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Condenser cooling system & effluent disposal system for steam-electric power plants: Improved techniques

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Abstract. In India, the current operation of condenser cooling system & effluent disposal system in existing power plants aims to reduce drawal of seawater and to achieve Zero Liquid Discharge to meet the demands of statutory requirements, water scarcity and ecological system. Particularly in the Steam-Electric power plants, condenser cooling system adopts Once through cooling (OTC) system which requires more drawal of seawater and effluent disposal system adopts sea outfall system which discharges hot water into sea. This paper presents an overview of closed-loop technology for condenser cooling system and to achieve Zero Liquid Discharge plant in Steam-Electric power plants making it lesser drawal of seawater and complete elimination of hot water discharges into sea. The closed-loop technology for condenser cooling system reduces the drawal of seawater by 92% and Zero Liquid Discharge plant eliminates the hot water discharges into sea by 100%. Further, the proposed modification generates revenue out of selling potable water and ZLD free flowing solids at INR 81,97,20,000 per annum (considering INR 60/Cu.m, 330 days/year and 90% availability) and INR 23,760 per annum (considering INR 100/Ton, 330 days/year and 90% availability) respectively. This proposed modification costs INR 870,00,00,000 with payback period of less than 11 years. The conventional technology can be replaced with this proposed technique in the existing and upcoming power plants.

Keywords: condenser cooling system; effluent disposal system; steam-electric power plants; once-through cooling (OTC) system; closed-loop cooling system; cooling tower system; zero liquid discharge plant

1. Introduction

In earlier days, Condenser cooling system utilized Once through cooling (OTC) system to meet condenser cooling requirements in Steam-Electric Power plants. Nowadays, Steam-Electric Power plants are focusing more on reduction of intake water drawal and elimination of hot water discharges into sea to meet the demands of statutory requirements, water scarcity and ecological

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Table 1 Quality of seawater obtained from bay of bengal for a steam-electric power plants in India

Sl No	Parameters	Units	Values (Min-Max)
1	Temperature	Deg C	30.0
2	pH	--	7.9 – 8.2
3	Biochemical Oxygen Demand (BOD)	mg/l	1.1 – 11.4
4	Chemical Oxygen Demand (COD)	mg/l	1.0 – 98
5	Total Suspended Solids (TSS)	mg/l	52.9 - 86.7
6	Sulphide as S	mg/l	0.03 – 0.1
7	Fluoride as F	mg/l	0.9 – 1.2
8	Chloride	mg/l	18238 – 19516
9	Percent Sodium	mg/l	1.06 – 1.12
10	Oil & Grease	mg/l	< 1.0
11	Boron as B	mg/l	0.6 – 0.8
12	Sulphate as SO_4	mg/l	1484 – 1878
13	Zinc as Zn	mg/l	BDL-Below detectable limit
14	Arsenic (as As)	mg/l	0.01 – 0.02
15	Copper (as Cu)	mg/l	13 – 120
16	Chromium (as Cr)	mg/l	0 – 32
17	Total residual chlorine	mg/l	Nil
18	Total Dissolved Solids (TDS)	mg/l	31856 – 35981

system. This paper presents a clear picture about more efficient intake water drawal and elimination of hot water discharges into sea using closed-loop cooling tower and Zero Liquid Discharge (ZLD) techniques. Also this technology ensures to safeguard ecological system with environment friendly nature.

2. Site observations on condenser cooling & outfall system and its schemes

Normally in Steam-Electric Power plants, Condenser cooling system works on Once through cooling (OTC) system (Raptis and Pfister 2016, Shi *et al.* 2016, Liu *et al.* 2015, Xia *et al.* 2015).

The source of cooling water for Condenser cooling system is seawater. The microbiological growth is controlled with the help of chemical (chlorine & Biocide) dosing at intake mouth of seawater intake system. The typical quality of seawater obtained from Bay of Bengal Sea is shown in Table 1.

The initial separation of suspended solids from the Sea water is accomplished by treating it in Pretreatment plant (Löwenberg *et al.* 2015, Jamaly *et al.* 2014). The separation of suspended solids is achieved in clarifier with the help of pretreatment chemicals like coagulant, flocculant etc., (Üstün *et al*. 2011). The sludge settles at the bottom of clarifier and handled in a separate sludge handling and disposal system. The clarified water from the clarifier is then stored in clarified water storage tank and then pumped to Desalination (RO) Plant as feed water to produce sweet/potable water. Further, permeate from desalination plant is pumped to potablization plant and RO-DM plant to meet the potable water, miscellaneous plant service water and heat cycle makeup water

