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Combined Thermal-Hydro Power Generation: A Novel Approach of Plant Capacity Addition.

Goutam Khankari*‡, Sujit Karmakar**

* Mejia Thermal Power Station, Damodar Valley Corporation, West Bengal- 722183, India.

** Department of Mechanical Engineering, NIT Durgapur, West Bengal- 713209, India.

(goutam_khankari@yahoo.co.in, sujitkarmakar@yahoo.com)

‡ Corresponding Author; Goutam Khankari, Mejia Thermal Power Station, Bankura, Damodar Valley Corporation, West Bengal- 722183, India, Tel: +91 890 041 7127

E-mail: goutam_khankari@yahoo.co.in

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Abstract- This paper proposes a hydro-power plant which is coupled with cooling water system of $500MW_e$ coal-fired thermal power plant to quantify the additional electric power and minimize the CO_2 emissions to atmosphere. About $16.77m^3/s$ of cooling water gravitationally flow from cooling tower basin to CW basin with a gross head difference of 1.5m for recycling it into the condenser and auxiliary cooling water system in a $500MW_e$ coal-fired thermal power plant. Maximum $195kW_e$ hydro-power can be generated through installation of a Kaplan turbine for plant capacity addition. Effect of gross head and flow rate variations are studied individually and result shows that power generation increases with head and flow. Hourly about 106.13 kg of coal and 47.94 kg of CO_2 emission can be reduced by generating $500MW_e$ combined thermal-hydro electric power. Generation cost and payback period of hydro power are about 71.62 paisa/kWh and 2.04 years respectively.

Keywords- CW & ACW system, Economics, Hydro-power, Kaplan turbine, Thermal power.

1. Introduction

Socio-economic development through industrialization and improvement in living standard with ever increasing population needs huge energy requirement for its sustainable growth. Securing a cheap energy supply and minimizing adverse environmental impact is the primary goal of any country. Coal is the primary source of energy in India whose reserve is about 6.8% of the world's total reserve [1] and about 65% of the total power generation is from coal-based thermal power plants. Thermal power plants are running with less efficiency due to large amount of heat energy being rejected from condenser through its cooling system. This depletes not only the natural resources (i.e. mainly coal) but also creates environmental hazards.These difficulties may be reduced through implementation of an alternative technology for power generation. In literature, many research [2-4] have been done to recover waste heat for power generation by using Kalina cycle system (KCS). O.K.Singh and S.C.Kaushik [5] has developed a simulation model by using Kalina cycle to generate power from low temperature flue gasses of coal fired thermal power plant. In recent years, few research works [6&7] deal with transcritical CO_2 power cycle for low-grade waste energy application. Yuhui Song et al. [6] has developed a mathematical model to generate power from solar energy with the help of transcritical CO_2 power cycle. As per authors' knowledge, there is no such research work related to scope of hydro-power generation in the coal-fired thermal power plant. Hydro-power generation technology is the one of the best solution as it is well developed technology. In the 19th century, with the advent of electricity, people began to use the force of water to generate electricity, first in Northumberland, England, in 1878[8]. Availability of suitable site and its location from consumers are the key issues for hydro-power installation in India. In this context, hydro-power plant installation in thermal power plant may be one of the best solutions for plant capacity addition. A $500MW_e$ coal-fired thermal power plant continuously uses clarified water with flow rate of about 16.25 m^3/s and 0.972 m^3/s for its condenser and de-mineralized (DM) water cooling system respectively. This large amount of hot cooling water from condenser and plate type heat exchanger (PHE) is fed to cooling tower (CT) for recycling it into the CW basin from CT basin with the gross head difference of 1.5m for avoiding the hydraulic jump and vortex effect.

In this work, an effort has been made to generate hydro-power from this cooling water system (CW &ACW) by installing a Kaplan turbine and an alternator as Kaplan turbine works efficienctly at low head application [9]. Bilal Abdullah Nasir [10] has designed a micro-hydro electric power station which is feasible for implementation in project side. Nasir also showed the variation of turbine efficiency in between 80 to 95%. Sarala and Adhau[11] has proposed to install the pico-hydro project after taking effective measures for cost reduction through the economic analysis of mini/micro-hydro power project. Gudukeya and Madanhire [12] also showed a case study for hydro-power plant efficiency improvement by 20-25% for micro-hydro plant with the view of turbine parameters such as surface texture, fabrication process and material used.

The objective of the present study covers the following aspects:

- To quantify the additional electric power through installing a Kaplan turbine at the exit of cooling tower (CT) channel of a 500MW$_e$ coal-fired thermal power plant cooling water system.
- To find out its suitable design parameters for electric power generation efficiently.
- To study the effect of key parameters (head and flow) variation on plant performance.
- To study its techno-commercial feasibility.

