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Efficiency improvement and CO_2 emission reduction of coal fired power plant by repowering through pressurized pulverized coal combustion and waste heated feed water heating

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Abstract
A theoretical analysis of partial repowering of a 250MW coal fired power plant is presented in this paper. In this repowering scheme, it is proposed that two of the five operating coal mills be taken out and the corresponding amount of pulverized coal combusted in a pressurized combustion chamber (PPCC). The product gas is expanded in a Gas Turbine (GT) after proper cleaning of the hot gas. The GT exhaust is fed to the existing boiler with modified burners. It is also proposed that waste heat from flue gas exiting the repowered plant boiler be used for feed water heating, which leads to a saving of bleed steam and an increase in the output of the steam cycle. The partial repowering boosts the capacity and overall efficiency of the plant by about 30.7% each and reduces the plant heat rate by about 23.5%. There is a fall of about 26.5% in the specific CO_2 emission of the plant after repowering.

Keywords: Repowering; power plant; PPCC; gas turbine; waste heat; capacity; efficiency; specific emission

1. Introduction

With continuous economic, social and industrial development, the increase in energy consumption is unavoidable around the globe – especially in developing countries like China and India. It is estimated that energy consumption would grow by 56% by 2040 [1]. Electricity generation accounts for a major part of the world's total energy demand. Among the different energy sources, coal provides 40% of the total worldwide electricity generation [1]. Total energy related global carbon dioxide emission is projected to rise 46% from 2010 to 2040 [1] which is a great matter of concern today in the context of the socio-economic scenario. CO_2 emissions from the power sector has been identified as a major source of GHGs emission. Accordingly, reducing CO_2 emissions and improving the efficiency and capacity of coal based thermal power plants are key issues. In this context, capacity augmentation can be met by a mix of increasing the number of new power plants while refurbishing old power plants. It might not always be possible to satisfy the thrust of increasing electricity demand by building new power plants, especially in highly populated parts of countries like India. Construction of new power plants is beset by various obstacles, including inadequate funding, problems with land acquisition as well as social and political issues. Repowering of old existing plants may help to overcome the rising energy demand in an environmentally friendly way. A remarkable improvement in the performance of existing coal based plant is possible through hot windbox repowering [2, 3], feed water repowering [4, 5 and 6] and combined cycle repowering using gas turbines [7, 8]. Repowering through exhaust reburning combined cycle technology delivered increases in the capacity and efficiency of Goi Thermal Power Station of 36% and 7.8% respectively [9]. Tucakovic *et al.* [10] performed a thermo-economic analysis of the reconstruction of an existing steam boiler to use exhaust gas from a gas turbine. Suresh *et al.* [11] showed that a conventional 62.5 MW coal fired power plant, repowered with pressurized pulverized coal firing in a combined cycle,delivered an additional 100 MW capacity and 6.3% efficiency and cut CO_2 emissions by 12%. Xu *et al.* [12] reported the effects of heat recovery from flue gas on net work output and coal consumption of a typical 1000 MW coal fired plant in China.

In the present paper a partial repowering scheme of an old coal fired power plant by PPCC technology coupled with GT and waste heated feed water heaters is presented. In this repowering scheme two of the five operating coal mills of the existing boiler are taken out and the corresponding amount of coal is combusted in a pressurized pulverized combustion chamber. Thereafter the hot gas is expanded in a GT after proper cleaning. The GT exhaust is sent to the furnace of the existing boiler. Along with this replacement of coal mills, waste heated feed water heaters are employed after the existing air preheater to utilize the heat available in the flue gas coming out from the boiler. A first law analysis is done to estimate the enhancement of the performance of the plant in terms of capacity, efficiency and CO_2 emission. In the present study typical high-ash Indian coal was considered. Recent technology developments have allowed use of high ash coal in pressurized combustion mode without much difficulty arising from ash melting in high-temperature combustor. Successful operation of pressurized combustion of high ash coal above ash melting point is reported [13-17]. Pressure as high as 16 bar and a temperature of 1600º C were also considered by an earlier researcher [17]. High temperature gas cleaning in the temperature range of 1000º -1400º C and even beyond that has been successfully demonstrated using ceramic based particulate capture system and hot alkali removal chemical capture process [13-17]. Willenborg *et al.* [13] showed that very good alkali oxide removal can be achieved with alumino silicates having an Al_2O_3/SiO_2 ratio of about 1/8, and that even better results can be achieved through the addition of alkaline earth oxides such as magnesia, sodium oxide and potassium oxide. Escobar *et al.* [15] showed that the best ability to sufficiently remove the alkalis from the hot gas was by passing it through a bed of kaolin and silica enriched bauxite, thereby fulfilling the demands of gas turbine manufacturers.