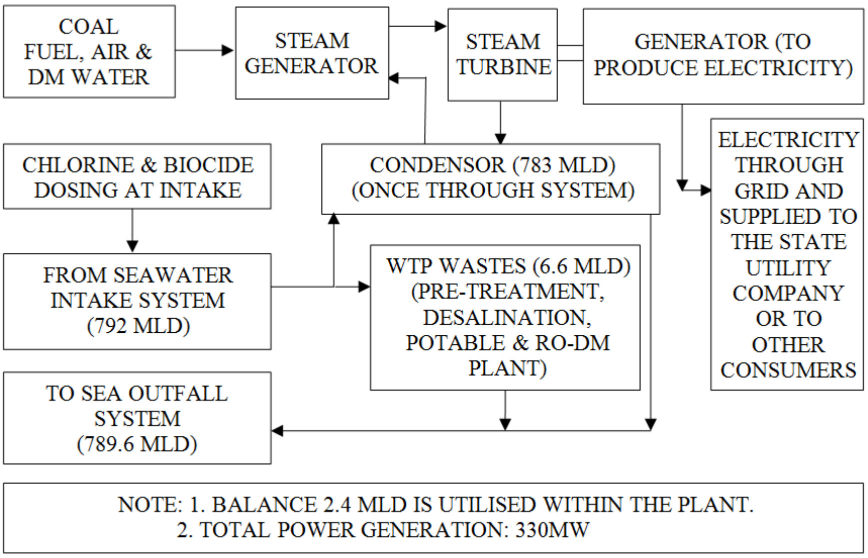

Fig. 1 Block diagram showing site observations on condenser cooling & outfall system and its scheme

Table 2 Quality of sea outfall discharges from a condenser's once through cooling (OTC) system of a steam-electric power plants in India

Sl No	Parameters	Units	Values
1	Temperature	Deg C	35
2	pH	--	8.2
3	Biochemical Oxygen Demand (BOD)	mg/l	11.8
4	Chemical Oxygen Demand (COD)	mg/l	102
5	Total Suspended Solids (TSS)	mg/l	< 100
6	Sulphide as S	mg/l	0.03
7	Fluoride as F	mg/l	0.95
8	Chlorides (as Cl)	mg/l	21428
9	Percent Sodium (as Na)	mg/l	1.12
10	Oil & Grease	mg/l	< 1.0
11	Boron as B	mg/l	0.8
12	Sulphates (as SO_4)	mg/l	1650
13	Zinc as Zn	mg/l	BDL-Below detectable limit
14	Arsenic (as As)	mg/l	0.02
15	Copper (as Cu)	mg/l	0.01
16	Chromium (as Cr)	mg/l	< 2
17	Total residual chlorine	mg/l	< 1
18	Total Dissolved Solids (TDS)	mg/l	36000

requirements.

The typical block diagram for condenser cooling & outfall system in Steam-Electric Power

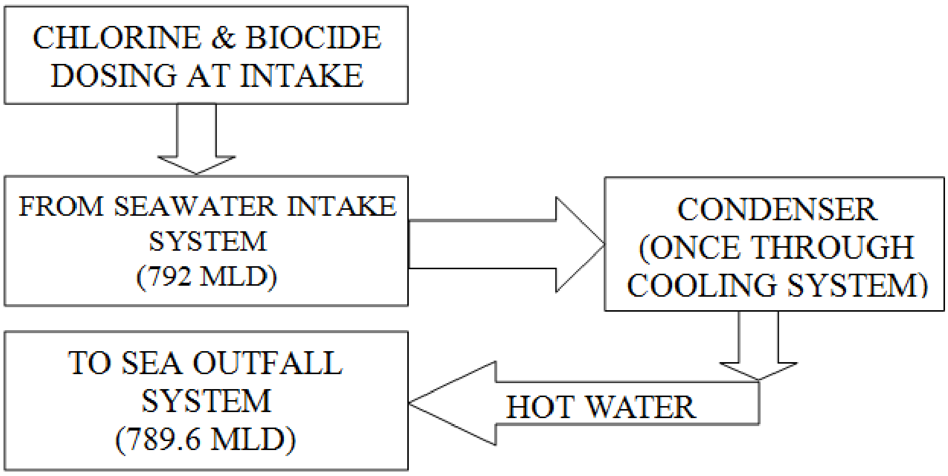

Fig. 2 Block diagram for condenser's once through cooling (OTC) system in steam-electric power plants

plants is shown in Fig. 1.

The typical quality of hot water discharges into sea obtained from a Condenser cooling system is shown in Table 2.

3. Case study analysis and discussion

3.1 Case I: (As per site condition)

The typical block diagram (as per site condition) for Condenser's Once Through Cooling (OTC) system (Raptis and Pfister 2016, Shi *et al.* 2016, Liu *et al.* 2015, Xia *et al.* 2015) in Steam-Electric Power plants is shown in Fig. 2.

