THE AMERICAN SOCIETY OF MECHANICAL ENGINEERS
345 E. 47th St., New York, N.Y. 10017

93-GT-252

PERFORMANCE CRITERIA FOR GAS TURBINE COGENERATION PLANT

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ABSTRACT

With current gas turbine practice up to two-thirds of the energy available in the fuel is lost in the form of unused heat, By making practical use of this waste heat in a recovery boiler to produce steam for district heating or process applications it is possible to reduce the energy wastage to as little as 10 percent.

In this paper different performance criteria for assessment of a gas turbine cogeneration plant (GTCP) have been defined and compared with each other, Also, the practical range of performance criteria have been determined.

NOMENCLATURE

$\dot{A}_f$ = availability rate of fuel input (KW)

$\dot{A}_p$ = availability rate of process steam (KW)

$\dot{C}_e$ = electrical energy price

$\dot{C}_h$ = process heat price

$\dot{Q}_f$ = energy rate of fuel input (KW)

$\dot{Q}_{fe}$ = energy rate of fuel input in a " Power only" plant (KW)

$\dot{Q}_{fp}$ = energy rate of fuel input in a " heat only" boiler (KW)

$\dot{Q}_g$ = turbine exhaust gas energy rate (KW)

$\dot{Q}_p$ = process steam energy rate (KW)

R_{ah} = process steam availability to process heat ratio

R_{pa} = power to process steam availability ratio

R_{ph} = power to process heat ratio

R_v = ratio of process heat price to electrical energy price

To = temperature of the environment (taken as 25 °C)

T_g = turbine exhaust gas temperature(°C)

T_s = Stack gas temperature(°C)

$\dot{W}_e$ = electrical power (KW)

η_1 = first law efficiency defined by Eq. (1)

η_2 = Second law effícency defined by Eq. (10)

η_B = "Heat only" boiler efficiency (taken as 0.85)

η_{cc} = Combined efficiency of separate generation of power and heat defined by Eq. (23)

η_e = thermal efficiency of a conventional "Power only" plant (taken as 0.40)

η_{eco} = economical efficiency defined by Eq. (17)

η_{pg} = Power generation efficiency defined by Eq. (27)

η_{RB} = recovery boiler efficiency defined by eq. (6)

η_w = Work efficiency defined by Eq. (4)

Presented at the International Gas Turbine and Aeroengine Congress and Exposition
Cincinnati, Ohio — May 24–27, 1993

INTRODUCTION

High temperature exhaust gas is one of the distinguishing features of a gas turbine simple cycle. So, exhaust gas from a gas turbine plant contains a considerable portion of the fuel energy. Clearly, re-using of exhaust gas energy can improve gas turbine cycle performance significantly. There are several methods for recovering of exhaust gas energy, one of them is to generate steam in a recovery boiler for district heating or process applications. Combined production of work and heat is called cogeneration.

Figure 1 shows a GTCP flow diagram.

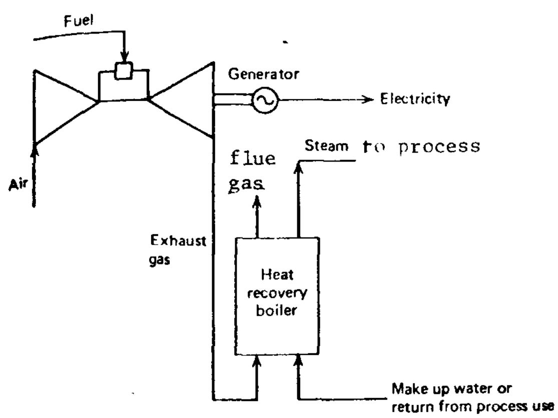

Fig. 1 Flow diagram of a gas turbine cogeneration system

PERFORMANCE CRITERIA FOR A COGENERATION PLANT

Based on different point of views, several parameters can be defined for assessment of a cogeneration system performance. Some of these are discussed in following sections:

Performance Prediction of a Cogeneration Systme From First Law Viewpoint

Applying the first law viewpiont or energy balance method for performance prediction of a cogeneration systme such as GTCP suffers from an inherent disadvantage. Because, based on this viewpiont, there is no qualitative difference between heat and work and both have the same value. So, this viewpiont though may predict correctly the overall performance of a "Power only" producing system but is unable to predict realistically the performance of a cogeneration system. The first law effeciency of a cogeneration system which is also called energy utilization efficiency is defined as

$$\eta_1 = \frac{\dot{W}_e + \dot{Q}_p}{\dot{Q}_f} \qquad (1)$$

The power to heat ratio is given by

$$R_{ph} = \frac{\dot{W}_e}{\dot{Q}_p} \qquad (2)$$

Now, inserting Eq.(2) into Eq. (1) gives

$$\eta_1 = \frac{\dot{W}_e}{\dot{Q}_f}\left(1 + \frac{1}{R_{ph}}\right) \qquad (3)$$