2. System Description

Fig.1 shows the schematic diagram of the proposed hydro-power scheme which is coupled with the cooling water system of 500MW$_e$ coal-fired thermal power plant. In Fig.1, condenser cooling water and auxiliary cooling water for DM water cooling has been supplied by running CW and ACW pumps respectively. Hot water from condenser and plate type heat exchanger (PHE) are mixed and then feed to natural draft cooling tower (NDCT) for reuse it in the cycle for cooling. Very few percentage of hot water is being released to ash plant to maintain the design cycle of concentration in cooling water system by taking fresh clarified water make up (CW make up) into CW basin. In original scheme, water flows from CT basin to CW basin through close concrete channel at 1.5 meter gross head difference. In the proposed scheme, water will flow from CT basin to CW basin through the penstock of 170 meter length and then it will pass through a Kaplan turbine for generating hydro-power. Water from Kaplan turbine will flow to CW basin through a draft tube. A bypass line is shown in Fig.1 for maintenance work of hydro-power project during main plant running condition.

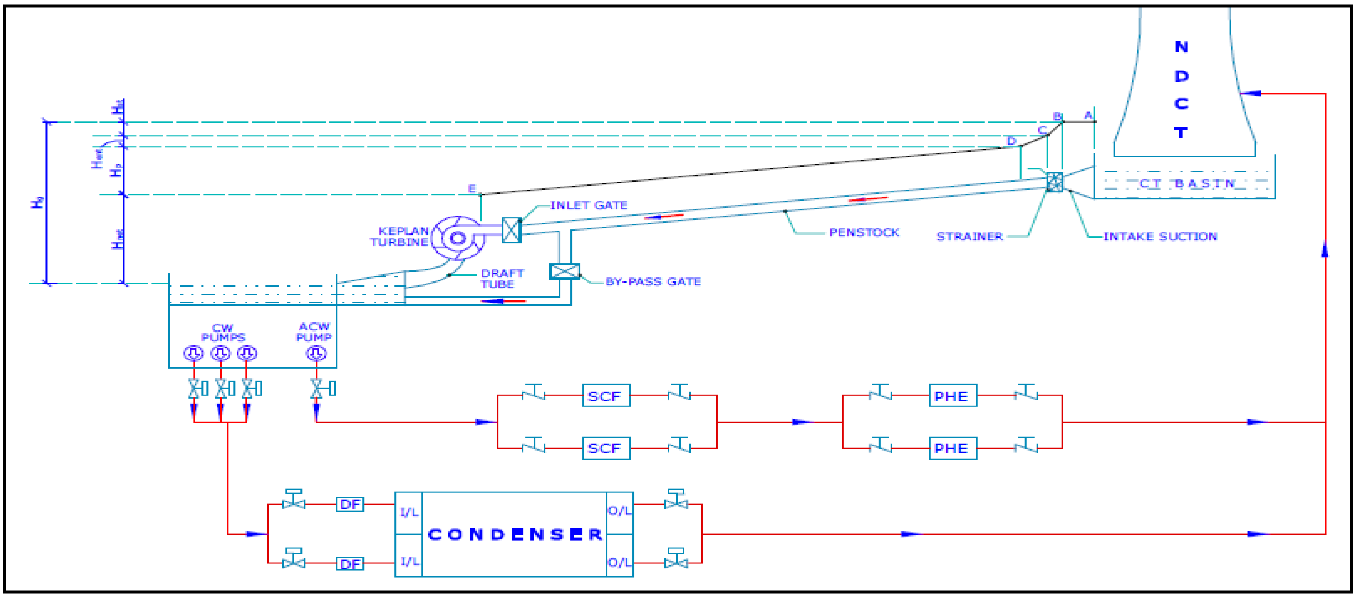

Fig.1 Schematic diagram of hydro-power plant coupled with 500MW$_e$ coal-fired thermal power plant cooling water system.

3. Design Methodology

Following assumptions have been made for designing the hydro-power project which is integrated with the cooling water system of 500MW$_e$ coal-fired thermal power plant.

- Each CW and ACW pump have discharge capacity of 5.42 m^3/s and 0.97 m^3/s respectively.
- 100%, 80% and 60% of rated thermal plant load are considered for this analysis.
- Three no. of CW pumps are required at and above 80% of rated thermal plant load and at lower load, two no. of CW pumps are required for condensation of steam at condenser.
- Around 2.62% water loss (evaporation loss, drift loss and hot blow down) is considered in CW & ACW system.

- 'CO' formation is neglected during coal combustion.

To design a mini-hydro-power project, following steps have been followed.

