Performance Analysis of Cogeneration Plants using Extraction Condensing Steam Turbine

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In the present work, different cogeneration systems, in particular extraction condensing steam turbines, were studied in the light of thermodynamic analysis and different performance criteria. These systems were (a) continuous district heating only; (b) continuous feed heating stops at T_u; and (c) continuous district and feed heating only. Performance evaluation of these systems with respect to energy utilization factor (EUF) and efficiency were carried out with simple computer programming at supply steam pressures of 65 bar, 50 bar and 20 bar with variation of heat power ratio (λ_{CG}). Computational results of thermodynamic performance are presented in the form of graphs (a) efficiency against λ_{CG}; and (b) EUF against λ_{CG}. As compared to the cogeneration systems under study, continuous district and feed heating shows best performance with respect to EUF and efficiency.

Keywords: Cogeneration plant; Performance analysis

INTRODUCTION

The cogeneration system is a proven technology for process industries where heat and electrical power are the major energy inputs. In today's economic crisis where 'focus on energy conservation' and 'concern for environment' are buzzwords, the cogeneration system is an important technology. The economic viability of a cogeneration plant is largely dictated by a careful balancing of heat and power output. For industries where the requirement for steam for process also exists, *eg*, fertilizer, paper, petrochemical and sugar industries, cogeneration of power and process steam is the obvious choice. By the careful study of the thermodynamic layout of the system, the gains are realized.

Inlet steam parameters normally used for small industrial power plants vary between 40 bars to 106 bars in pressure and $400^\circ C$ to $520^\circ C$ in temperature. There are various combinations possible within these limits of pressures and temperatures. Selection of these parameters is normally dependent upon the fuel and the type of the boiler used in the plant. One more aspect that has to be analyzed in detail is the exhaust steam conditions which vary from industry to industry depending upon their process steam requirements.

In cogeneration applications, where large quantities of steam are extracted for the process, it is essential to check whether the extracted steam can be used directly in the process without a further loss of power. Because of pressure reducing and desuperheating station (PRDS) extraction conditions are dependent upon inlet parameters and turbine efficiency. Hence, it is important to determine these parameters in such a manner that the power output is maximum within acceptable limits of extraction pressure and temperature to suit the process applications.

The concepts of thermodynamic analysis of cogeneration plants are given by Horlock[1]. The present study relates to the performance analysis of cogeneration plants concerning the extraction type steam turbine operations at different inlet steam pressures and with constant condenser pressure. The performance parameters, *ie,* energy utilization factor (EUF) and overall efficiency were analyzed with useful heat to work ratio (λ_{CG}). The calculations were carried out at three different conditions:

Inlet at 20 bar, $350^\circ C$, Exit at 0.07 bar, $39^\circ C$

Inlet at 50 bar, $400^\circ C$, Exit at 0.07 bar, $39^\circ C$

Inlet at 65 bar, $450^\circ C$, Exit at 0.07 bar, $39^\circ C$

THERMODYNAMIC ANALYSIS

In a big steam turbine plant, steam may be extracted for both feed heating (FH) and district heating (DH). Figure 1 shows this practice. General extraction for both feed heating and district heating will be under taken at the low pressure, but extraction for feed heating alone will be taken a higher-pressure levels. A simple analysis of this cycle based on a particular assumption for the turbine expansion line is that the difference between local steam enthalpy (h) and the enthalpy of water at the same pressure (h_f) is constant (equal to β) which is equal to area on *T-s* diagram giving corresponding enthalpy difference.

That this is quite a good assumption may be illustrated by modification of the Rankine cycle to allow the steam expansion in the turbine to take place according to the condition that β = constant, rather than along an isentropic (Figure 2). The