The work efficiency of a cogeneration system is defined by

$$\eta_w = \frac{\dot{W}_e}{\dot{Q}_f} \qquad (4)$$

So, Eq. (3) Can be written in the form

$$\eta_1 = \eta_w\left(1 + \frac{1}{R_{ph}}\right) \qquad (5)$$

The efficiency of a non-fired waste heat recovery boiler is defined as

$$\eta_{RB} = \frac{\dot{Q}_p}{\dot{Q}_g} = \frac{\dot{Q}_p}{\dot{Q}_f - \dot{W}_e} \qquad (6)$$

Inserting Eq. (2) and Eq. (4) into Eq. (6) gives

$$\eta_{RB} = \frac{\eta_w}{R_{ph}(1-\eta_w)} \qquad (7)$$

or

$$R_{ph} = \frac{\eta_w}{\eta_{RB}(1-\eta_w)} \qquad (8)$$

Now, introducing Eq. (8) into Eq. (5) gives

$$\eta_1 = \eta_w + \eta_{RB}(1-\eta_w) \qquad (9)$$

Eq. (9) shows that η_1 depends on both η_w and η_{RB}. Theoretically, when η_{RB} tends to 1, η_1 will also tend to 1 regardless of the value of η_w.

Performance Prediction of a Cogeneration System From Second Law Viewpiont

Performance prediction of a cogeneration system from second law viewpoint or availability balance method is based on this fact that work is an energy with higher quality comparing to thermal energy, and also the quality of a given quantity of thermal energy depends on its availability . So, in the second law analysis of a cogeneration system, the availability and not the energy of process steam is considered as one of the plant useful products. The second law efficiency of this system is defined as

$$\eta_2 = \frac{\dot{W}_e + \dot{A}_p}{\dot{A}_f} \tag{10}$$

The power to process steam availability ratio is given by

$$R_{pa} = \frac{\dot{W}_e}{\dot{A}_p} \tag{11}$$

Now, introducing Eq. (11) into Eq. (10) gives

$$\eta_2 = \frac{\dot{W}_e}{\dot{A}_f}\left(1 + \frac{1}{R_{pa}}\right) \tag{12}$$

Since the fuel availability and fuel heating value are almost the same [4], then, Eq. (12) can be written in the form

$$\eta_2 = \eta_w\left(1 + \frac{1}{R_{pa}}\right) \tag{13}$$

The process steam availability to its energy ratio is given by

$$R_{ah} = \frac{\dot{A}_p}{\dot{Q}_p} = \frac{R_{ph}}{R_{pa}} \tag{14}$$

For a typical GTCP with process steam in the form of saturated vapor, R_{ah} is in the range of 0.25 and 0.40 [2] , so, if we assume an average value of $\frac{1}{3}$ for R_{ah} then Eq. (13) can be written as

$$\eta_2 = \eta_w\left(1 + \frac{1}{3R_{ph}}\right) \tag{15}$$

Now, introducing Eq. (8) into Eq.(15) gives

$$\eta_2 = \eta_w + \frac{1}{3}\eta_{RB}(1-\eta_w) \tag{16}$$

Performance Prediction of a Cogeneration System Based on Economical Considerations.

From economical point of view a performance criterion which we call it economical efficiency can be defined as

$$\eta_{eco} = \frac{\dot{W}_e + R_v\dot{Q}_p}{\dot{Q}_f} \tag{17}$$

Where R_v is the ratio of process heat price to electrical energy price and is given by

$$R_v = \frac{C_h}{C_e} \tag{18}$$

The Eq. (17) can also be written in the form

$$\eta_{eco} = \eta_w\left(1 + \frac{R_v}{R_{ph}}\right) \tag{19}$$

Practically the process heat production price is always less than electricity production price and R_v can approximately be supposed eaual to $\frac{1}{3}$. So, we have

$$\eta_{eco} = \eta_w\left(1 + \frac{1}{3R_{ph}}\right) \tag{20}$$

Comparing Eq. (20) with Eq. (15) shows that the second law efficiency is almost equal to economical efficiency. So, we arrive at this important result that the second law efficiency of a cogeneration system represents properly the economical performance of this system. Whereas, the first law efficiency of a cogeneration system economically gives a very optimistic and unrealistic picture from this system.

