COOLING WATER SYSTEM OPTIMIZATION TO REDUCE WATER USAGE

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Abstract

Water is used in many operations such as for extraction, condensation, stripping, process, steam, washing, and cooling. In the cooling water system, it consists of cooling water network, heat exchanger and cooling tower. In the cooling tower, a lot of water is lost due to evaporation, drift and blowdown. Therefore, make up water is needed to replace it. In general, cooling water network is designed using parallel configuration. If it is combined using series and parallel configurations, then there is a possibility that the amount of cooling water can be reduced as the water can be reused from one HE to the other HE. In this work, water pinch analysis was used to optimize the cooling network to get the minimum cooling water. After that, an effort to reduce the make up water was carried out by treating the produced water in order that it can be recirculated in the system. Two methods were applied, that is water pinch analysis and superstructure. ***Using water pinch analysis can reduce the cooling water needed up to 37.6%.*** *Superstructure approach with the mathematical model showed that a reduction of 35.7 % of the cooling water needed could be obtained. A further reduction to 38.9 % was also obtained as the treated water was recirculated as the additional make up water for ....and 40% for.... .*

Keywords : *composite curve, cooling water, make-up water, minimization, water pinch*

INTRODUCTION

The problem with cooling water system is the need for additional antiscalant, blowdown and makeup water requirements are large (Wang et.al, 2008). Cooling water evaporation is the largest water losses in the industry. Makeup water requirement is about 70-80% of water needs in industry. This indicates inefficient energy management (Zhelev, 2005).

As the environmental regulations are more tightened, industry should have started looking for ways to make use of water and thus the waste water disposal is minimized. Many ways can be used to regenerate waste water, for example at this time many industries recirculated cooling water, to remove heat to the environment and to conserve raw water (Kim, Savulescu and Smith, 2001).

In 1994 a method to minimize process water and waste water was introduced by Wang and Smith, namely *water pinch analysis (WPA).* They presented a graphical approach, which was adapted from the heat integration with *pinch* technology. The composite curve of mass pickup concentration vs. composition, can specify a minimum allocation of raw water needs and determine the minimum capacity of waste water prior to its effluent network distribution (Wang and Smith, 1994).

Previous studies mostly concerned with the problems of cooling water treatment, reducing water usage, energy conservation and other problems that often occur in cooling water systems, each was done seperately. Then, Kim and Smith (2001) developed method to integrate cooling water networks and cooling towers. Later, Kim and Smith (2004) introduced a systematic method to design the cooling water network system, which considers the interaction between water usage and cooling systems to reduce makeup water. Makeupwater for water recirculation cooling water tower is needed to cover water loss on evaporation and blowdown.

Cooling water system consists of cooling water towers, cooling water network and recirculation system. The water used in heat exchanger will be hot and will be cooled back in the cooling tower by combining heat transfer between water and air. Blowdown is necessary because the recirculated water decreases by evaporation, so that some particulate matter concentration in the water increases. Total loss of water in the cooling water tower approximately 1% of the incoming flow rate for each decrease of 5.6 ^{o} C temperature and drift loss was 0.3% of the water circulation rate (Kim and Smith, 2004).

Flow in the cooling water tower is assumed to be *counter-current contact.* Cooling water systems to be studied includes three main structures, namely: (a) Cooling Towers (CT), Cooling Water Network (CWN) and (c) Heat Exchanger Network (HEN). All three structures are highly dependent on each other, and therefore should be considered as a whole with a systematic approach. In general, the third structural, optimized separately. Cooling water system can be seen in Figure 1 (Kim and Smith, 2001; Smith, 2005).