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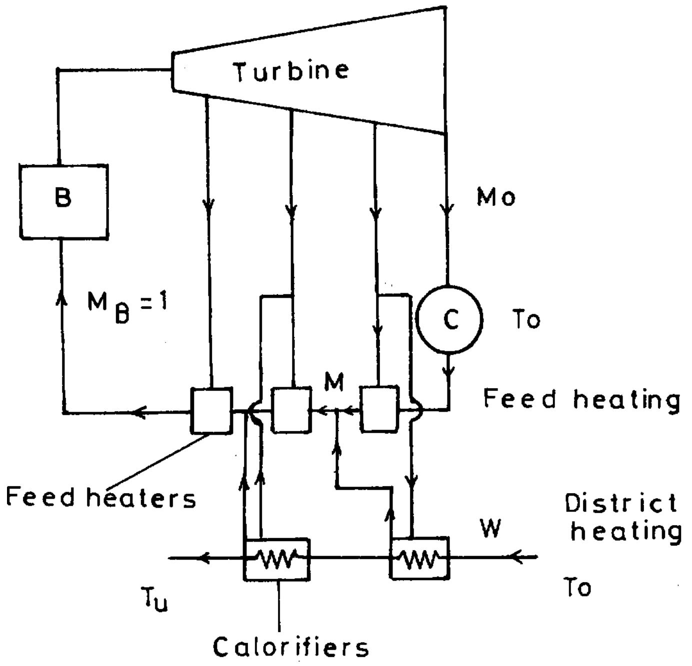
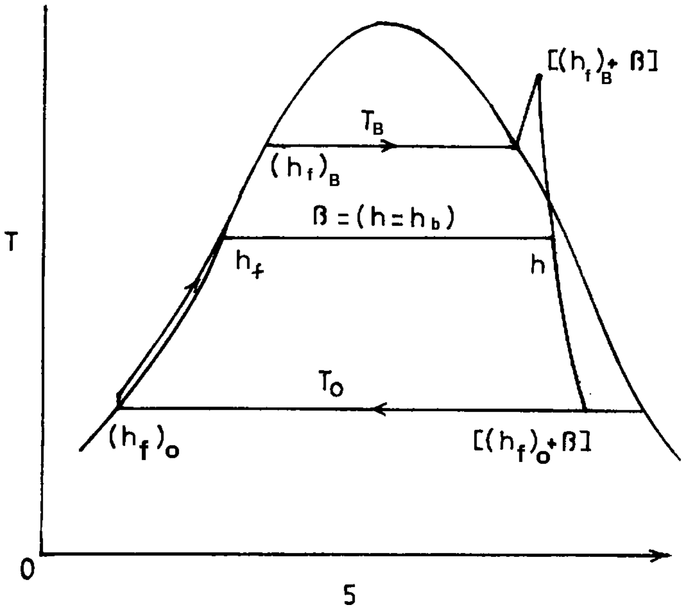


Figure 1 Combined district and feed heating



enthalpy drop in the turbine is equal to the difference between the enthalpy of saturated water at the boiler pressure $(h_f)_B$ and the enthalpy of the saturated water at the condenser pressure $(h_f)_O$. Hence, the enthalpy drop in the turbine is equal to the area on the *T-s* diagram giving enthalpy difference $\alpha = (h_f)_B - (h_f)_O$. In terms of β = constant and the simple expressions are derived[1] for the change in performance of the plant if steam is bled for district heating alone and for district and feed heating.

To simplify the analysis (and subsequent numerical calculations), it is assumed that the useful temperature T_u (for district heating) is the arithmetical mean of the temperatures T_O (condenser temperature) and T_B (boiler temperature).

Comparative thermodynamic performance analysis is made for the cycle with 'continuous bleed' (for district and feed heating) taking the following three cases in particular. A simple computer program was used incorporating the corresponding equations[1] to calculate the performance parameters efficiency (η_c), energy utilization factor (EUF) in terms of heat to power ratio (λ_{CG}).

Case 1

Continuous district and feed heating takes place between T_O and T_u with subsequent feed heating only, from T_O to T_B. In this case, the efficiency and EUF are expressed as

$$\eta_{CG} = \frac{\left(1 - e^{-\alpha/\beta}\right)}{(\lambda_{CG} + 1) + (2\beta\lambda_{CG}/\alpha)\left(e^{-\alpha/2\beta} - 1\right)}$$