In condenser's once through cooling system (Raptis and Pfister 2016, Shi *et al.* 2016, Liu *et al.* 2015, Xia *et al.* 2015), seawater from intake system is circulated within condenser to exchange heat from the turbine exhaust and become hot water. The hot water from the condenser is returned back to sea as sea outfall (Maalouf *et al.* 2014, Shawky *et al.* 2013). Biofouling in condenser tubes are controlled by the help of chlorine and biocide dosing which is dosed at the mouth of the intake system. About 792MLD seawater is circulated to meet the requirements of both condenser cooling system (783 MLD) and water treatment plants (9 MLD). About 2.4 MLD is consumed within the plant usages. Out of 2.4MLD, 1.4MLD shall be used to meet potable water requirement for plant & township and 1.0MLD shall be used for Demineralisation plant to meet heat cycle makeup. Balance 789.6MLD seawater is returned back to sea as sea outfall.

The dosage of chlorine at the rate of 5ppm (continuously) and Biocide at the rate of 600 kgs once in 20 days shall be carried out at the mouth of the intake system. Chlorine at the rate of 5 ppm shall be dosed continuously to the seawater intake system to maintain 0.2 to 0.5 ppm FRC (Free Residual Chlorine) throughout the system. The estimated chlorine requirement shall be 165 kg/hr (i.e., 792MLD×5 ppm).

Biocide shall be dosed at the rate of 120 kg/hr for 5 hours once in 20 days. The estimated biocide requirement shall be 600 kgs (i.e., (792MLD/24)×3.6 ppm×5 hours once in 20 days).

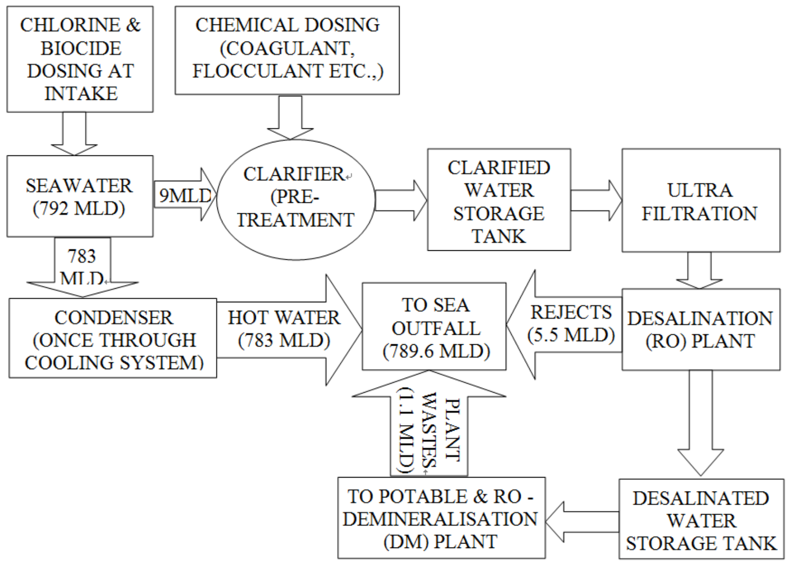

Fig. 3 Block diagram for sea outfall system in steam-electric power plants ts

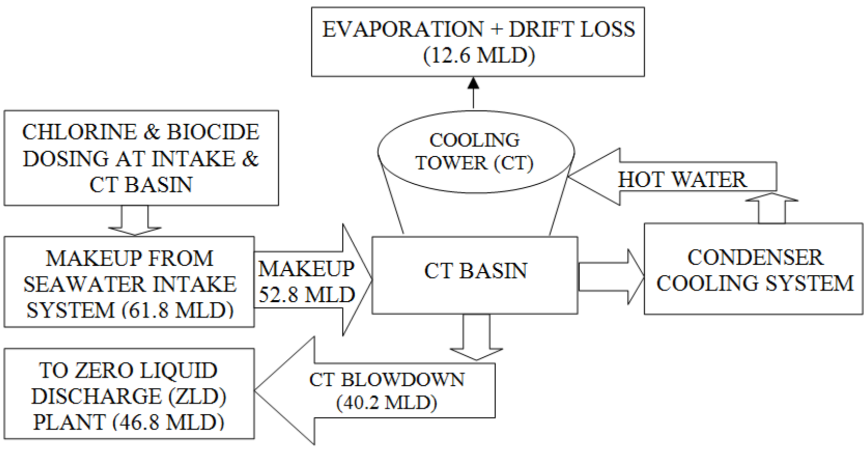

Fig. 4 Block diagram (modified) for the cooling tower configuration in steam-electric power plants

The typical block diagram (as per site condition) for Seawater Outfall system in Steam-Electric Power plants is shown in Fig. 3.

