Performance Enhancement of Cooling Towers in Thermal Power Plants through Energy Conservation

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***Abstract*-This paper provides an analysis of induced draft cooling tower (CT) performances. The present heat transfer effectiveness of the cooling towers is in the range of 46.4 – 50.9 %. The overall CT fan efficiencies are varying between 25.9 – 42.8 %. These effectiveness and efficiencies are lower due to design deficiencies, hesitation in adopting new technology, etc. In this paper, detailed performance results of replacing the existing Glass Reinforced Plastic (GRP) blade by the modern technology Fibre Reinforced Plastic (FRP) blades is presented. The operational optimization of cooling tower is also discussed in detail.**

The effectiveness of cooling towers is improved to 71.7 – 80.7 % and the efficiency is improved to 39.5 – 64.2 % by replacing the existing GRP fan blade by the modern technology FRP blades. This technology up-gradation shows the reduction of auxiliary power of Cooling tower by 30 – 35 %. The specific energy consumption (SEC) of fan has reduced. The automation of CT fan operation reduces the energy consumption.

***Keywords:* FRP, GRP, Range, Approach, Effectiveness, SEC, Fan efficiency**

I. NOMENCLATURE

A – Approach of cooling tower in ^{o}C
A_0, A_1, A_2 – Constants (coefficients of curve fits)
B_0, B_1, B_2 – Constants (coefficients of curve fits)
C_0, C_1, C_2 – Constants (coefficients of curve fits)
CT – Cooling tower
CTI – Cooling Technology Institute
CW – Circulating water
CWT – Circulating water temperature
D_0, D_1, D_2 – Constants (coefficients of curve fits)
EFF – Effectiveness of cooling tower in %
E_0, E_1, E_2 – Constants (coefficients of curve fits)
FE – Fan efficiency in %
FRF – Fibre Reinforced Plastic
GRP – Glass Reinforced Plastic
$\overset{o}{m}$ – Mass flow of air in m^3/s
P – Power in kW
R – Range of cooling tower in ^{o}C
SEC – Specific energy consumption in W/t of air
WBT – Wet bulb temperature, ^{o}C

II. INTRODUCTION

Coal fired stations are the backbone of the Indian power generating sector and account for over 76 % of the generated power (1), (2). The auxiliary power used by cooling tower fans forms between 2.21 – 3.06 % of total auxiliary power (0.23 – 0.38 % of plant load)(3).

Generally in a Thermal Power Plant, there are two types of water cooling systems i.e., first is open cycle cooling water system (once through system) where the cooling water is passed once through the condenser and this system is implemented where a large source of water is available(4). The second is closed cycle system (re-circulated system) where the circulating water is re-circulated after cooling the hot water in the cooling tower (CT) and adding less quantity of make up water than the first method stated above (5).

Since the advent of electric generation based on steam, once through cooling systems have been a de facto component of the power production process (6). Initially, once-through cooling system was the favored approach. The large size of the source water guarantees cold cooling water temperatures with almost very modest seasonal variation. However, in the early 1970's, new steam-electric generation began using re-circulated cooling. The primary reason for this trend can be found in the Federal Water Pollution Control Act (FWPCA) enacted by U.S. Congress in 1972. Recognizing that electric power generation based on steam, uses large volumes of water, Sections 316(a) and 316(b) were designed to address potential impacts on the aquatic environment. Section 316(a) regulates cooling system thermal discharges and Section 316(b) requires the use of best technology available for minimizing environmental impact in the location, design, construction and capacity of a cooling water intake (7). With lower makeup (intake) flows and lower discharge (cooling tower blowdown) flows, re-circulated cooling systems were increasingly adopted in direct response to Sections 316(a) and 316(b). Such systems are in use in India.

In this re-circulated system, two type of CTs are used i.e., natural draft and induced draft. The natural draft CT requires large space and more construction cost, lower make-up water and minimum auxiliary power compared to induced draft cooling tower. The induced draft CT requires comparatively less space, lower construction cost, higher auxiliary power and higher water make up. The majority of the CTs are of closed cycle, induced draft CT (using CT fans) with cross airflow.

The CT fan blades are manufactured with different materials like aluminum, wood, GRP, etc. With the advent of Fibre reinforced plastic, the CT fan blades are manufactured with FRP (8),(9). These FRP blades are made with good quality epoxy resin to resist the very corrosive air system, polypax coating having high resistance to ultra-violet degradation and abrasion resistance. Fan achieves a low noise level due to aerofoil profile of the blades, use of non-resonant material and a highly polished surface leads to better performance.