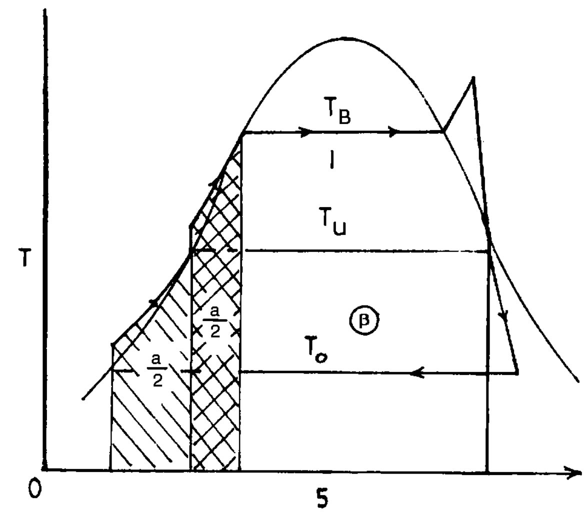


Figure 2 Basic cycle showing 'constant β' turbine expansion line

$$(\mathrm{EUF})_{CG} = \frac{(\lambda_{CG} + 1) + \left(e^{-\alpha/2\beta} - 1\right)}{(\lambda_{CG} + 1) + (2\beta\lambda_{CG}/\alpha)\left(e^{-\alpha/2\beta} - 1\right)}$$

Case 2

If feed heating stops at T_u (in a cycle with feed and district heating between T_O and T_u), the efficiency and EUF are given by equations

$$\eta_{CG} = \frac{\left(1 - e^{-\alpha/2\beta}\right) + (\alpha/2\beta)}{\left[1 + (\alpha/2\beta)\right]\left[1 + \lambda_{CG} - (2\beta\lambda_{CG}/\alpha)\left(1 - e^{-\alpha/2\beta}\right)\right]}$$

$$(\mathrm{EUF})_{CG} = \frac{(\lambda_{CG} + 1) + \left[(\alpha/2\beta) + \left(1 - e^{-\alpha/2\beta}\right)\right]}{\left[1 + (\alpha/2\beta)\right]\left[1 + \lambda_{CG} - (2\beta\lambda_{CG}/\alpha)\left(1 - e^{-\alpha/2\beta}\right)\right]}$$

Case 3

If there is no feed heating, but continuous district heating between T_O and T_u, then the expressions used are

$$\eta_{CG} = \frac{(\alpha/\beta)}{[1+(\alpha/\beta)] + (\lambda_{CG}\,\alpha/4\beta)}$$

$$(EUF)_{CG} = \frac{(1+\lambda_{CG})(\alpha/\beta)}{[1+(\alpha/\beta)] + (\lambda_{CG}\,\alpha/4\beta)}$$

RESULTS AND DISCUSSIONS

The assumptions made for evaluating the performance of these cogeneration plants using extraction type steam turbine are:

Boiler efficiency	: η_B	=	0.90
Convention plant efficiency	: η_C	=	0.40
Efficiency of cogeneration	: η_{CG}	=	0.23
Efficiency of the lower cycle	: η_L	=	0.10
Efficiency of the upper cycle	: η_H	=	0.33
Heat load	: λ_D	=	0.10
Heat/work ratio	: λ_{CG}	=	1 to 5
Constant added to compensate heat loss	: ϕ	=	0.10

For different values of steam inlet pressure (65 bar, 50 bar and 20 bar) keeping the condenser pressures constant (*ie,* 0.007 bar) enthalpy drop values were taken from the steam tables. The values of λ_{CG} ranging from 1 to 5 were considered. Performance results were plotted with respect to EUF against λ_{CG} and efficiency against λ_{CG} as shown in Figures 3-8. Performance evaluation of the cogeneration systems are discussed with respect to (i) efficiency against λ_{CG}; and (ii) EUF against λ_{CG}.