Step-1: Site Survey

The main goal of the site survey is to estimate the flow rate, duration of flow and head of the site. These data are needed to determine the potential power for this site and to select the right equipment for site conditions. Flow duration curve depends on the main thermal power plant running condition. Flow rate and gross head are determined from the following equations as per Fig. 2 (Turbine elevation from CW basin level are very negligible for gross head calculation).

$$\dot{Q} = (n\,\dot{m}_{CW} + m\,\dot{m}_{ACW}) - 2.62\%\,(n\,\dot{m}_{CW} + m\,\dot{m}_{ACW}) \tag{1}$$

Where, $\dot{Q}$: mass flow rate of water into Kaplan turbine, n: No of running CW pump, m: No of running ACW pump, $\dot{m}_{CW}$: Discharge flow rate of each CW pump, $\dot{m}_{ACW}$: Discharge flow rate of each ACW pump.

$$\text{Gross head } (H_g) = L_a \tan\theta \tag{2}$$

$$\text{Penstock length } (L_p) = \frac{L_a}{\cos\theta} \tag{3}$$

L_a : Axial distance between intake strainer and turbine (150m).

θ : Angle of inclination of penstock with horizontal (0.49^0).

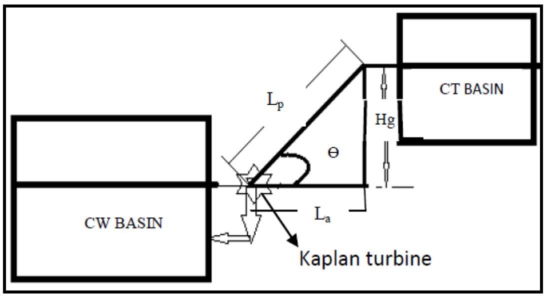

Fig.2 Diagram for gross head (H_g) calculation.

Step-2: Intake suction at CT basin

Open type channel at intake suction of CT basin should be designed in such a way so that uniform acceleration of water is maintained to reduce head loss and vortex effect. Slopping down roof and convergent wall are the best designed option [10] that may be chosen. For this study, this type of intake suction is already established in original main plant scheme. So, construction cost is not considered for this work.

Step-3: Suction strainer

To prevent the entrance of floating debris into the penstock, six nos. of strainer with total width of 10meter and depth of 4.5 meter are installed at the exit of intake suction channel. These strainers are installed at 90° with horizontal. Head loss due to strainer is calculated by below given equation.

$$H_{st} = K_{st}\left(\frac{t}{b}\right)^{1.33} V_{st}^2\,\frac{\sin 90}{2g} \tag{4}$$

Where strainer co-efficient (K_{st}) =0.8 and $\frac{thickness(t)}{width(b)}$ = 0.2 is considered for our study.

$$Velocity\ across\ strainer(V_{st}) = \frac{\dot{Q}}{A_{st}} \tag{5}$$

A_{st} is the cross section area of strainer (perpendicular to flow).

Step-4: Penstock

It is a circular close conduit which is used for conveying water from intake suction to Kaplan turbine through its inlet guide vane. It is placed at an angle of 0.49° with horizontal with the support of saddles. Penstock length is determined from equation 3. Internal diameter and thickness of penstock are calculated as follows [10].

$$D_p = 2.69\left(\frac{n_p^2\dot{Q}^2L_p}{H_g}\right)^{0.1875} \tag{6}$$

$$t_p = 1.2 + \frac{(D_p+508)}{400} \tag{7}$$

Manning's co-efficient (n_p) = 0.013 is considered for this work.

Head loss due to entrance of water at inlet of penstock is calculated as;

$$H_{ent} = 0.375\,\frac{V_p^2}{2g} \tag{8}$$

$$\text{Penstock water velocity } (V_p) = \frac{\dot{Q}}{A_p} \tag{9}$$

$$\text{Frictional head loss } (H_p) = 4fL_p\,\frac{V_p^2}{2gD_p} \tag{10}$$

Where, co-efficient of friction (f) = $\frac{0.079}{R_e^{0.25}}$, $R_e = \frac{\rho V_p D_p}{\mu}$ and A_p indicates the cross section area of penstock.

Step-5: Net head (H_{net}) calculation

Net head available for hydro-power generation at turbine inlet is given as;

$$H_{net} = H_g - H_{st} - H_{ent} - H_p \tag{11}$$

Head loss at inlet suction open channel of CT basin is negligible and neglected.

Step-6: Kaplan turbine design

A. Turbine Power:

Shaft power developed by Kaplan turbine is given by following equation. Turbine efficiency (η_{ht}) is considered as 90%.

Shaft power (SP) = $\eta_{ht}\, \rho\, g\, H_{net}\, \dot{Q} / 1000$ (kW) (12)

Net power available from generator terminal is determined as follows with considering gear box and generator efficiency as 95% and 98% respectively.

Net power (p^{net}_{hydro}) = SP $\eta_{Gen}\, \eta_{Gear}$ (kW) (13)

Hydro-plant efficiency$(\eta_{hydro}) = \dfrac{1000\, p^{net}_{hydro}}{\rho\, g\, H_g\, \dot{Q}}$ (14)

B. Blade design:

To find out suitable design parameters, a MS Excel based computer simulation program has been developed and its calculation [9] and optimization flowchart is given in Fig.4. A schematic diagram of moving blade velocity profile is shown in Fig.3.