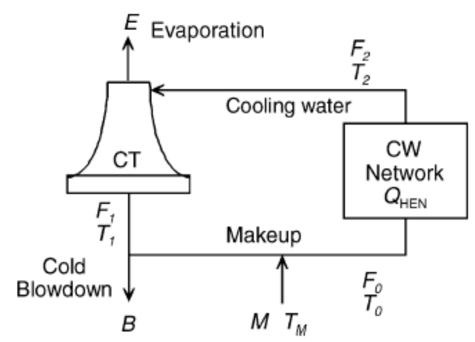


Figure 1: Cooling Water System

From Figure 1 on the model of the cooling water system, one can obtain equations as below (Kim and Smith, 2001).

$$T_1 = f(F_2, T_2, G) \tag{1}$$

$$F_1 = f(F_2, T_2, G) \tag{2}$$

$$E = f(F_2, T_2, G) \tag{3}$$

Make-up/blowdown

$$F_0 = F_1 - B + M \tag{4}$$

$$F_0 T_0 = (F_1 - B)T_1 + MT_M \tag{5}$$

Evaporation loss

$$E=\{C_E (Tin\text{-}Tout)\}F_2/560 \tag{6}$$

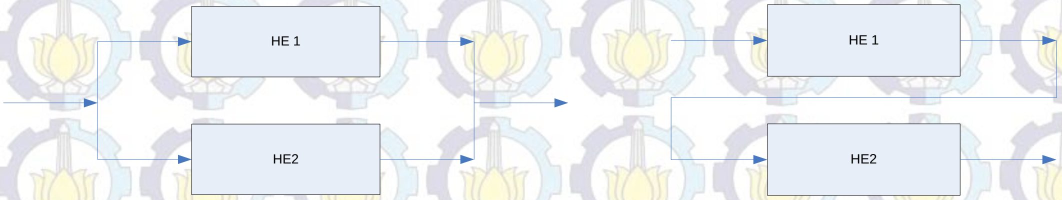
HEN heat load:

$$Q_{HEN} = F_2 Cp(T_2 - T_0) \tag{7}$$

A key factor in designing and operating the cooling water tower is the concentration limits of certain parameters after several cycles. Concentration cycle is defined as the ratio of the concentration of dissolved component in the blowdown flow rate to the makeup water flow rate. Blow down and the makeup water is calculated from the loss of water due to evaporation and drift loss. Overall heat of the cooling water network is needed to determine the desired heat removal in the cooling water tower.

Generally the cooling water quality is not as good as processes water quality. Therefore, there is the possibility fresh make up cooling water is replaced by water reused or effluent of waste water treatment results, provided that their quality can meet the criteria of the cooling water. Reuse of water and effluent of waste water treatment results will reduce fresh water requirements.

Parallel design as can be seen in Figure 2a will maximize the cooling water flow rate, but the returned cooling water temperature to the tower will be minimum. This condition will cause the cooling water tower performance drop, according to the effectiveness formula (Smith, 2005). The effluent temperature of one HE could be still eligible to be input at another HE. Water usage in series, as can be seen in Figure 2b will minimize the flow rate and increase the temperature returned to the the cooling tower. Kim and Smith (2001, 2004) found that the structure of cooling water networks in series is more efficient than parallel.



a. Parallel b. Series

Figure 2: Design of Cooling Water Networks in Parallel and Series

The higher the returned temperature of cooling water, the smaller the flow rate entering the cooling tower, hence increased the effectiveness of the cooling tower (Smith, 2005; Panjeshahi and Ataei, 2008). From the existing data, it can be seen that the effectiveness of water cooling towers can still be improved by increasing the returned temperature and also by minimizing the flow rate.

Panjeshahi and Ataei (2008) increased water recirculation cycle to 15 times, by integrating the cooling water system and waste water treatment by ozone. In general the cooling water recirculation cycle ranges from three to five times, and then discharged directly into wastewater treatment unit. Panjeshahi and Ataei (2008) research showed reduction of the raw water needs by 60%, while the method applied by Kim and Smith showed a 50% reduction.

Minimization of water needs and waste water capacities treatment can be achieved by reuse, reuse and regeneration or reuse and recycling. In practice not all water in the industry is reused, although the quality is still eligible for reuse. For example, the condensate from the steam lost usually useless, but quality is still good to be exploited.

Meanwhile, the *makeup water* for *cooling tower* does not require high water quality to the process, so it can use water that has been used, or even effluent of waste water treatment, as long as their quality is still eligible. In this research, network design will be optimized, so fresh water needs can be minimized.