The hot water (783 MLD) return from condenser & Auxiliary coolers, rejects (5.5 MLD) from desalination plant and plant wastes (1.1 MLD) are sent to sea outfall (Maalouf *et al.* 2014, Shawky *et al.* 2013) by gravity through seal pit arrangements. About 789.6 MLD is returned back to sea as sea outfall.

3.2 Case II: (Proposed technique)

3.2.1 Proposed modification in condenser's once through cooling (OTC) system to cooling tower configuration

Table 3 Typical quality of effluents generated from cooling tower blowdown, rejects from desalination plant and other plant wastes from an effluent disposal system of a steam-electric power plants in India

Sl No	Parameters	Units	Values (Min-Max)
1	Temperature	Deg C	32.5
2	pH	--	7.9 – 8.2
3	Biochemical Oxygen Demand (BOD)	mg/l	14.82 (max)
4	Chemical Oxygen Demand (COD)	mg/l	127.4 (max)
5	Total Suspended Solids (TSS)	mg/l	112.71 (max)
6	Sulphide as S	mg/l	0.13 (max)
7	Fluoride as F	mg/l	1.56 (max)
8	Chloride	mg/l	25370.8 (max)
9	Percent Sodium	mg/l	1.456 (max)
10	Oil & Grease	mg/l	< 1.3
11	Boron as B	mg/l	1.04 (max)
12	Sulphate as SO_4	mg/l	2441.4 (max)
13	Zinc as Zn	mg/l	BDL-Below detectable limit
14	Arsenic (as As)	mg/l	0.026 (max)
15	Copper (as Cu)	mg/l	156 (max)
16	Chromium (as Cr)	mg/l	41.6 (max)
17	Total residual chlorine	mg/l	< 1
18	Total Dissolved Solids (TDS)	mg/l	46775.3 (max)

The typical block diagram of the proposed modification for Condenser Cooling system in Steam-Electric Power plants is shown in Fig. 4.

The proposed condenser cooling system is to be configured with cooling tower (Bahadori 2016, Lavasani *et al.* 2014, Shen *et al.* 2015, Singh and Das 2016) such that the part of makeup (52.8 MLD) from seawater intake system (61.8 MLD) is utilized in cooling tower and balance seawater (9 MLD) shall be utilized in existing water treatment plant for plant usages in Steam-Electric power plant. Induced draft cooling tower (IDCT) operates at 1.3 Cycle of concentration (CoC), range of 10℃, wet bulb temperature of 29℃ and Approach of 3℃.

The dosage of chlorine at the rate of 5 ppm (continuously) and Biocide at the rate of 46 kgs once in 20 days shall be carried out at the mouth of the intake system. Chlorine at the rate of 5 ppm shall be dosed continuously to the seawater intake system to maintain 0.2 to 0.5 ppm FRC (Free Residual Chlorine) throughout the system. The estimated chlorine requirement shall be 13 kg/hr (i.e., (61.8MLD/24)×5 ppm).

Biocide shall be dosed at the rate of 9 kg/hr for 5 hours once in 20 days. The estimated biocide requirement shall be 46 kgs (i.e., (61.8MLD/24)×3.6 ppm×5 hours once in 20 days).

To maintain the required water quality for the cooling towers (Bahadori 2016, Lavasani *et al.* 2014, Shen *et al.* 2015, Singh and Das 2016) in Steam-Electric power plant, a portion of the concentrated circulating water, referred to as blowdown (40.2 MLD), would be released to the Zero Liquid Discharge (ZLD) plant (Assiry 2011, News 2015, Ahirrao 2014) and replaced with fresh sea water.

In this proposed cooling water system, cooling tower (Bahadori 2016, Lavasani *et al.* 2014,