Efficiency Increase Ratio

Another performance criterion developer for cogeneration system involves comparison between first law or fuel utilisation efficiency of a cogeneration system and combined efficiency that can be defined for separate generation of power and heat. The thermal efficiency of a conventional "Power only" plant is defined as

$$\eta_e = \frac{\dot{W}_e}{Q_{fe}} \tag{21}$$

Also, The efficiency of a "heat only" boiler is

$$\eta_B = \frac{\dot{Q}_p}{Q_{fp}} \tag{22}$$

The combined efficiency can be defined as

$$\eta_{cc} = \frac{\dot{W}_e + \dot{Q}_p}{Q_{fe} + Q_{fp}} \tag{23}$$

Inserting Eqs. (21) ,(22) , and (2) into Eq.(23) gives

$$\eta_{cc} = \frac{R_{ph}+1}{\frac{R_{ph}}{\eta_e}+\frac{1}{\eta_B}} \qquad (24)$$

Combination of Eq. (8) and Eq. (24) yields

$$\eta_{cc} = \frac{\eta_w+\eta_{RB}(1-\eta_w)}{\frac{\eta_w}{\eta_e}+\frac{\eta_{RB}(1-\eta_w)}{\eta_B}} \qquad (25)$$

The efficiency increase ratio is given by

$$\frac{\Delta\eta}{\eta_{cc}} = \frac{\eta_1-\eta_{cc}}{\eta_{cc}} = \frac{\eta_w}{\eta_e}+\frac{\eta_{RB}(1-\eta_w)}{\eta_B}-1 \qquad (26)$$

This ratio is also equal to fuel saving ratio i.e. the ratio of the fuel saving in cogeneration systme to the fuel required in the separate generation of heat and work.

The Efficiency Of Power Generation In A Cogeneration System

Usually electrical power can practically be obtained from a power utility, but steam can not. Therefore, the quantity of fuel necessary is at least that which would be consumed in a simple steam boiler for generating the process steam. The additional fuel necessary for generating electric power is therefore given by the difference between the fuel consumption of the cogeneration system and that of the steam boiler. Based on this viewpoint, an efficiency for power generation in a cogeneration system can be defined as

$$\eta_{pg} = \frac{\dot{W}_e}{\dot{Q}_f-\frac{\dot{Q}_p}{\eta_B}} \qquad (27)$$

Eq.(27)can be written in the form

$$\eta_{pg} = \frac{1}{\frac{1}{\eta_W}-\frac{1}{\eta_B}\cdot\frac{1}{R_{ph}}} \qquad (28)$$

Inserting Eq.(8) into Eq. (28) yields

$$\eta_{pg} = \frac{\eta_W}{1-(1-\eta_W)\frac{\eta_{RB}}{\eta_B}} \qquad (\eta_{RB}<\eta_B) \qquad (29)$$

DISCUSSTION OF RESULTS

In this section the effects of recovery boiler efficiency (η_{RB}) and work efficiency (η_W) on performace parameters of a GTCP are discussed.

Fig. 2 shows the variation of a GTCP first and second law efficiencies with η_{RB} for three different values of η_W. Clearly, we observe that the second law efficiency of a GTCP is considerably less than its first law efficiency, Also, both efficiencies increase with increase in η_{RB} and η_W, of course, the effect of η_{RB} on η_1 is much higher than that on η_2. The practical range of η_1 and η_2 can be determined from Eq. (9). and Eq. (16) respectively, or from Fig.2, if we indicate η_W and η_{RB} ranges. The range of η_W for today's gas turbine power plants is 0.25-0.32 and the range of η_{RB} may be known if we write the Eq.(6) in the form

$$\eta_{RB} = \frac{T_g-T_s}{T_g-T_o} \qquad (30)$$

Turbine exhaust gas temperature is in the range of 400 and 600 °C. Also, stack gas temperature, depending on the quality of fuel, may be in the range of 110-160 °C. Therefore, η_{RB} will be in the range of 0.65 and 0.82. Consequently, the practical range of η_1 and η_2 are obtained as 0.75-0.9 and 0.40-0.55 respectively. So, the GTCP performance from first law viewpoint is much better than that from second law viewpoint. In a word, first law viewpoint overestimates considerably a GTCP performance.

Figs 3,4, and 5 show performance criteria variations versus η_{RB} respectively for $_W$ of 0.25, 0.30, and 0.32.