2. Configuration of Existing plant

A schematic diagram of the existing plant is shown in Fig. 1.The diagram shows all the components such as high-pressure turbine (HPT), intermediate pressure turbine (IPT), low pressure turbine (LPT), generator (GEN), condenser (CON), high pressure heaters (HPH 1 & 2), low-pressure feed water heaters (LPH1, 2 & 3), deaerator (DEA), condensate extraction pump (CEP), boiler feed pumps (BFP), cooling water circulation pump (CWCP), furnace (CC), evaporator (EVP), superheater (SPH), reheater (RH) & economizer (ECO), circulating water pump (CWP), air pre-heater (APH), forced draft (FD) fan, induced draft(ID) fan and stack. Some steam is extracted after expansion in the HPT to send to HPH2 as shown in Fig.1. Steam is also extracted from various points of intermediate and low pressure turbines for feed water heating, as shown in Fig.1. The feed water heaters are cascaded to each other. The drip from the HPH is fed to the deaerator (DEA) and the drip from LPHs is fed to the condenser.

3. Configuration of Repowered plant

A schematic diagram of the repowered plant is shown in Fig. 2. The coal, previously supplied

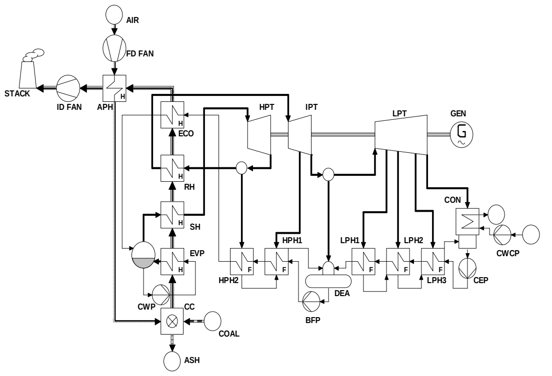

Fig.1. Schematic diagram of the existing steam power plant

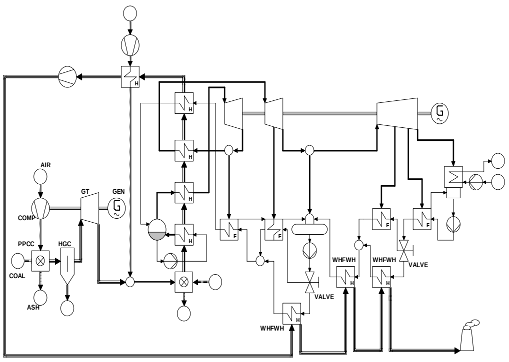

Fig.2. Schematic diagram of the repowered power plant

from two replaced coal mills, is combusted in a pressurized pulverized coal combustion (PPCC) chamber and the after combustion gas is expanded in a GT after high temperature, high pressure cleaning of the gas in a hot gas cleanup system (HGC) consisting of slag removal, particulate removal and alkali removal components, as described earlier. The exhaust gas from the gas turbine block is sent to the furnace of the existing boiler for reburning. The boiler walls need to be modified at the affected burner positions to provide an entry for the hot GT exhaust. All other configurations of the old plant remain the same as before, only the waste heated feed water heaters (WHFWH) are incorporated by replacing fully or partially old feed water heaters (HPH / LPH) for waste heat utilization of the flue gas coming out from the boiler of the repowered plant.

4. Assumptions

The lower heating value (LHV) of coal is 17000kJ/kg. The isentropic efficiency values for the turbines, pumps and fans are considered as 88%, 86% and 86%, repectively whereas the generator efficiency is considered as 95%. The following composition (by mass) of coal is considered: 34.46% C, 2.43% H_2, 0.69% N_2, 6.97% O_2, 0.45% S, 12% H_2O and 43% ash [11]. The isentropic efficiencies of the compressor and gas turbine of GT unit are considered as 87%. The waste heat utilization is done by cooling the flue gas to 100° C. A GE H-series [18] gas turbine is considered to be used in the GT cycle where turbine inlet temperature (TIT) can be taken up to be 1300° C.