III. PERFORMANCE RESULTS OF REPLACEMENT OF GRP FANS BY FRP FANS

The performance tests were conducted on the cooling towers of different units of 210 MW plants as per CTI (USA) code for "***Field performance test of cooling tower fans***" for the existing GRP bladed fans. The CT fans of Unit 1 and 4 are replaced with FRP blades and again the performance tests were carried out as per CTI code to compare the results and the results are presented in Table 1.

The cooling tower performance & energy efficiency mainly depends on the wet bulb temperature, airflow through the cooling tower and energy consumed by the fan motors.

Table 1: Performance results of replacement of GRP fans by FRP fans

Sl. No.	Particulars	CT#1		CT#4	
		GRP	FRP	GRP	FRP
1	No. of fans in service	9	9	9	9
2	Average Wet bulb temp.,(°C)	23.5	23.8	21.52	22.1
3	Average Dry bulb temp., (°C)	26.9	26.1	31.4	30.8
4	Average CW inlet temperature, (°C)	44.2	45.1	42.05	43.1
5	Average CW outlet temperature, (°C)	34.5	33.5	32.53	31.73
6	Condenser absolute pressure, (kPa)	9.5	9.4	9.3	9.6
7	Condensate hot well temperature, (°C)	45.8	46.1	46.5	45.4
8	Total power, (kW)	522.63	342.99	487.17	316.35
9	Reduction in power, (%)	-	**34.37**	-	**35.06**
10	Average Air velocity, (m/s)	6.99	9.10	8.57	9.57
11	Total Air flow, (m^3/s)	4632.1	6030.4	5679.2	6341.8
12	Increase in air flow, (%)	-	**30.19**	-	**11.67**
13	Range, (°C)	9.7	11.6	9.52	11.37
14	Approach, (°C)	11.0	9.7	11.01	9.63
15	Effectiveness, (%)	46.86	54.46	46.37	54.14
16	Increase in effectiveness, (%)	-	**7.6**	-	**7.77**
17	SEC, (W/t of air)	26.12	13.17	19.86	11.55
18	Reduction in SEC, (%)	-	**49.58**	-	**41.84**
19	Average Fan efficiency, (%)	32.55	64.58	42.82	73.63
20	Increase in fan efficiency, (%)	-	**32.03**	-	**30.81**

In order to improve the performance of the cooling tower, initially the fan blades were replaced from GRP to FRP blades. The airflow through the fan depends mainly on the pitch angle of blade, the air gap between the tip of the blade and the casing, etc. The pitch of the FRP blade has been increased optimally to increase the airflow through the system and optimize the air gap to reduce the air leakage (10), (11). The higher lift to drag ratio, larger chord width along the blade twist and lower drag losses of FRP fans improves the fan efficiency considerably.

The increased fan efficiency and reduced weight of fan blades, reduce the electrical power input to the fan motor. The results are presented below:

A. Range

The cooling load is directly proportional to the *range* of the cooling tower. The *range* of CT is one of the performance indices, which help in evaluating the performance of CT.

The *range* of the cooling tower is computed as

$$R = CWT_{in} - CWT_{out} \quad {}^{O}C \qquad (1)$$

where CWT_{in} is circulating water temperature at CT inlet in °C and CWT_{out} is circulating water temperature at CT outlet in °C

The performance of the GRP bladed and FRP bladed fans were monitored through out the year for different weather conditions. Figure 1 gives the variation of range for GRP and FRP bladed fans. The *range* changed with the change in wet bulb temperature and is improved from 2.5 – 16.0 °C to 4.5 – 17.0 °C after replacement. The *range* of the cooling tower can be curve fitted:

$$R = A_0 + A_1 * WBT + A_2 * WBT^2 \quad {}^{O}C \qquad (2)$$

where *WBT* is wet bulb temperature in °C, A_0, A_1 & A_2 are constants and are given in Table 2.