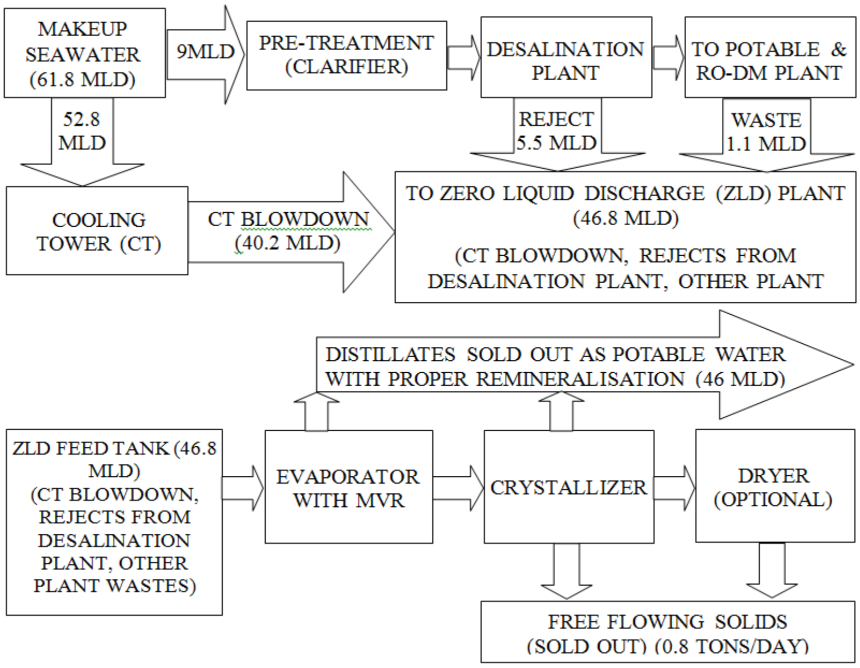

Fig. 5 Block diagram (modified) for zero liquid discharge plant in steam-electric power plants

Shen *et al.* 2015, Singh and Das 2016) is introduced in place of once through cooling system (Raptis and Pfister 2016, Shi *et al.* 2016, Liu *et al.* 2015, Xia *et al.* 2015) to reduce drawal of intake seawater and to meet statutory requirement.

The typical quality of effluents generated from cooling tower blowdown, rejects from desalination plant and other plant wastes obtained from an effluent disposal system is shown in Table 3.

The merits of the proposed modification on condenser cooling system in Steam-Electric power plant are shown in Table 4.

3.2.2 Proposed modification in sea outfall system to achieve zero liquid discharge (ZLD) plant

The typical block diagram (proposed modification) for Sea Outfall system (Maalouf *et al.* 2014, Shawky *et al.* 2013) to achieve Zero Liquid Discharge (ZLD) Plant (Assiry 2011, News 2015, Ahirrao 2014) in Steam-Electric Power plants is shown in Fig. 5. The typical feed water quality for ZLD plant is shown in Table 3.

In this proposed Zero Liquid Discharge (ZLD) plant (Assiry 2011, News 2015, Ahirrao 2014), entire plant discharges i.e., CT Blowdown (40.2 MLD), rejects (5.5 MLD) from Desalination plant, other plants wastes (1.1 MLD) totaling 46.8 MLD is treated in ZLD plant to achieve Zero Liquid Discharge instead of sending back to sea as sea outfall (Maalouf *et al.* 2014, Shawky *et al.* 2013) as followed in earlier existing system.

This proposed ZLD plant ensures Zero liquid discharges and safeguard the ecological system by completely eliminating the hot water discharges into the sea through sea outfall as typically followed in earlier existing system.