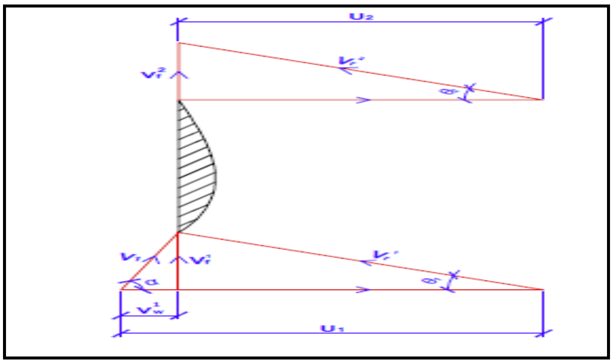

Fig.3 Velocity diagram of moving blade for Kaplan turbine.

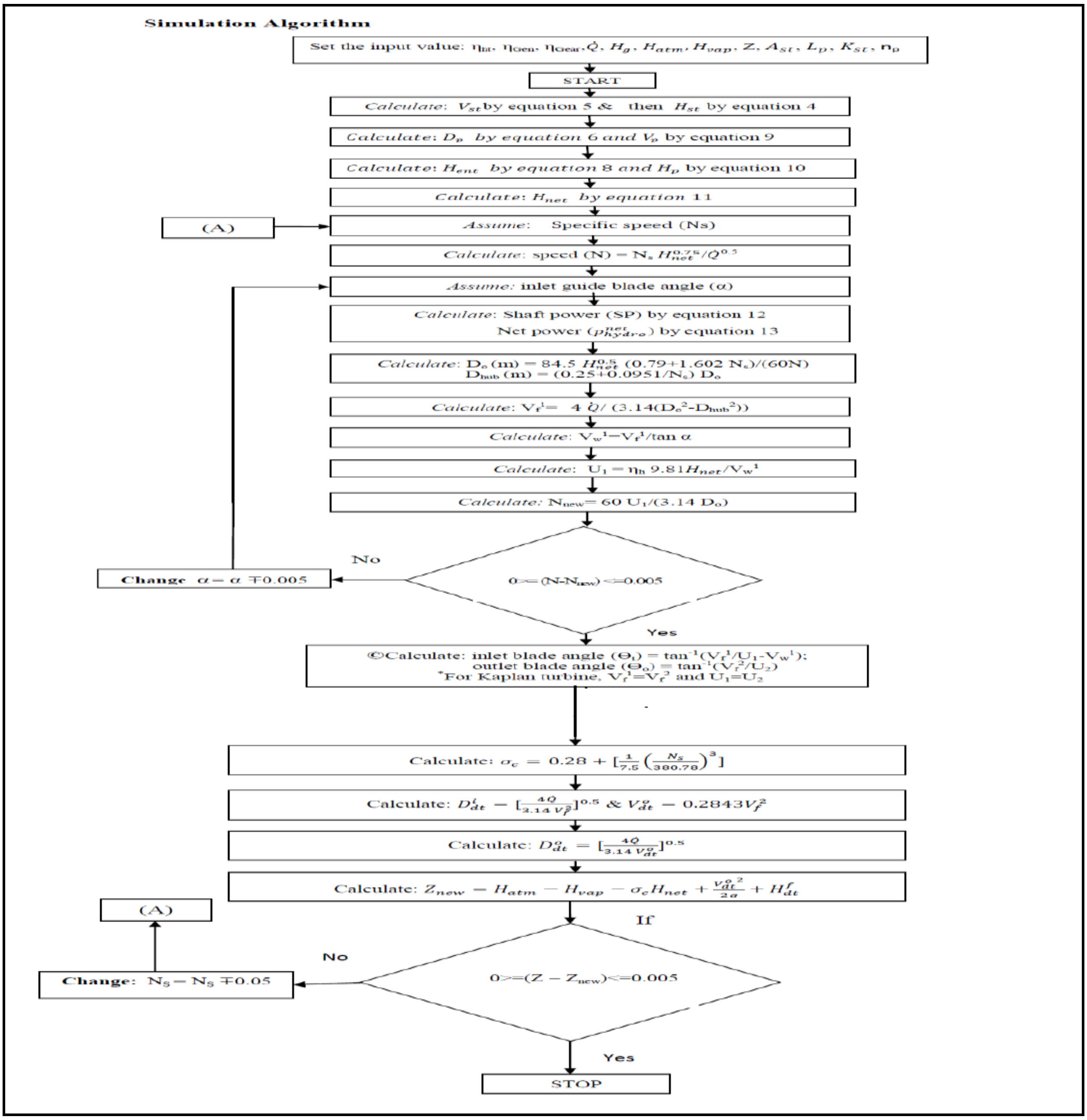

Fig.4 Simulation flow chart for Kaplan turbine design.

Step-7: Cavitation

Cavitation may occur at the exhaust of turbine due to its pressure fall below the vapor pressure. It creates pitting action on the turbine blade surface and reduces efficiency and creates vibration. To avoid cavitation, draft tube is normally used at exit of turbine and placed above the CW basin level (Z).