5. Performance Analysis

The existing steam power plant (ST) and the repowered plant (RP) are modelled in Cycle Tempo [19] flow simulation software. The operating parameters of the steam cycle are taken from existing plant data. The performances of the existing steam power plant as well as the repowered plant are analyzed using first law analysis and heat balance calculations. The net power output of the plant is given as:

$$W_{net} = W_{gross} - W_{auxiliary} \tag{1}$$

Where, W denotes the work output.
The net efficiency of the plant is given as:

$$\eta = \frac{W_{net}}{Q_{in}} \times 100\% \tag{2}$$

where η and Q denote the efficiency and heat input respectively.
The total net output of the repowered plant is given as:

$$(W_{net})_{RP} = (W_{net})_{ST} + (W_{net})_{GT} \tag{3}$$

The net efficiency of the repowered plant is given as follows:

$$\eta_{RP} = \frac{W_{RP}}{(Q_{in})_{RP}} \times 100\% \tag{4}$$

6. Estimation of CO_2 analysis

Carbon dioxide emission is estimated taking data of dry flue gas (dfg) analysis [20] existing plant. The amount (%) of CO_2 by mass in the flue gas is given as follows.

$$m_{co_2} = \frac{44 \times CO_2}{44 \times CO_2 + 28 \times CO + 32 \times O_2 + 28 \times N_2} \times 100\% \tag{5}$$

where CO_2, CO, O_2, N_2 are the corresponding volume percentage in the dry flue gas.
Assuming no ash present in the flue gas (fg), the total mass flow rate of dry flue gas in the existing plant is estimated by the following equations as suggested by Sengupta *et al.* [21].

$$m_{fg} = 0.57 \times m_{coal} + m_{air} \tag{6}$$

$$m_{dfg} = m_{fg} - (m_{H_2O})_{fg} \tag{7}$$

where m denotes the mass flow rate.
The specific CO_2 emission of the existing plant is given as:

$$\xi_{CO_2} = \frac{m_{co_2} \times m_{dfg}}{(W_{net})_{ST}} \tag{8}$$

where ξ denotes the specific emission.
The amount of CO_2 present in the GT exhaust gas (eg) is estimated from the cycle tempo interface and can be expressed as:

$$(\chi_{CO_2})_{GT} = \frac{m_{eg}}{29.06} \times molar\ \%\ of\ CO_2 \times M_{CO_2} \tag{9}$$

where M and χ denote the molecular weight of CO_2 and total emission.
It is assumed that the total amount of CO_2 emission is equally contributed by each coal mill of the existing plant. So, the total CO_2 emission from the repowered plant is given as:

$$(\chi_{CO_2})_{RP} = \frac{3}{5} \times m_{CO_2} \times m_{dfg} + (\chi_{CO_2})_{GT} \tag{10}$$

The specific CO_2 emission of repowered plant is given as:

$$(\xi_{CO_2})_{RP} = \frac{(\chi_{CO_2})_{RP}}{(W_{net})_{RP}} \tag{11}$$

7. Results and Discussions

The major operating and performance parameters of the existing plant at full load are given in Table 1. The major performance parameters and heat balance of the PPCC and GT block are given in Table 2. 16.88 % of O_2 (by mass) is present in the GT exhaust. So, the amount of secondary air for the repowered plant boiler is reduced by an equivalent amount which contains oxygen coming from GT exhaust.

Table 1. Major operating and performance parameters of the existing steam plant.

Quantity	Value
Steam flow rate, kg/s	220.031
Steam Pressure, bar	152
Steam Temperature, °C	540
Coal flow rate, kg/s	41.2
Primary air supply, kg/s	40.56
Secondary air supply, kg/s	230
Gross power from steam cycle, MW	260.92
Power Consumption by BFP, kW	5079.81
Power Consumption by CEP, kW	194.64
Power Consumption by CWP, kW	418.71
Power Consumption by CWCP, kW	3524.01
Power Consumption by FD Fan, kW	837.11
Power Consumption by ID Fan, kW	856.42
Net power, MW	250
Net efficiency, %	35.67

Table 2. Major operating and performance parameters of the GT block.