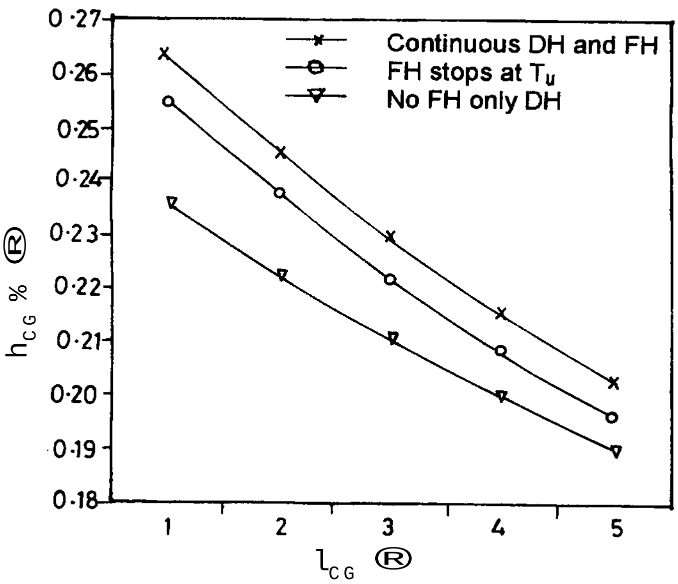


Figure 3 **Variation of efficiencies with heat to power ratio for an inlet pressure of 20 bar**

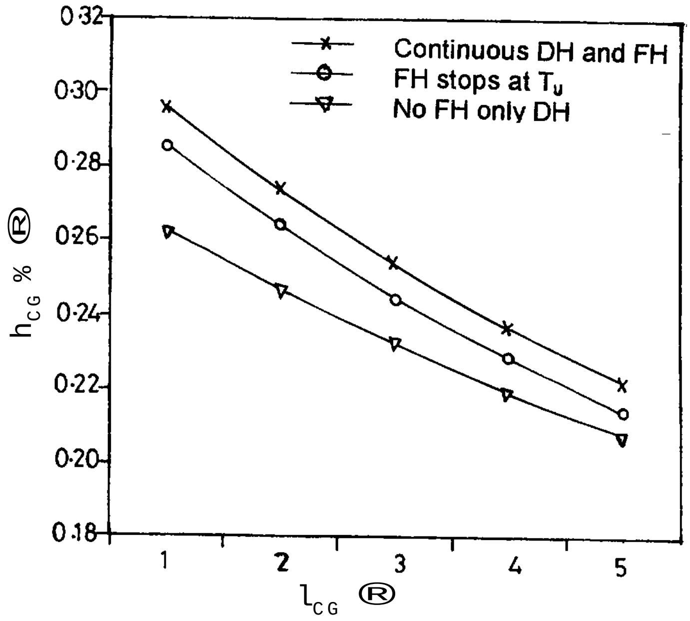


Figure 4 **Variation of efficiencies with heat to power ratio for an inlet pressure of 50 bar**

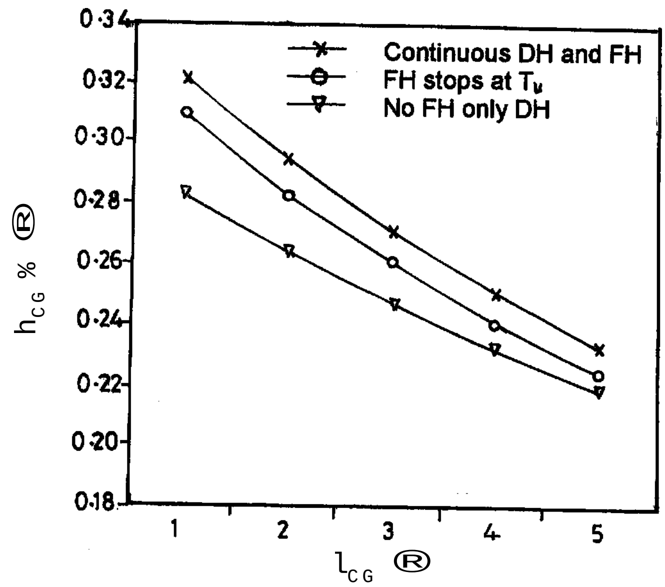


Figure 5 **Variation of efficiencies with heat to power ratio for an inlet pressure of 65 bar**

Efficiency against λ_{CG}

Basic Cycle

Basic cycle efficiency remains constant with respect to the values of λ_{CG}, since, it depends only on enthalpy drop (α and β) this being a non-cogeneration plant. As the inlet pressure increases, the basic cycle efficiency increases.