RESEARCH METHOD

In this study, Water Pinch Method applied to determine the minimum water requirements and the structure of cooling water network. Difficulties with the pinch method arise, when one has a lot of HE and therefore it will be difficult to design the structure of cooling water networks graphically. A comparison between water pinch analysis and superstructure model is investigated for the structure of cooling water network. The existing condition of cooling water network can be seen in Figure 3. Number of existing HE is 14, with each inlet temperature 32 ^{o}C and outlet temperature ranges from 34.4^{o}C to 54.5^{o}C. Heat duty for each HE is obtained from existing condition. The mcp for each HE can be determined by equation (Smith, 2005):

$$Q = mcp\ dT \tag{8}$$

Q value total of the existing is 135.73 MW, with total value of mcp is 20.21 MW/^{o}C or m value is 17, 319 tons/hour. In existing conditions the returned inlet temperature into the water tower is 38.72 $^{\circ}$C. To minimize water requirements, the returned water temperature into the cooling tower can still be increased. In this study, Q values are fixed, so that HE specification will not change.

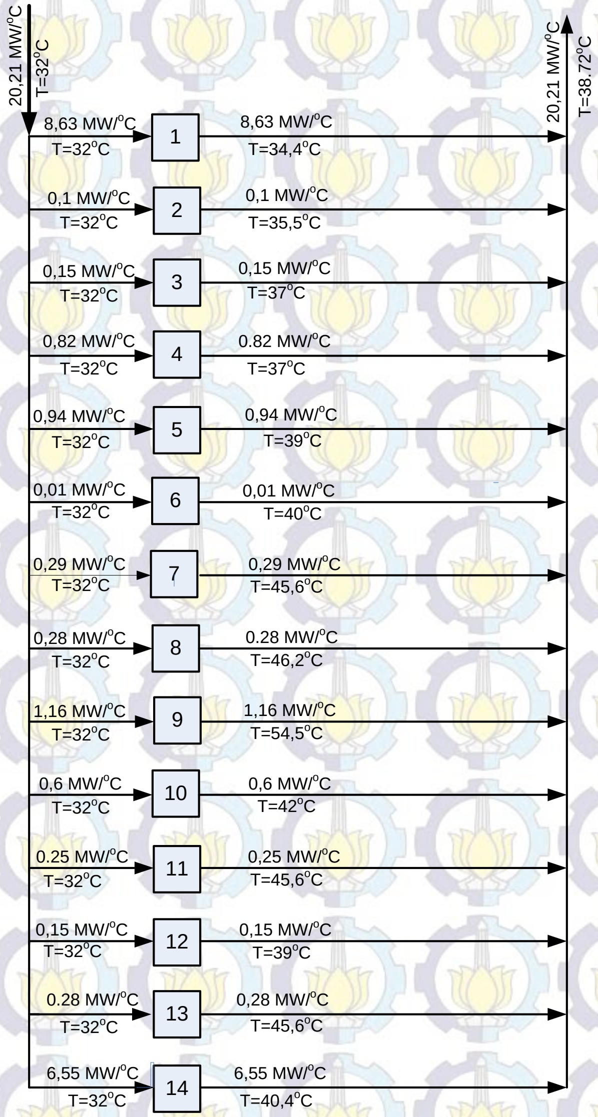


Figure 3: Existing Condition of Cooling Water Network

Water Pinch Analysis Method

Targeting the Minimum Water Requirement

Water Pinch Method optimization consists of two steps, where the first phase is targeting minimum water requirement and the second phase is the design of the network structure of water usage. The purpose of the first phase is to find the minimum water consumption also means a minimum of waste water production by using graphical methods. The second phase is the design of the network structure of water usage by creating a grid diagram to determine the optimal design of the minimum water usage.

Structural Design of Cooling Water Network by Grid Diagram

Once the minimum water requirement is determined, then the next step is to design the cooling water network structure, so that a minimum target could be achieved. Cooling water network design is done by using grid diagrams. This diagram created by dividing the temperature into three different temperature level, namely, the lowest inlet temperature, the pinch temperature and maximum oulet temperature. This classification is used to design the structure of the cooling water network by considering water reuse as much as possible.