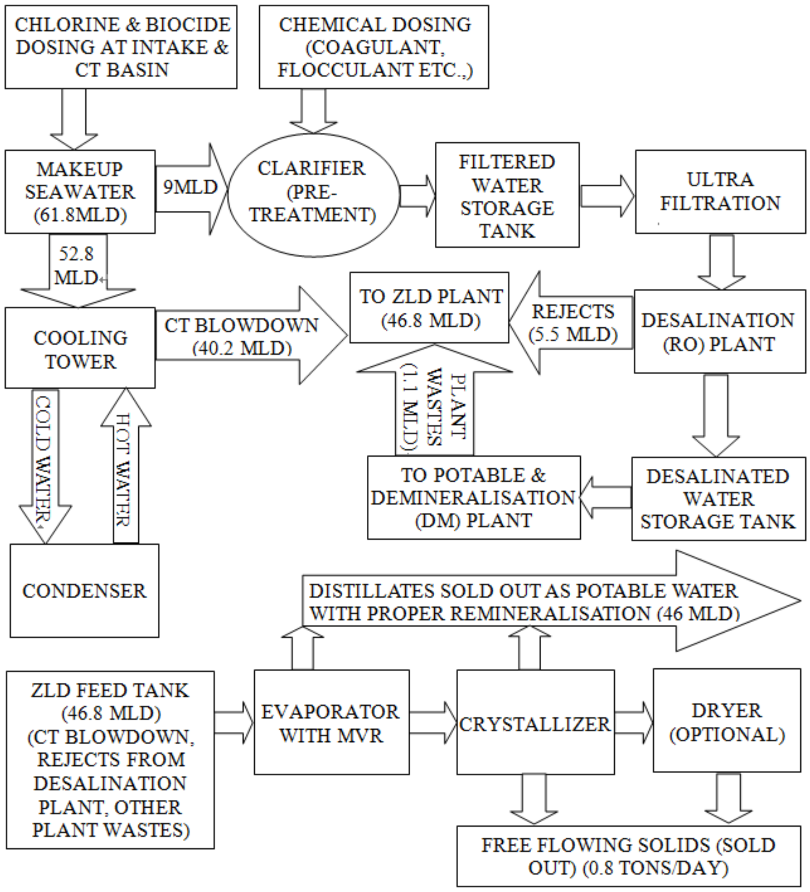

Fig. 6 Flow diagram (modified) showing closed-loop cooling water system & zero Liquid discharge (ZLD) plant in steam-electric power plants

In this proposed effluent disposal system, ZLD plant (Assiry 2011, News 2015, Ahirrao 2014) is introduced in place of sea outfall system to achieve Zero Liquid Discharge and to meet statutory requirement.

The merits of the proposed modification on sea water outfall to achieve ZLD plant (Assiry 2011, News 2015, Ahirrao 2014) in Steam-Electric power plant are shown in Table 5.

The typical flow diagram (proposed modification showing Condenser cooling system and effluent discharge system is given in Fig. 6.

In this proposed Condenser cooling system, the Cooling tower (Bahadori 2016, Lavasani *et al.* 2014, Shen *et al.* 2015, Singh and Das 2016) facility in Steam-Electric power plant essentially needs to utilize the exhaust heat from the turbine. Cooling tower is installed in condenser cooling system to reduce the drawal of intake seawater by 92% and to meet statutory requirement. Cooling tower system requires only makeup seawater from the seawater intake system and thus drawal of intake seawater got reduced. Once through (OTC) system (Raptis and Pfister 2016, Shi *et al.* 2016, Liu *et al.* 2015, Xia *et al.* 2015) requires drawal of seawater at 792 MLD whereas Cooling tower system requires only 61.8 MLD. Thus drawal of intake seawater got reduced up to 92%.

Table 4 Technology proposed against normal or conventional methods in condenser cooling system

Normal or conventional method	Technology proposed
Once Through Cooling (OTC) system (Raptis and Pfister 2016, Shi *et al.* 2016, Liu *et al.* 2015, Xia *et al.* 2015) in Condenser cooling system	Cooling tower (Bahadori 2016, Lavasani *et al.* 2014, Shen *et al.* 2015, Singh and Das 2016) configuration in condenser cooling system
Drawal of seawater intake system for OTC system shall be 792 MLD	Drawal of seawater intake system for Cooling tower configuration shall be 61.8 MLD and it got reduced by 92%
In OTC system, hot water discharges into sea as sea outfall system	In CT system, cold water discharges into ZLD plant to achieve Zero discharge.
In OTC system, ecological system gets affected because of hot water discharges into sea.	Complete elimination of hot water discharges into sea is achieved thereby safeguard the ecological system
Statutory requirement to install Cooling tower (CT) in place of OTC system cannot be achieved	Statutory requirement to install Cooling tower (CT) in place of OTC system can be achieved
There is no operation losses in OTC system	There are operational losses namely Evaporation loss, Drift loss and Blowdown loss in CT system
Not applicable for capital cost	Capital cost for the conversion of OTC to CT system is INR 70,00,00,000

Table 5 Technology proposed against normal or conventional methods in effluent discharge system

Effluent discharge system	
Normal or conventional method	Technology proposed
Sea outfall system (Maalouf *et al.* 2014, Shawky *et al.* 2013)	Zero Liquid Discharge (ZLD) plant (Assiry 2011, News 2015, Ahirrao 2014)
Hot water discharge in sea outfall system shall be 789.6 MLD	There is no discharge of effluents and thus eliminates seawater discharges by 100%
Impacts on sea Ecological system are severe in sea outfall system	There is no impact on sea ecological system
Statutory requirement to achieve zero discharge plant cannot be achieved	Statutory requirement to achieve zero discharge plant can be achieved
Not applicable for capital cost	Capital cost for the installation of ZLD plant is INR 800,00,00,000
Not applicable for revenue generation	Revenue on potable water & free flowing solid production from ZLD plant shall be INR.81,97,20,000 & INR 23,760 respectively