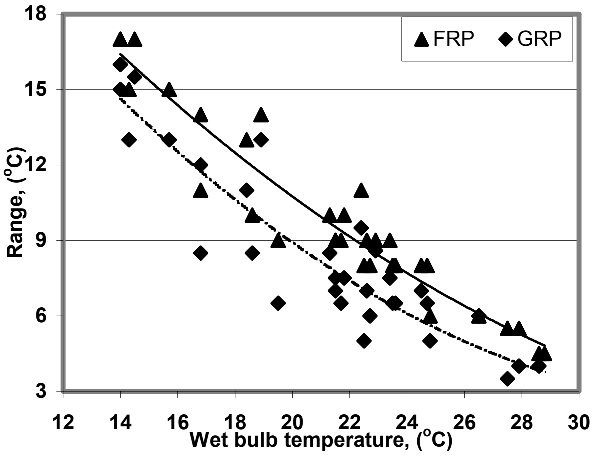

Figure 1: Variation of range with wet bulb temperature.

During the performance test the range of CT#1 is improved from 9.7 °C to 11.6 °C and for CT#4 it is improved from 9.52 °C to 11.37 °C (Table 1) due to change of blades to FRP blades.

Table 2: Constants of the curve fits.

	Range			Approach		
	A_0	A_1	A_2	B_0	B_1	B_2
FRP	34.698	-1.5610	0.0182	-2.4384	1.4523	-0.0407
GRP	34.952	-1.7993	0.0249	-2.6924	1.6904	-0.0474
	Effectiveness			SEC		
	C_0	C_1	C_2	D_0	D_1	D_2
FRP	110.8	-4.568	0.0789	12.798	0.0298	0.0001
GRP	107.2	-4.801	0.0782	16.321	0.9691	-0.021
	Efficiency					
	E_0	E_1	E_2			
FRP	79.484	-0.152	-0.0012			
GRP	53.045	-1.373	0.0302			

B. Approach

The *approach* is computed as the difference between the circulating water temperature at CT outlet and wet bulb temperature.

$$A = CWT_{out} - WBT \qquad {}^{O}C \tag{3}$$

Figure 2 shows the variation of *approach* with the variation in wet bulb temperature. The *approach* of the cooling tower can be curve fitted:

$$A = B_0 + B_1 * WBT + B_2 * WBT^2 \qquad {}^{O}C \tag{4}$$

where B_0, B_1 & B_2 are constants and are given in Table 2.

During the performance test the *approach* of CT#1 reduced from 11.0 °C to 9.7 °C and for CT#4 it reduced from 11.01 °C to 9.63 °C (Table 1).

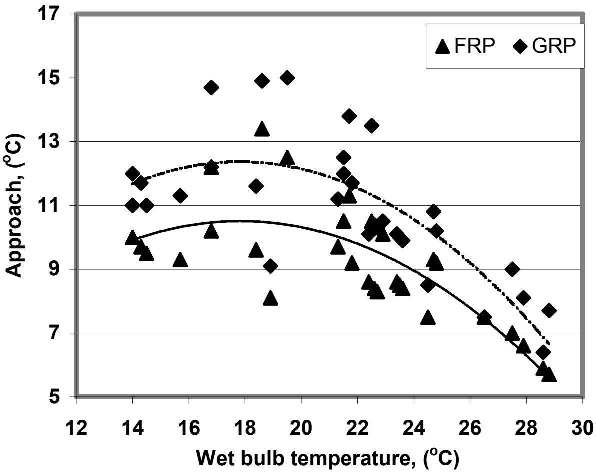

Figure 2: Variation of approach with wet bulb temperature.

C. Effectiveness

The effectiveness of the cooling tower helps in predicting the thermal efficiency of the CT and is computed as:

$$EFF = \frac{CWT_{in} - CWT_{out}}{CWT_{in} - WBT} * 100 = \frac{R}{R + A} * 100\,\% \tag{5}$$

Figure 3 presents the variation of effectiveness of FRP & GRP fan cooling towers with wet bulb temperature. The heat transfer effectiveness has decreased with the increase in wet bulb temperature. The effectiveness is increased after the replacement of fan blades from 24.5 – 59.3 % to 39.5 – 64.2 %.

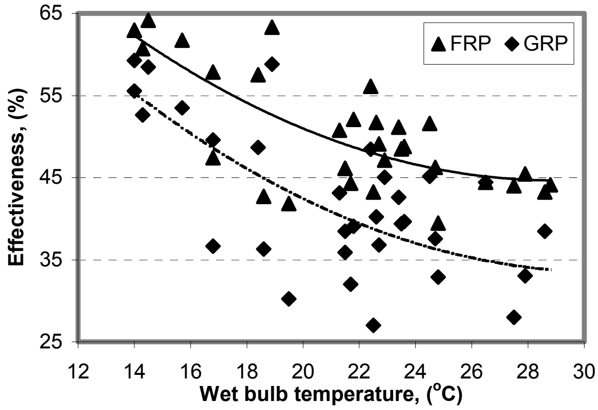

Figure 3: Variation of effectiveness with wet bulb temperature.