Superstructure optimization by Mathematical Models

If the design includes a large number of HE, it will be difficult to do the optimization process graphically, so one can use the superstructure method using mathematical models (Smith, 2005). Superstructure can accommodate all possible configurations of structure, because the entire flow can go into the next process, or likely to bypass. In this method, the superstructure optimization will use mathematical models, run by commercial software Lingo 8.0.

RESULTS AND DISCUSSION

Targeting Cooling Water Requirement

The existing data inlet temperature, outlet temperature and Q for hot stream and cold stream of each HE can be seen in Table 1. The returned water temperature of the cooling water into cooling tower will be 38.72 ° C with mcp is 20.21 MW / ^{o}C.

Table 1: Existing Condition of Hot Stream and Cold Stream

		Hot Stream				**Cold Stream**			
No.	**HE**	**Tcw in (^{O} C)**	**Tcw out (^{O} C)**	**mcp (MW / °C)**	**Q (MW)**	**Tcw in (^{O} C)**	**Tcw out (^{O} C)**	**mcp (MW / °C)**	**Q (MW)**
1	127-C	107.2	36.7	0.294	20.72	32	34.4	8.633	20.72
2	167-C	64	37	0.013	0.34	32	35.5	0.097	0.34

3	128-C	71.3	37	0.022	0.76	32	37	0.152	0.76
4	116-C	115	37	0.053	4.12	32	37	0.824	4.12
5	124-C	51.5	37 37	0.455	6.60	32	39	0.943	6.60
6	142-C	80.3	37	0.002	0.10	32	40	0.013	0.10
7	115-C	96.6	37	0.066	3.92	32	45.6	0.288	3.92
8	130-C	112	37	0.052	3.91	32	46.2	0.275	3.91
9	107-C	87.8	33.5	0.479	26.03	32	54.5	1.157	26.03
10	101-Jimt	131	38.5	0.064	5.95	32	42	0.595	5.95
11	174-C	100.6	40	0.056	3.39	32	45.6	0.249	3.39
12	LO/SO	63	44	0.055	1.04	32	39	0.149	1.04
13	172-C2	387.8	93.3	0.013	3.85	32	45.6	0.283	3.85
14	101-JTC	103	58.5	1.236	55.00	32	40.4	6.548	55.00
	Total							20.206	135.73

Targeting minimum water requirement can be achieved by application of water pinch method. In general, for this method is necessary to know the flow of hot and cold stream for each Heat Exchanger (HE). In the existing condition, there was HE which discharge temperature reaches 54.5 $^{\circ}$C. Outlet temperatures of the existing HE can reach 62 ^{o} C by the additing antiscale. Without antiscale the maximum water returned temperature of cooling water back into the tower is 48.8 ^{o}C (Kern, 1965). From the existing data the composite curve is drawn to minimize fresh water requirements as can be seen in Figure 4.

