion, *Applied Energy*, Vol. 84, 2007, pp 1079-1091.
- [24] L.A.B. Cortez and E.O. Gomez, A method for exergy analysis of sugar cane bagasse boilers, *Braz. J. of Chemical Engineering*, Vol. 15, issue 1, 1998, pp 1-13.
- [25] B. Vijayaraj, R. Saravanan and S. Renganarayanan, Energy and exergy analysis of sugar cane bagasse drying, *Procee of Advances in Energy Research-AER-2006*, Chennai, Anna University, pp 77-82.

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