The effectiveness can be correlated with wet bulb temperature in the following relation

$$EFF = C_0 + C_1 * WBT + C_2 * WBT^2 \qquad \% \tag{6}$$

where C_0,, C_1 & C_2 are constants and are given in Table 2

The effectiveness of FRP bladed CT fans is increased from 46.86 % to 54.46 % for CT#1 and improved from 46.37 % to 54.14 % for CT#4 during the performance test (Table 1).

D. Specific Energy Consumption (SEC)

The Specific energy consumption is an important performance index, which helps in evaluating the power required by the fan to induce unit air airflow through fans, and is computed as:

$$SEC = \frac{P * 10^6}{\overset{o}{m} * 3600 * 1.2} \qquad W/t \ of \ air \tag{7}$$

where P is power in kW, $\overset{o}{m}$ is mass flow of air in m^3/s

Figure 4 shows the variation of specific energy consumption with the wet bulb temperature. The SEC is increases as the wet bulb temperature increases. The SEC with FRP fans is reduced considerably because of power reduction as well as increased airflow in the cooling tower system. The SEC is reduced from 24.3 – 28.5 to 12.64 – 14.22 kWh/t of air handled. The air through put is increased by 11.67 – 30.19 %. The energy consumption is reduced by 34.37 - 35.06 %.

The correlation of SEC with wet bulb temperature is as follows

$$SEC = D_0 + D_1 * WB + D_2 * WB^2 \quad \% \quad (8)$$

where D_0, D_1 & D_2 are constants and are given in Table 2

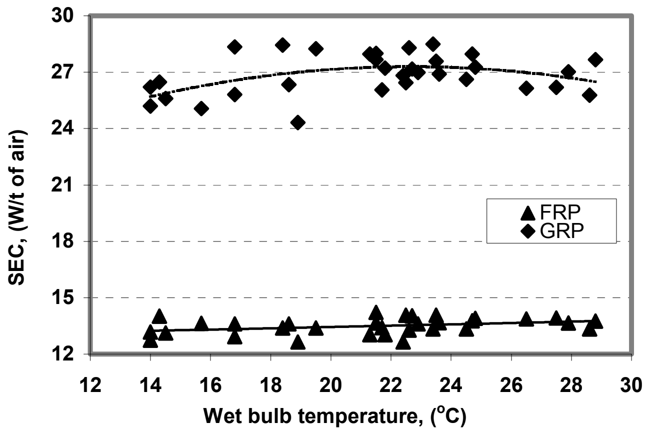

Figure 4: Variation of SEC with wet bulb temperature.

E. Fan efficiency

The fan efficiency is an important performance index which gives the overall performance of the cooling tower fans i.e., energy consumption, heat removal capacity, etc.

Figure 5 shows the variation of fan efficiency with wet bulb temperature for GRP & FRP fans. It can be seen from the Figure that the efficiency decreases as the wet bulb temperature increases i.e., it requires more power. By replacing the GRP fans by FRP fans the efficiency had increased from 24.5 – 59.3 % to 71.7 – 80.7 %.

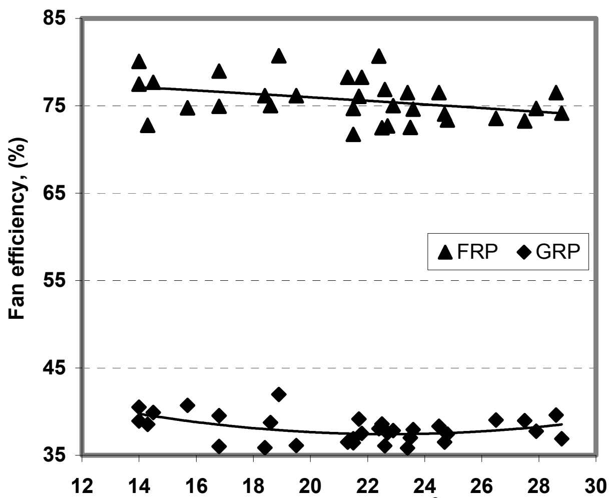

Figure 5: Variation of SEC with wet bulb temperature.