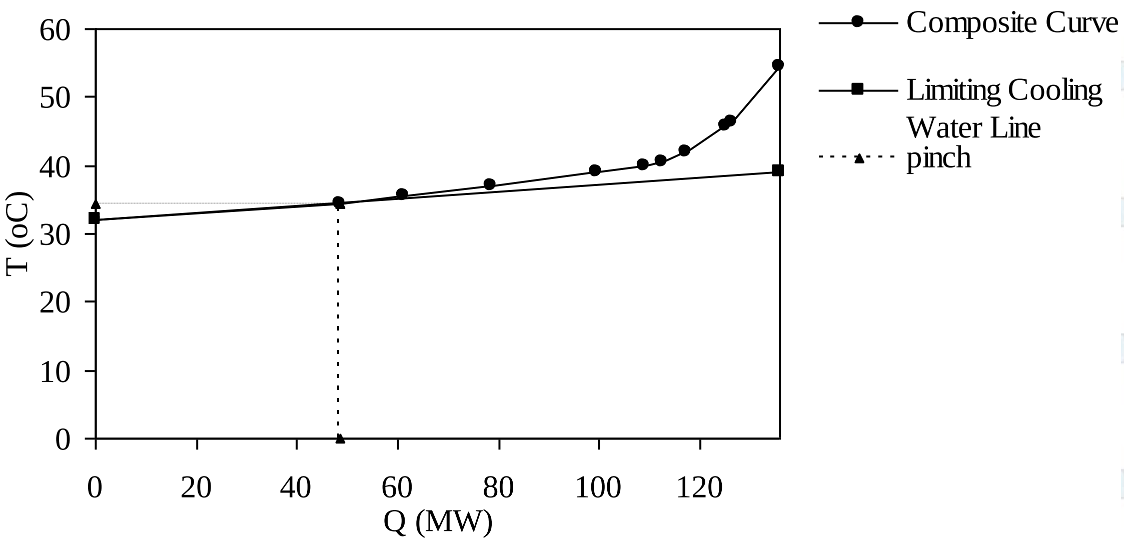


Figure 4: Existing Composite Curve

From Figure 4 can be known the temperature of pinch point is 34.4 ^{o}C and Q is 48.89 MW. From both results it can be determined minimum mcp is 20.21 MW/^{o}C. This result is similar to existing condition. This means there is no cooling water can be reduced. To minimize water demand, the inlet temperature of each HE can be improved, but as constrains Q are fixed and the maximum outlet temperature is 62 ^{o}C.

In the design of minimum water requirements the ΔT_{min} is to be considered. The first step to minimize water requirements is to determine the limiting cooling water profile. For example HE No. 174C, ΔT_{min} outlet hot stream and inlet cold stream is 8 ^{o}C as can be seen in Figure 4. This ΔT_{min} can be optimized to achieve ΔT_{min} at 5 ^{o}C by increasing inlet temperature from 32^{o}C to 35 ^{o}C and outlet temperature to 48.6 ^{o}C.

The same way applied to the whole HE, so ΔT_{min} 5 ^{o} C is obtained. This is to be used as constraints a *feasible* or *infeasible* temperature on the cooling water network design. As long as the temperature cooling water fed into a HE under *limiting cooling water profile*, then considered as a *feasible* temperature.

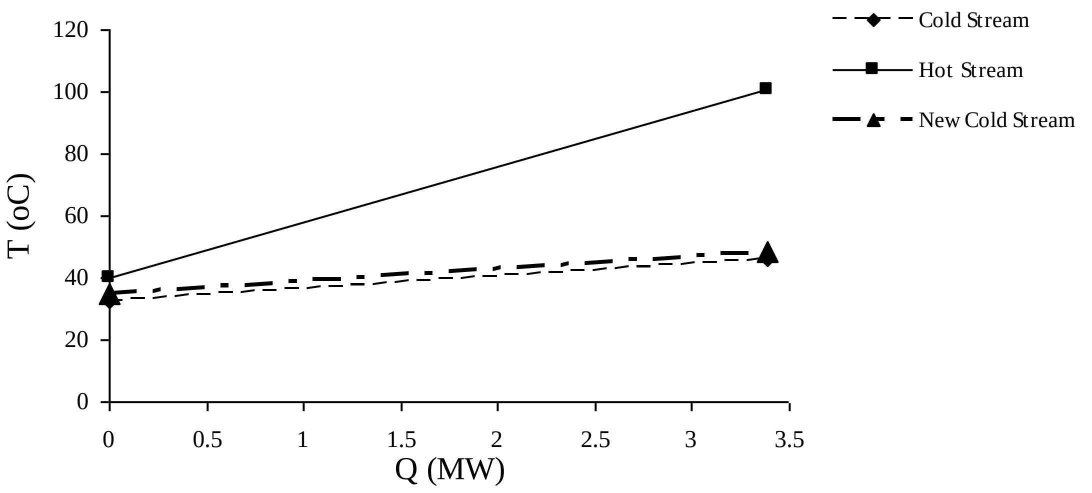


Figure 4: Determination of the cooling water inlet temperature based on ΔT_{min}

From Table 1 it can be seen that some parts of HE has a ΔT_{min} is greater than 5 ^{o} C. From the boundaries of ΔT min, there was an existing condition ΔT min is equal to 1.5 ^{o} C on HE 107C or below 5 ^{o}C, so that temperature for this HE designed to be fixed, which means in accordance with the specifications exiting HE . The above data indicate a potential for minimizing cooling water demand and increasing the returned temperature to the water tower. Temperature limits to be used in the experiment was designed as can be seen in Table 2, where the value of Q is fixed.