From these figures or from Eq.(8) we can conclude that R_{ph} is in the range of 0.40 and 0.85, a GTCP is a

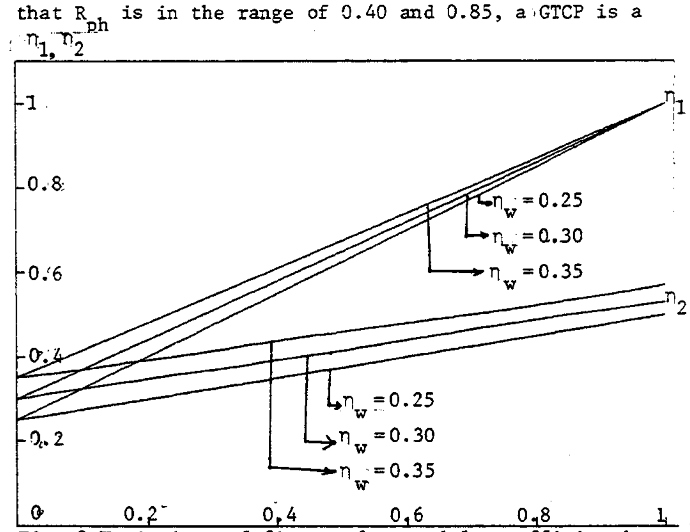

Fig. 2 Variations of first and second laws efficiencies versus recovery boiler efficiency.

desirable choice for cases in which the heat demand is 1.20-2.5 times of power demand.

The efficiency increase ratio or fuel saving ratio is a suitable criterion when we would like to compare a cogeneration system performance with performance of the separate generation of heat and work. Eq.(29) shows that practically for a GTCP, this ratio is in the range of 0.20 and 0.53. Also, these figures indicate that the separate generation is economical only when $_{RB}$ is very low (η_{RB}=0.4). However this is not a practical case.

The efficiency of power generation in a cogeneration in a cogeneration system (η_{pg}) is a suitable parameter if we would like to compare a cogeneration system performance with producing the process steam in site and purchasing the electricity from a power utility. This parameter can also be used in evaluating the electricity production cost in a cogeneration system. Eq.(29) shows that practically η_{pg} for a GTCP is in the range of 0.60 and 1.

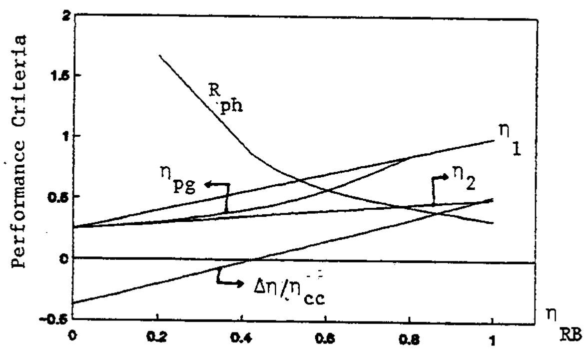

Fig. 3 Performace criteria versus recovery boiler efficiency for η_w=o.25

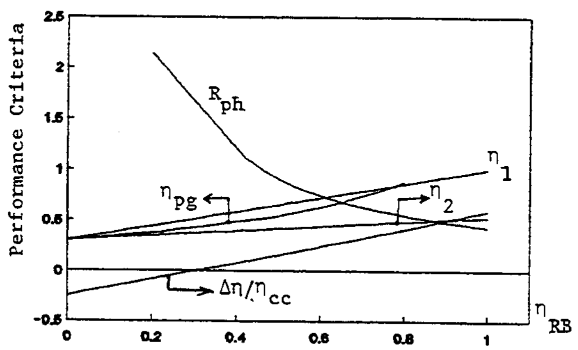

Fig. 4 Performance Criteria versus recovery boiler efficiency for η_w=o.30

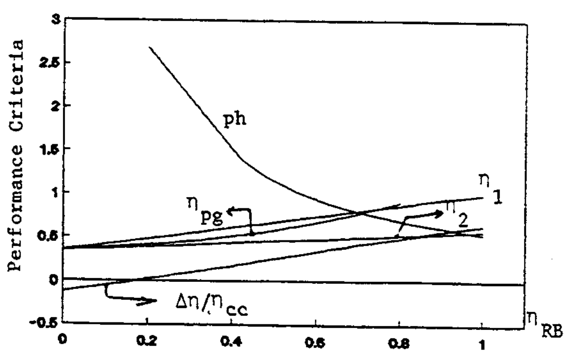

Fig. 5 Performace Criteria Versus recovery boiler efficiency for η_w=0.35

CONCLUSION

A methodology for performance evaluation of a gas turbine cogeneration plant from different point of views has presented and practical rang of them determined. It was shown that performance evaluation based on first law viewpiont is not in consistent with reality as well as economical considerations. Whereas, the second law viewpoint may predict the overall performance of a GTCP with a reasonable accuracy and in good agreement with economical considerations. Also, two other performance parameters, i.e., the efficeincy increase ratio and power generation efficiency have been introduced and discussed. Furthermore, it was shown that a GTCP is a suitable choice for cases in which the heat demand is 1.2-2.5 times of power demand.

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