The correlation of fan efficiency with wet bulb temperature is as follows

$$FE = E_0 + E_1 * WB + E_2 * WB^2 \quad \% \quad (9)$$

where E_0, E_1 & E_2 are constants and are given in Table 2

IV. PERFORMANCE RESULTS OF REPLACEMENT OF GRP FANS BY FRP FANS AND MOTOR

After replacement of GRP fans by FRP fans, the load factor of motor was found to be in the range of 45.4 – 56.3 %. Because of poor loading of motor the power factor of motor had reduced to 0.76 – 0.80. The detailed study has been carried out to replace the existing motor of 67 kW to 45 kW (12), (13). The techno-economic evaluation of the motor replacement along with blade replacement was carried out and is presented in Table 3. As a trial, one fan motor is replaced with 45 kW and the performance is being monitored (the performance results are given in Table 4). The motor loading has increased to 75 – 80 % and the power factor is improved to 0.85 – 0.91.

Table 3: The techno-economic analysis of replacing the GRP fan blade of 67 kW motor with FRP fan blade of 45 kW motor.

Particulars	Present motor with GRP blade	Present motor with FRP blade	Replaced motor with FRP blade
Motor rating, (kW)	67	67	45
Average motor load factor, (%)	86.7	56.9	69.07
Motor efficiency, (%)	89	75	92
Motor input, (kW)	58.07	38.11	31.08
Energy consumed for 9 fans, (MWh/day)	522.63	342.99	279.71
Power factor	0.85	0.75	0.82
Energy savings, (MWh/day)	-	179.64	242.92
Energy savings, (MWh/month)	-	129.34	174.90
Savings, ($/month) (energy generation cost @ $ 0.029 per kWh)	-	3,787.23	5,127.66
Investment for FRP fan blades & motors, ($)	-	71,808.51	81,382.98
Pay back period, (months)	-	23	19

The adoption FRP fan blades leads to energy saving of 129.34 MWh/month. The payback period for an initial investment of $ 1,587 (9 Nos. for one 210 MW plant) is 23 months. The replacement of both the fan blades and motor will enhance the energy savings by 174.9 MWh/month. The anticipated capital investment is $ 1,798 and the payback period is 19 months. The latter is more attractive

V. OPERATIONAL OPTIMIZATION

Presently all the 9 fans in a 210 MW plant are being operated continuously throughout the year. During the winter when the wet bulb temperature is lower, the operation of number of fans can be reduced based on the wet bulb temperature and CW temperature at CT outlet.

The performance test is conducted by switching-off the CT fan manually when the wet bulb temperature was low (i.e., varying between 14.1 – 14.6 °C) and the results are given in Table 5. It can be seen from the Table that the energy consumption was reduced by 10.93 %, 22.77 %, 33.09 % & 44.44 % respectively for 8 fans, 7 fans, 6 fans & 5 fans in service with marginal variation in range and effectiveness.

Table 4: Comparison of performance results of new 45 kW fan motor with existing 67 kW motor.

Sl. No.	Particulars	GRP fan blade with existing 67 kW motor	FRP fan blade with existing 67 kW motor	FRP fan blade with new 45 kW motor
1	Average Wet bulb temperature, (°C)	23.9	23.9	23.9
2	Average CW inlet temperature, (°C)	44.6	44.5	44.5
3	Average CW outlet temperature, (°C)	34.8	33.3	33.5
4	Power, (kW)	59.8	37.9	31.08
5	Motor loading, (%)	89.25	56.57	69.07
6	Power factor	0.87	0.78	0.82
7	Frequency, (Hz)	49.9	49.9	49.9
8	Average line voltage, (V)	419	419	419
9	Average current, (A)	94.7	67.0	52.2
10	Average motor body temperature, (°C)	36.5	35.4	37.1
11	Average fan body temperature, (°C)	37.8	36.8	37.5
12	Average motor bearing temperature, (°C)	39.1	37.8	38.9
13	Average fan bearing temperature, (°C)	38.7	38.5	39.1
14	Average air velocity, (m/s)	6.85	9.4	9.3
15	Total Air flow, (m^3/s)	504.37	692.13	684.77
16	Range, (°C)	9.8	11.2	11.0
17	Approach, (°C)	10.9	9.4	9.6
18	Effectiveness, (%)	47.34	54.37	53.40
19	SEC, (W/t of air)	27.45	12.68	10.51