Continuous District Heating Only

When there is only district heating and no feed heating, the efficiency will be slightly higher when compared with the previous case. The efficiency reduces as the value of λ_{CG} increases and increases slightly with the increase in the inlet

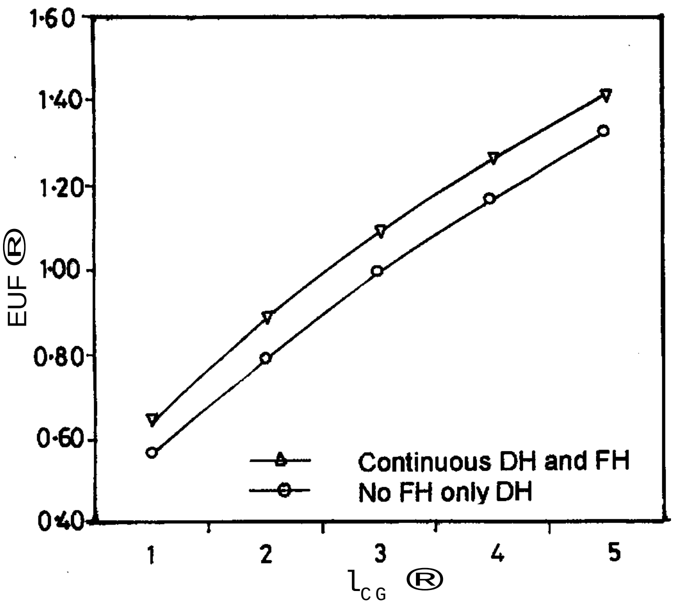


Figure 6 Variation of energy utilisation factor with heat to power ratio for an inlet pressure of 20 bar

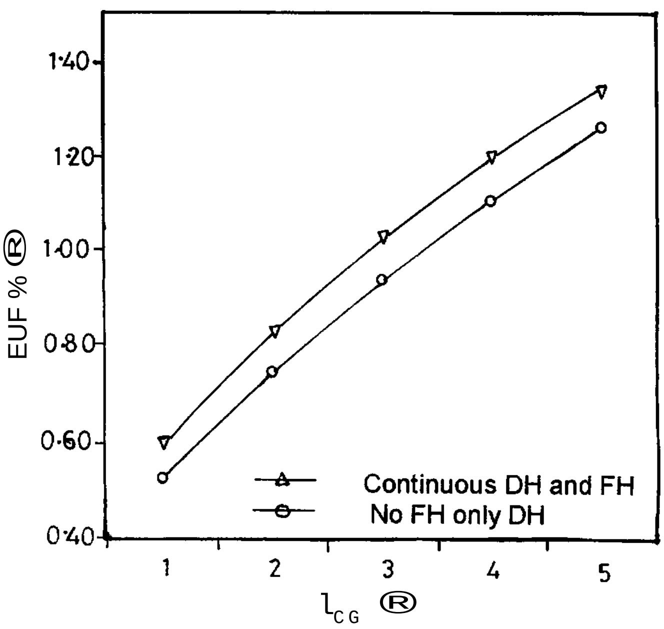


Figure 7 Variation of energy utilisation factor with heat to power ratio for an inlet pressure of 50 bar

pressure as seen from Figure 3. At a particular value of $\lambda_{CG} = 2$, the reduction in efficiency is 10.28% (at 65 bar), 9.88% (at 50 bar) and 9.25% (at 20 bar) taking continuous DH and FH as base line for comparison as shown in Table 1.

Continuous Feed Heating up to T_u

When the feed heating stops at T_u, the efficiency against λ_{CG} curve lies between the curve representing continuous district heating only and continuous district and feed heating. Here, also the efficiency decreases as λ_{CG} increases. For higher inlet pressures the efficiency will be slightly higher as seen from Figure 4. At a particular value of $\lambda_{CG} = 2$, the reduction in