Quantity	Value
Air flow rate, kg/s	307.197
Coal flow rate, kg/s	16.48
Pressure Ratio	15.79
Combustion pressure, bar	16
TIT, °C	1142.93

TOT, °C	546.23
Net output from GT block, MW	91.7

The amount of primary air is kept in the same proportion. The comparison of the condition of gas flow before and after the repowering scheme is given in Table 3. Table 3 indicates that the flue gas presents a high temperature at the APH exit of the repowered plant, which risks being wasted in the environment. This waste heat is proposed to be utilized for feed water heating by cooling the flue gas near to 100° C after the force flow section of boiler, integrating WHFWH replacing LPH2 & HPH1 partially and LPH1 fully of the existing cycle, as shown in Fig. 2.

Table 3. Comparison between the flue gas flow through boiler in existing and repowered plant.

Quantity	Before	After
Primary air flow rate, kg/s	41.2	25
Secondary air flow rate, kg/s	230	NA
GT Exhaust flow rate, kg/s	NA	316.59
flue gas flow rate, kg/s	294.05	355.69
Temperature of flue gas before APH, ° C	291.55	246.42
Temperature of flue gas after APH, ° C	124.17	233.51

This arrangement delivers a saving of bleed steam from IPT and LPT, which helps increase the output of the steam cycle. The major performance parameters and heat balance of the plant after repowering are given in Table 4. Table 4 shows that the total net output of the steam cycle is 235 MW. This reduction in the work output from the steam cycle occurs because of a reduction in the mass flow rate of steam through the steam generator circuit. This happens due to the change in temperature profile of the flue gas at different sections of the heat exchanging network of the steam generator, keeping the steam parameters fixed. On the other hand 91.7 MW is added to the existing plant by the GT cycle. As a result the total net output from the plant is increased by more than 30%. There is a decrease in the work input into the CEP, CWP and BFP but an increase in work input into CWCP. The work requirement decreases because, after repowering, a lower amount of working fluid flows through CEP, CWP and BFP. A greater amount of steam condenses in the condenser, after repowering, leading to an increase in the supply of cooling water. This in turn increases the work input in CWCP.

Table 4. Major operating and performance parameters of the repowered plant.

Description	Quantity
Steam Flow rate, kg/s	196.562
Steam Pressure, bar	152
Temperature, °C	540
Energy input to steam cycle, MW	420.58
Energy input to GT Cycle, MW	280.16
Gross power from Steam Cycle, MW	245.04
Gross power from GT, MW	223.59
Power consumption by BFP, kW	4542.08
Power consumption by CEP, kW	184.48
Power consumption by CWP, kW	374.42
Power consumption by CWCP, kW	3557.8
Power consumption by FD Fan, kW	80.97
Power consumption by ID Fan, kW	1297.28
Power consumption by COMP, MW	130.022
Net power from Steam cycle, MW	235.007
Net power from GT cycle, MW	91.698
Net Total generated power , MW	326.706
Net Efficiency, %	46.62

Table 5. Performance comparison between the existing and repowered plant.

Parameters	Existing plant	Repowered plant
Net power from Steam cycle, MW	250	235
Net power from GT Unit, MW	NA	91.7
Net Heat rate, kJ/kWh	10092.5 1	7722
Net plant Efficiency, %	35.67	46.62
Specific CO_2 emission, t/MW-h	0.835	0.614
Net plant Output, MW	250	326.70
Specific Fuel consumption, Kg/kWh	0.593	0.454

A comparison of performance of the plant before and after repowering in terms of both energy and CO_2 emission is given in Table 5. Table 5 shows that total capacity increases about 30% and overall efficiency increases more than 30%, simultaneously the specific CO_2 emission is reduced by about 26%. Specific fuel consumption decreases by 23%.

8. Conclusion

In this paper theoretical investigation of the repowering of an old coal based power generating unit is done through pressurized pulverized coal combustion coupled with GT and waste heated feed water heating replacing existing coal mills. The addition of a GT block helped increase the net output of the plant by 91.7 MW. Total output from the plant increased by more than 30%. The net efficiency of the plant increased by about 31% and the net heat rate decreased from 10092.51kJ/kWh to 7722.007 kJ/kWh. The specific CO_2 emission of the plant decreased by about 26.5%. The results obtained clearly indicate that the proposed repowering scheme boosts the capacity and overall efficiency of the existing plant and reduces the heat rate, the specific CO_2 emission of the plant and the specific fuel consumption of the plant.

This study clearly demonstrates that this partial repowering scheme can enhance the performance of an old coal fired plant in terms of both energy and GHG emission with minimal additions and alterations to the existing infrastructure. This could help satisfy the increasing energy demand while meeting environmental targets.

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