Table 5: Performance results of CT fans with number of CT fans

Particulars	Number of CT fans in service with GRP fan blades				
	9	8	7	6	5
Average Wet bulb temperature, (°C)	14.3	14.4	14.1	14.4	14.6
Average Dry bulb temperature, (°C)	21.4	20.5	22.1	21.1	20.3
Average CW inlet temperature at CT, (°C)	38.2	38.4	38.6	38.7	38.9
Average CW outlet temperature, (°C)	28.1	28.5	28.7	28.9	29.1
Average CW inlet temperature at condenser, (°C)	39.5	39.6	39.7	39.7	39.9
Average CW outlet temperature at condenser, (°C)	27.4	28.9	30.1	30.8	31.7
Average Condenser absolute pressure, (kPa)	9.00	9.50	9.30	9.50	9.20
Condensate hot well temperature, (°C)	38.7	38.9	41.5	42.8	44.8
Condensate sub-cooling, (°C)	-5.06	-4.13	-2.89	-2.01	0.62
Total power, (kW)	522.6	465.5	403.7	349.7	290.4
Reduction in power, (%)	-	10.93	22.77	33.09	44.44
Range, (°C)	10.1	9.9	9.9	9.8	9.8
Approach, (°C)	13.8	14.1	14.6	14.5	14.5
Effectiveness, (%)	42.26	41.25	40.40	40.32	40.33

When the wet bulb temperature is low, the circulating water temperature at condenser inlet will also be low (when all the 9 fans are in service), then the condensate is cooled below its saturation temperature (14) for example: when 9 fans are in service, the condenser absolute pressure is 9.0 kPa, the corresponding saturation temperature of condensate will be 43.76 °C but the actual condensate temperature at hot well is 38.7 °C (less by 5.06 °C). This temperature has to be gained in the LP heaters.

The experiments were conducted (with variation in wet bulb temperature from 14 – 21 °C) by switching off of fans one by one when the wet bulb temperature is low. Figure 6 gives the variation of condensate sub-cooling with the variation in wet bulb temperature for different combination of CT fans.

When the wet bulb temperature was in the range 14 – 17°C, only five CT fans were operated and the power is reduced by 33.5 – 41.2 % with marginal variation in effectiveness and the *range* of cooling tower.

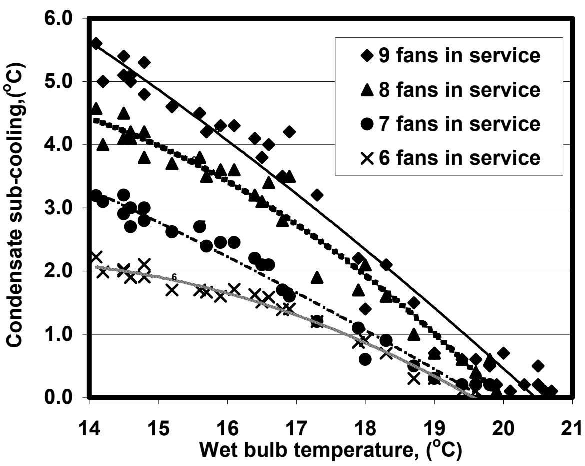

Figure 6: Variation of condensate sub-cooling with wet bulb temperature.

To automate the operation of fans, the thermostatic controller is being introduced to control the operation of the fans by sensing the wet bulb temperature and circulating water outlet from the cooling tower (15).

VI. CONCLUSIONS

The replacement of GRP bladed fans by modern technology FRP bladed fans reduced the power consumption by 30 – 35 %, the effectiveness had increased by 7 – 8 %, the SEC had decreased by 41 – 50 % and the overall fan efficiency had improved by 30 – 32 %. The replacement of these fans releases an additional energy of about 2.1 MU per year for one 210 MW thermal power plant. The operational optimization will also reduce the auxiliary power and also help in reducing the condensate sub-cooling problem.

VII. ACKNOWLEDEMENT

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IX. BIOGRAPHIES

Rajashekar P. Mandi was born in Banhatti in Bagalkot District of Karnataka state in India, on June 17, 1965. He received M.Tech. degree in Energy Systems Engineering from Visweswaraiah Technological University, Belgaum. Presently doing Ph. D. in Optimal integration and control of Renewable energy systems through research at Bangalore University.

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