To avoid cavitation, following condition must be followed for designing the hydro-power plant.

$$\frac{N_s}{995} \leq 0.686\delta_c^{0.5882} \tag{15}$$

Where, N_s indicate specific speed of turbine. Draft tube is designed by following formulas;

$$\sigma_c = 0.28 + [\frac{1}{7.5}\left(\frac{N_s}{380.78}\right)^3] \tag{16}$$

$$Z(m) = H_{atm} - H_{vap} - \sigma_c H_{net} + \frac{{V_{dt}^o}^2}{2g} + H_{dt}^f \tag{17}$$

$$D_{dt}^i = [\frac{4\dot{Q}}{3.14\, V_f^2}]^{0.5} \tag{18}$$

$V_{dt}^o = 0.2843V_f^2$ and $V_f^2 = V_{dt}^i$ are considered for this work.

$$D_{dt}^o = [\frac{4\dot{Q}}{3.14\, V_{dt}^o}]^{0.5} \tag{19}$$

4. Plant Performance Parameters

Combined plant performance parameters are calculated based on thermal and hydro power plant designed parameters. Design value of coal and its consumption rate at different load for the 500MW thermal plant are given in Table1. Net thermal power plant output is determined by following equation.

$$p_{thermal}^{net} = (\dot{P}_{TG} - \dot{P}_{aux})10^3 \tag{20}$$

Where, $\dot{P}_{TG}(MW) and\ \dot{P}_{aux}$ indicates turbo-generator output and auxiliary power consumption of thermal plant.

$$\text{Combined plant efficiency}(\eta_{combined}) = \frac{p_{thermal}^{net} + p_{hydro}^{net}}{\dot{m}_{coal} HHV} \tag{21}$$

Where, $\dot{m}_{coal}$ and HHV indicates the coal flow rate (kg/s) and higher heating value (kJ/kg) respectively.

Coal saving is due to addition of hydro power generation in thermal power plant is calculated as follows by keeping total plant generation same as before.

$$\dot{m}_{coal}^{saving}\text{(kg/h)} = SFC\ p_{hydro}^{net} \tag{22}$$

Where, SFC (kg/kWh) indicates specific fuel consumption.

CO_2 emission can be reduced from thermal power plant and it is given by following formula.

$$CO_2^{reduction}\left(\frac{kg}{hr}\right) = \frac{\dot{m}_{coal}^{saving}\{\%C - \%Ash\,(0.80\frac{\%UC_{FA}}{100} + 0.20\frac{\%UC_{BA}}{100})\}}{100} \tag{23}$$

Table 1. Coal analysis report of 500MW$_e$ coal-fired thermal power plant.

Proximate analysis of coal					Unburnt carbon		100% load	80% load	60% load
TM (%)	ASH (%)	VM (%)	C (%)	HHV (kJ/kg)	BA (%)	FA (%)	$\dot{m}_{coal}$ (kg/s)	$\dot{m}_{coal}$ (kg/s)	$\dot{m}_{coal}$ (kg/s)
6	40	16	38	17163	2.5	1.5	75.55	61.66	47.77

TM: Total moisture; VM: Volatile matter; FC: Fixed carbon; BA: Bottom ash; FA: Fly ash; $\dot{m}_{coal}$: Coal consumption rate for thermal power generation. (All are in mass basis)

5. Results and Discussion

5.1. Operating design parameters for hydro-power plant

The above design methodology is implemented in MS-Excel and VBA coded computer program (Fig.4). The result is shown in Table 2. This study is very significant for different capacity of thermal power plant which have different cooling water flow rate. From this study, it is observed that maximum 195.09 kW$_e$ hydro-power can be generated from 500MW$_e$ thermal power plant cooling water system. This amount can be increased for higher capacity thermal power plant. Plant capacity can be increased by additional hydro power generation and power industry can make profit due to its less generation cost.

Table 2. Design operating data for mini hydro-power project.