In this proposed effluent discharge system, the ZLD plant (Assiry 2011, News 2015, Ahirrao 2014) facility in Steam-Electric power plant essentially needs to treat the effluent discharges from cooling tower (Bahadori 2016, Lavasani *et al.* 2014, Shen *et al.* 2015, Singh and Das 2016) as blowdown (40.2 MLD), desalination plant as rejects (5.5 MLD) & other plant effluents (1.1 MLD). ZLD plant is installed in seawater outfall system to achieve Zero Liquid Discharges and to meet statutory requirements and to safeguard ecological system by completely eliminating hot water discharges let out into sea. Sea outfall system (Maalouf *et al.* 2014, Shawky *et al.* 2013) let out hot water at 789.6 MLD whereas ZLD plant completely eliminates the discharges by 100% and encourages the sales of potable water which has comes out as distillates from ZLD plant's evaporator and crystallizers at about 46 MLD. Revenue generated out of selling potable water with proper remineralization treatment worked out to be INR 81,97,20,000 per annum (considering INR 60/Cu.m, 330 days/year and 90% availability) and revenue over selling of free flowing solids at INR 23,760 per annum (considering INR 100/Ton, 330 days/year and 90% availability).

The merits of the proposed modification on Condenser cooling system and effluent discharge system are shown in Table 6.

4. Discussion on technology used for condenser cooling system & effluent disposal system in steam-electric power plants

Existing Steam-Electric power plant adopts Once Through Cooling (OTC) system and sea outfall system for condenser cooling and effluent disposal systems which cannot reduce drawal of seawater and hot water discharges into sea.

Hence, it is necessary to go for an enhanced technology for Condenser cooling system and effluent disposal system making it efficient drawal of seawater and zero liquid discharge plant in Steam-Electric Power plants.

Cooling tower configuration and zero liquid discharge has potential to be an alternative to Once through cooling and sea outfall systems for reduced drawal of seawater and zero liquid discharged.

Zero Liquid Discharge (ZLD) plant can generate revenue by selling of distillates as potable water with proper remineralization and free flowing solids as industrial salts to outside vendors.

The Steam-Electric power plant requires coal, fuel and air to produce necessary heat energy and transfers the heat to circulating Demineralised (DM) water in boiler to produce high pressure steam. The superheated steam thus produced from boiler rotates turbine and generator to produce electricity and supplies through grid to end users.

The pretreatment plant (Löwenberg *et al.* 2015, Jamaly *et al.* 2014) uses a clarifier which removes floating/solid particulates or suspended solids from seawater. The suspended solids get settled at the bottom of the clarifier as it becomes dense due to chemical addition and are removed as sludge. The clarified water is then stored in clarified water storage tank which is then pumped to desalination plant to produce sweet/potable water.

Cooling tower configuration in Condenser cooling system is a type of heat exchanger that removes heat from circulating water (CW) and transfers it to atmospheric air. As warm/hot water from the condenser allowed falling through the fill, some of it evaporates, which cools the remaining water and hence it is called as evaporative cooling process. The evaporation of water sustains the cooling process. The cooled water collected at the bottom of the cooling tower is returned to the condenser for removing heat from low pressure turbine exhaust steam through CW pumps and thus the cycle repeats. When water is evaporated in the cooling tower, dissolved solids/salts in the system are left behind and total dissolved solids (TDS) level increases. This will increases the cycle of concentration (CoC) in the circulating water system. CoC refers to the ratio of impurities or the TDS in the circulating water to the TDS in the makeup water. Maintaining a particular CoC in a CW system is mandatory to avoid any deposition in the condenser heat transfer tubes, which hamper the condenser performance and thus the plant efficiency. Hence, blowdown is to be carried out on continuous basis to maintain the CoC. Other losses are evaporation and drift losses. Makeup water is required to meet these losses. This makeup water reduces the drawal of seawater by 92% thereby lowering water crisis and meets the statutory requirement of installing cooling towers in place of once through cooling system.

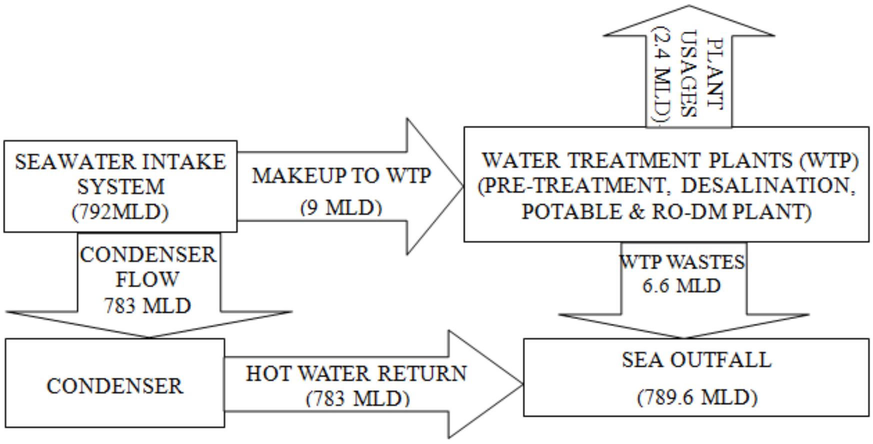

Fig. 7 Typical mass balance showing conventional condenser cooling system and effluent discharge system in steam-electric power plant