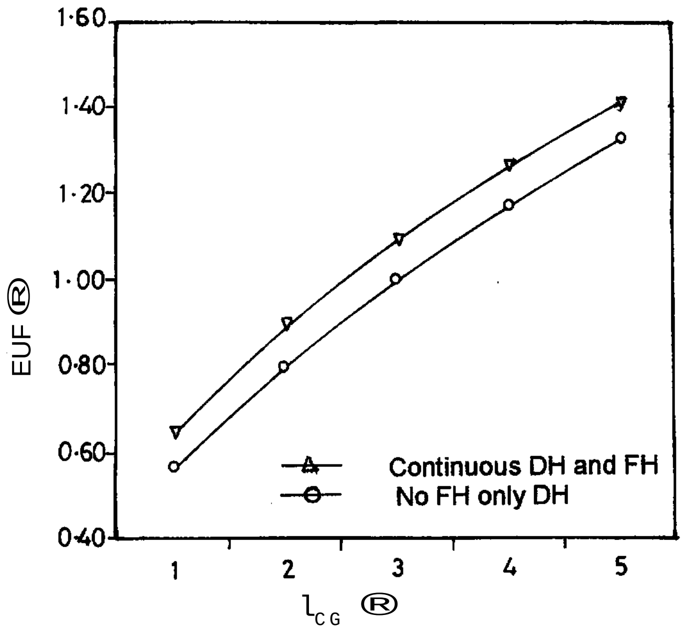


Figure 8 Variation of energy utilisation factor with heat to power ratio for an inlet pressure of 65 bar

Table 1 Percentage reduction in EUF and efficiency values of different cogeneration systems with respect to continuous DH and FH at $\lambda_{CG} = 2$

Systems	Inlet Pressures					
	65 bar		50 bar		20 bar	
	EUF, %	η, %	EUF, %	η, %	EUF, %	η, %
Continuous DH only	10.28	10.28	9.88	9.88	9.24	9.25
Continuous feed heating stops at T_u	10.28	3.87	9.88	3.54	9.24	3.18

efficiency is 3.87% (at 65 bar), 3.54% (at 50 bar) and 3.18% (at 20 bar) taking continuous DH and FH as base line for comparison (Table 1).

Continuous District and Feed Heating

The efficiency will be higher when compared with all other cases when there is continuous district and feed heating. The efficiency decreases as the value of λ_{CG} increases. The efficiency will be higher for higher inlet pressures (Figure 5).

EUF against λ_{CG}

Continuous District Heating Only

When there is only district heating, the EUF will be slightly higher which further increases with λ_{CG} and also with pressure. At 20 bar inlet pressure, EUF reaches the maximum value of about 4, at 65 bar inlet pressure, EUF reaches the maximum value of 1 when the λ_{CG} value is about 3 (Figure 6). For $\lambda_{CG} = 2$, the reduction in EUF is 10.28% at 65 bar, 9.88% at 50 bar and 9.24% at 20 bar as shown in Table 1 with respect to DH and FH as base line.

Continuous Feed Heating up to T_u

From computational results under the 3 steam supply pressure conditions (65 bar, 50 bar and 20 bar) the system 'feed heating stops at T_u' shows exactly equivalent performance with variation of λ_{CG} of continuous district heating (Figure 7). It is seen from Table 1 that the percent reduction in EUF at these pressures are same in both cases of DH only and FH up to T_u at $\lambda_{CG} = 2$.

Continuous District and Feed Heating

When there is continuous district and feed heating, the EUF will be higher than all other cases, which further increases with λ_{CG} and pressure. At an inlet pressure of 20 bar, EUF reaches the maximum value of 1, when the λ_{CG} value is about 3.5. At a higher inlet pressure, say at 65 bar, the EUF reaches the maximum value of 1, when λ_{CG} value is about 2.5 (Figure 8).

CONCLUSIONS

1. Higher efficiencies and higher EUF's can be obtained by increasing the steam pressure.

2. With increase of λ_{CG} (ranging from 1 to 5) EUF increases and efficiency decreases in all cases of cogeneration plants under considerations.

3. It is observed that continuous district heating (DH) and feed heating (FH) gives best performance with respect to EUF and efficiency.

4. The case of the feed heating up to T_u gives relatively lower values of EUF and efficiency as compared to continuous district heating and feed heating.

5. The case of continuous district heating only shows lower values of EUF and efficiency as compared to feed heating up to T_u.

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