Design operating data	Value		
Water flow rate(m^3/s)	16.77	11.50	5.28
Gross head (H_{gross}) (m)	1.50	1.50	1.50
Net Head (H_{net}) (m)	1.42	1.43	1.44
Net power output(kW)	195.09	134.72	62.51
Penstock area (m^2)	10.68	8.05	4.49
Penstock water velocity (m/s)	1.57	1.43	1.18
Inlet guide blade angle (α)	81.60	81.58	81.54
Guide balde outer diameter(m)	1.35	1.12	0.76
Hydro-turbine effIciency (%)	90.00	90.00	90.00
Specific speed (rpm)	1403.10	1399.70	1394.25
Speed(rpm)	149.62	181.21	268.74
Runner outer diameter(D_{out}) (m)	2.04	1.69	1.14
Runner hub diameter(D_{hub}) (m)	0.65	0.54	0.36
Axial flow velocity at blade inlet(V_f^1) (m/s)	5.28	5.29	5.31
Whirl velocity at blade inlet (V_w^1) (m/s)	0.78	0.79	0.79
Blade velocity at inlet (U_1) (m/s)	15.97	15.99	16.04
Water velocity at blade inlet (V_1) (m/s)	5.33	5.34	5.36
Outlet balde angle(Θ_2)	18.30	18.31	18.32
Inlet blade ange(Θ_1)	19.17	19.19	19.21
Water vapor pressure (m)	0.43	0.43	0.43
Water velocity at draft tube inlet (V_{dt}^1) (m/s)	5.28	5.29	5.31
Draft tube inlet diameter(m)	2.01	1.66	1.13
Water velocity at draft tube outlet (V_{dt}^2) (m/s	1.50	1.50	1.51
Draft tube outlet diameter(m)	3.77	3.12	2.11
Thomas cavitation factor (σ_t)	6.95	6.90	6.83
Turbine above the tail race(m)	0.15	0.15	0.15
Hydro-plant efficiency (%)	79.05	79.62	80.52

5.2. *Effect of cooling water flow variation on hydro-power plant performance*

Thermal power plants are running at different part load. This part load variation reduces the cooling water flow requirement for saving the auxiliary power consumption of the plant. İn this paper, the effect of cooling water flow variation on hydro-power plant performance is studied at constant gross head.

Result shows (Fig.5) that power output increases with flow rate but hydro-plant efficiency decreases. From Fig.6, it is observed that hydro-plant efficiency decreases due to decrease of net available head at turbine inlet as higher water flow velocity for a particular penstock. Turbine speed variation is also studied and given in Fig.7.

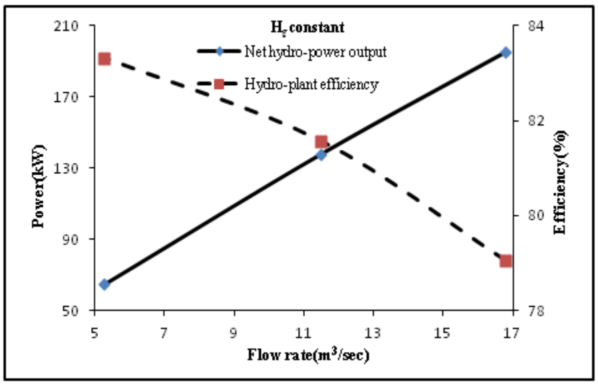

Fig.5 Effect water flow on hydro-plant performance.

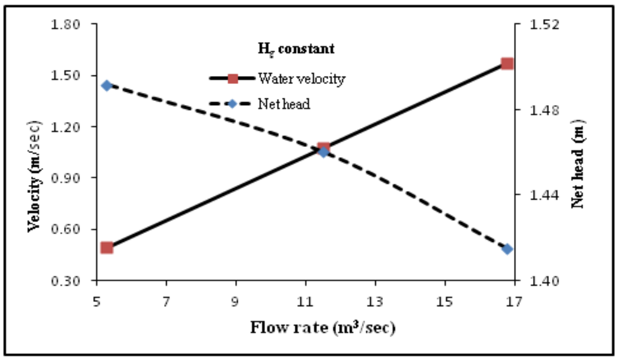

Fig.6 Effect of water flow variation on net head and water velocity.

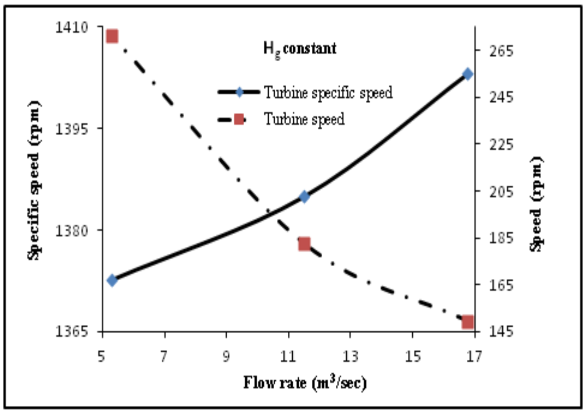

Fig.7 Effect of flow rate variation on turbine speed.

5.3. *Effect of gross head variation on hydro-power plant performance*

Gross head variation on hydro-power plant performance are studied at different value and for the instance, variation of gross head at 1.5m, 2m and 2.5m are shown in Fig.8. Result shows that net power output and hydro-plant efficiency both increases with gross head. It is also observed that efficiency improvement slope slightly decreases at higher head due to decrease in slope of net head (H_{net}) to gross head (H_g) ratio (Fig.9). Turbine speed also increases with gross head and is shown in Fig.9. It may be concluded that hydro-power generation will be more in higher head and it is the key factor for designing an efficient hydro-power plant compared with flow rate.