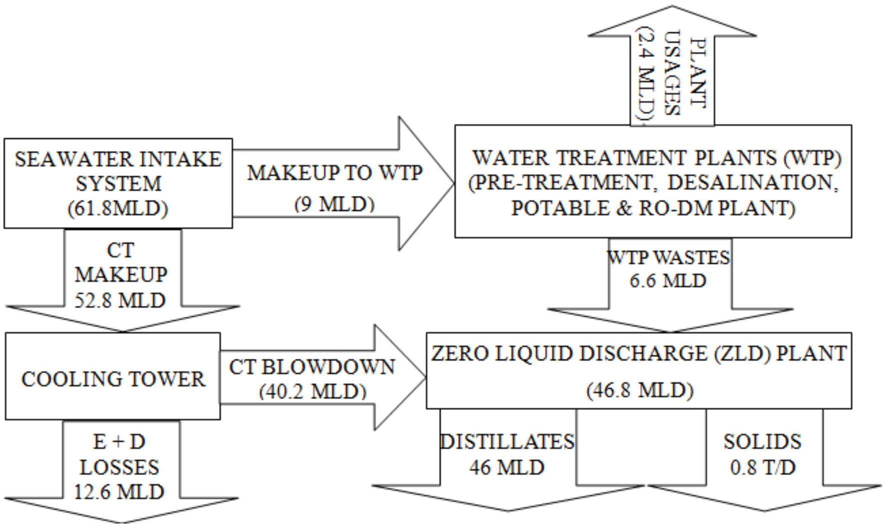

Fig. 8 Typical mass balance showing proposed condenser cooling system and effluent discharge system in steam-electric power plant

The proposed effluent disposal scheme i.e., Zero Liquid discharge (ZLD) plant utilizing the blowdown from CT, rejects/brine from desalination plant and other plant wastes to distillate & salt production units thereby increases revenue to the company thus safeguard the ecological system and meets the statutory requirement of achieving zero discharge plant in Steam-Electric power plants whereas existing one is returned back to sea as outfall.

The typical mass balance showing conventional condenser cooling system and effluent discharge system in Steam-Electric power plant is given in Fig. 7.

The typical mass balance showing proposed condenser cooling system and effluent discharge system in Steam-Electric power plant is given in Fig. 8.

The comparison of technical details shown in Figs. 7 & 8 is given in Table 6.

Table 6 Comparison of Technical details shown in mass balance proposed against normal or conventional method

Parameters	Normal or conventional method (OTC & Sea Outfall)	Technology proposed (CT & ZLD)	Comparison
Basis: Typical 330MW Steam-Electric power plant			
Drawal of seawater intake system	792 MLD	61.8 MLD	Drawal of Sea water intake system got reduced by 92%. i.e., 730.2 MLD
Sea outfall system	789.6 MLD	NIL	Zero Liquid Discharged. 100% elimination of hot water discharged into sea as sea outfall
Revenue over Potable water production	NIL	46 MLD	Revenue at INR 81,97,20,000 per annum (considering INR 60/Cu.m, 330days/year and 90% availability) over Potable water production with proper remineralization treatment is achieved from ZLD plant
Revenue over free flowing solids	NIL	0.8 Tons/day	Revenue at INR 23,760 per annum (considering INR 100/Ton, 330days/year and 90% availability) over free flowing solids from ZLD plant
Capital Cost	NA	INR 870,00,00,000	Capital Cost incurred on conversion of OTC to CT system and ZLD plant
Payback period	NA	10.6 years	Capital cost can be get back within 10.6 years from the revenue of potable water

5. Conclusions

The following conclusions were derived based on the proposed modifications on the conventional techniques followed in the Steam-Electric Power plants pertaining to condenser cooling system and effluent discharge system.

- Cooling tower configuration reduces drawal of seawater intake system by 92%.
- Zero Liquid Discharge system eliminates hot water discharge into sea.
- Distillates from ZLD plant can be sold out as potable water with proper remineralisation treatment thereby increasing revenue by INR 81,97,20,000 per annum.
- Large quantity of free flowing salt can be produced from ZLD plant which can be sold out thereby increasing revenue by INR 23,760 per annum.
- The cooling tower configuration and ZLD system modifications provides better ecological solutions and lower demands of water crisis.
- The capital cost for cooling tower configuration and ZLD plant would costs INR870,00,00,000 with payback period of less than 11 years.

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