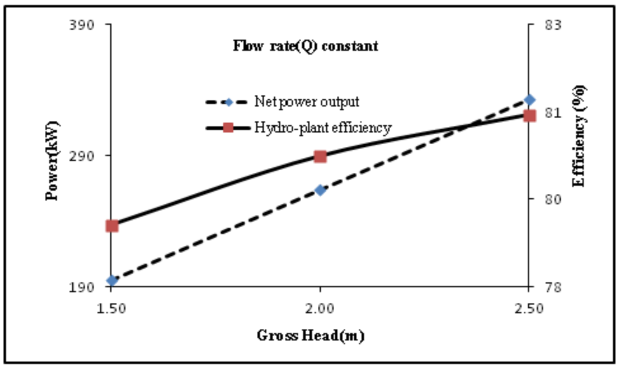

Fig.8 Effect of gross head variation on hydro-plant performance.

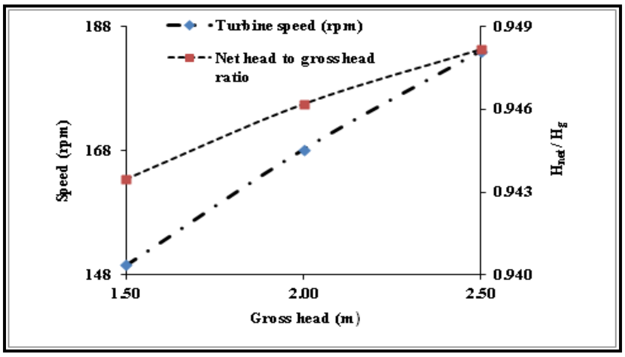

Fig.9 Effect of gross head variation on turbine speed.

5.4. *Effect of hydro-power on combined thermal-hydro power plant performance*

The plant energy efficiency of 500MW$_e$ thermal power project is around 37-38%. Combined thermal-hydro power plant efficiency increases due to plant capacity addition by generation hydro-power and it is shown in Fig.10.

Efficiency improvement of the plant is also studied at different part load of thermal power plant and result is given in Fig11. Maximum efficiency improvement is observed at 80% of rated thermal power load. Positive improvement slope is also seen at the load range of 60% to 80% due to poor thermal plant efficiency at low load and addition of hydro power at 80% of rated thermal power plant load is more than 60% due to more cooling water flow rate. This improvement gradually decreases towards 80% of rated thermal power due to improvement in thermal plant efficiency as there is less throttling effect of steam turbine control valves at higher load [13]. Above 80% of rated thermal power, improvement slope drastically reduces as hydro power generation is not further changed with thermal power plant load due to constant cooling water flow rate.

As a consequence, CO_2 formation from coal combustion (Table 3 and Fig. 12) reduces by saving coal during fixed unit generation as before . Hourly about 106.13 kg of coal and 47.94 kg of CO_2 emission can be reduced by generating 500MW$_e$ combined power. It is observed that CO_2 reduction increases with load due to addition of hydro power which is more at higher load and above 90% of rated combined load, CO_2 reduction slightly decreases due to change in specific fuel consumption.

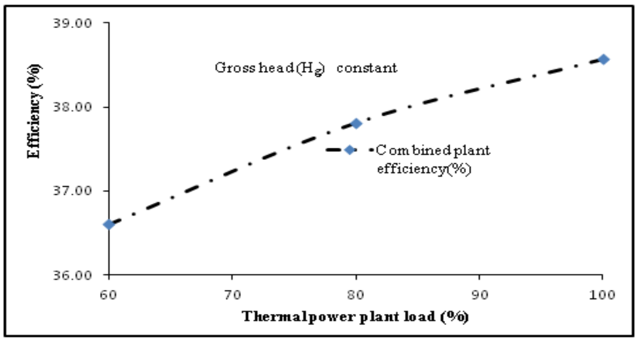

Fig.10 Combined plant efficiency variation at different thermal power plant load.

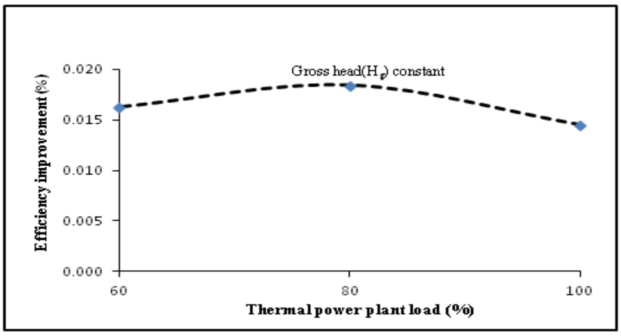

Fig.11 Efficiency improvement of combined power plant over 500MW$_e$ thermal power plant.

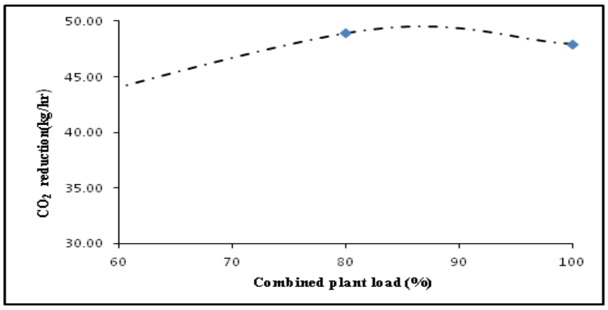

Fig.12 Effect of combined thermal-hydro power generation on CO_2 reduction of a 500MW$_e$ coal-fired power plant.

Table 3.Effect of combined thermal-hydro plant on CO_2 reduction and coal saving.

Combined plant Load (%)	Specific fuel consumption (kg/kWh)	Coal saving (kg/h)	CO_2 reduction (kg/h)
100	0.544	106.13	47.94
80	0.555	108.27	48.91
30	0.573	79.13	35.74

Table 4. Economic analysis of hydro-power plant.

Economic analysis at 80% plant availabity factor	
Unit Capacity (kW)	195.09
Capital cost for equipments (Lacs)	36.15
Civil cost (Lacs)	50.00
total capital cost (Lacs)	86.15
O&M cost@1% of total capital cost(Lacs)	0.86
Anuual depriciation cost (Lacs) (Indian Electricity Act,1948)	1.61
Interest charge @8% of total cost (Lacs)	7.32
Annual fixed cost (Lacs)	9.79
Annual total cost (Lacs)	95.95
Annual power generation (kWh)	1367211.74
Generation cost(paisa/kWh)	71.62
Installation cost (Rs./kWh)	44160.05
Annual profit (Rupees)	4216144.09
Payback Period (years)	2.04

5.5. Economic analysis of hydro-power

Economic analysis of 195.09kW capacity hydro-power plant is done with considering 80% plant availability factor [11]. In this analysis, total capital cost for installation is considered as Rs. 44,160/KW [14]. Construction cost for dams are excluded here. Civil cost associated with project engineering and mechanical, electrical with control equipments cost are considered as 52% and 48% of total capital cost respectively [15].Operation and maintenance (O&M) and interest charge are considered as 1% and 8% of total capital cost respectively.

$$\text{Payback period} = \frac{\textit{Total capital cost.}}{\textit{Annual profit}} \qquad (24)$$

Economic analysis result (Table 4) shows that it has low generation cost (71.62 paisa/kWh) and less payback period (2.04 years).

6. Conclusion

Plant capacity addition of 195.09kW$_e$ power is possible by this novel approach. Net output from the integrated hydro-power plant increases with flow rate and available gross head. Gross available head is the key factor for designing an efficient hydro-power plant as hydro-power plant efficiency increases with gross head but decreases with flow rate.

Combined thermal-hydro power plant efficiency increases over the thermal power plant efficiency due to additional extra power from hydro-power project which is integrated with the main thermal power plant cooling water system.

Maximum plant efficiency improvement is observed at 80% of rated thermal power load. About106-108 kg/hr of coal can be saved at 500MW$_e$ combined thermal-hydro power generation. As a result, CO_2 emission can be reduced by 48-49 kg/hr. It is a techno-commercial feasible project as it has low generation cost (71.62 paisa/kWhr) and less payback period (2.04 years).

Acknowledgements

The authors are indebted to Sri Mrinal Biswas, Chief Engineer (O&M), Damodar Valley Corporation, West Bengal, India for their continued support and encouragement to carry out this research work.

Nomenclature

A Area (m^2)
C Fixed carbon of coal (%)
D Diameter (m)
f Axial flow direction of water at turbine blade
g Gravitation acceleration(m/s^2)
H Head (m)
HHV Higher heating value of coal (kJ/kg)
m Meter
$\dot{m}$ Volumetric flow rate of water (m^3/s)
$\dot{m}_{coal}$ Mass flow rate of coal (kg/s)
N_s Specific speed of turbine (rpm)
P Power (kW)
$\dot{Q}$ Mass flow rate of water (m^3/s)
R_e Reynolds number
SFC Specific fuel consumption (kg/kWhr)
t Penstock thickness (mm)
TM Total moisture (%)
UC Unburnt carbon (%)
V Velocity (m/s)
VM Volatile matter(%)
η Efficiency (%)
ρ Water density (kg/m^3)
μ Viscosity (Ns/m^2)
σ_c Thomas cavitation factor
α Turbine inlet guide blade angle (degree)
Θ Turbine blade angle (degree)
S sec

Subscripts

ACW Auxiliary cooling water
atm Atmospheric pressure (m)
CW Cooling water
dt Draft tube
ent Entrance
g Gross head
Gen Generator for hydro-power plant
Gear Gear box for hydro-power plant
net Net head (m)
p Penstock
st Strainer
w Whirl of turbine
TG Turbo-Generator cycle

Supercripts

i/o Inlet and outlet sate of draft tube
½ Inlet and outlet state of turbine blade

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