Table 2: Design Cold Stream Temperature

No.	HE	Tcw in (^{o} C)	Tcw out (^{o} C)	mcp (MW/ ^{o} C)	Q (MW)
1	127-C	32	34.4	8.633	20.72
2	167-C	32	35.5	0.097	0.34
3	128-C	32	37.0	0.152	0.76
4	116-C	32	37.0	0.824	4.12
5	124-C	32	39.0	0.943	6.6
6	142-C	32	40.0	0.013	0.1
7	115-C	32	45.6	0.288	3.92
8	130-C	32	46.2	0.275	3.91
9	107-C	32	54.5	1.157	26.03
10	101-Jimt	33.5	43.5	0.595	5.95
11	174-C	35	48.6	0.249	3.39
12	LO/SO	39	46.0	0.149	1.04
13	172-C2		62.0	0.283	3.85
14	101-JTC	53.6	62.0	6.548	55
			Total	20.21	135.73

From Table 2 one draws individual stream curves, and composite curve T vs. Q. Composite curve obtained by counting the stream resultant at the same temperature limits. The temperature limits and the resultant calculation are then plotted on the cooling water composite curve. Optimization produces pinch point at a temperature 34.4 ^{o}C and Q 30.28 MW as can be seen in Figure 5.

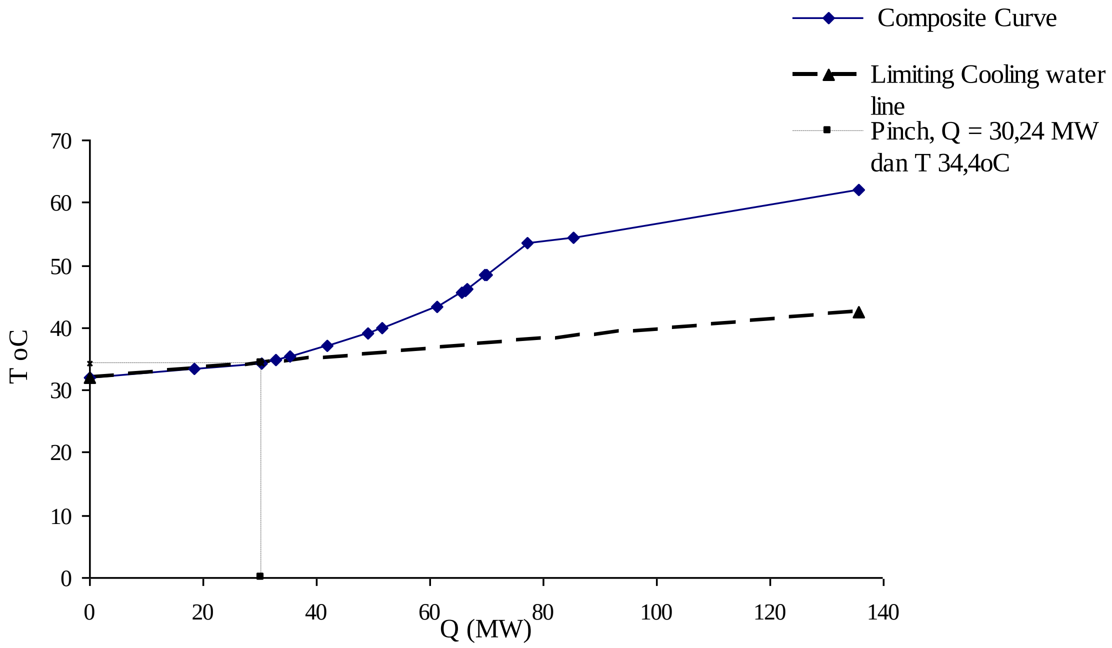


Figure 5: Cooling Water Network Composite Curve

From this pinch point the minimum water demand can be calculated, with a value of 12.61 MW / ^{o}C. This means the water demand is reduced by 37.6%. To achieve the target reduction in water demand, hence the parallel water network design should be changed to a combination of parallel and series. From the minimum inlet temperature, pinch temperature and maximum outlet temperature, one can made grid diagrams. Cooling water network structure designed from the grid diagram is shown in Figure 6.

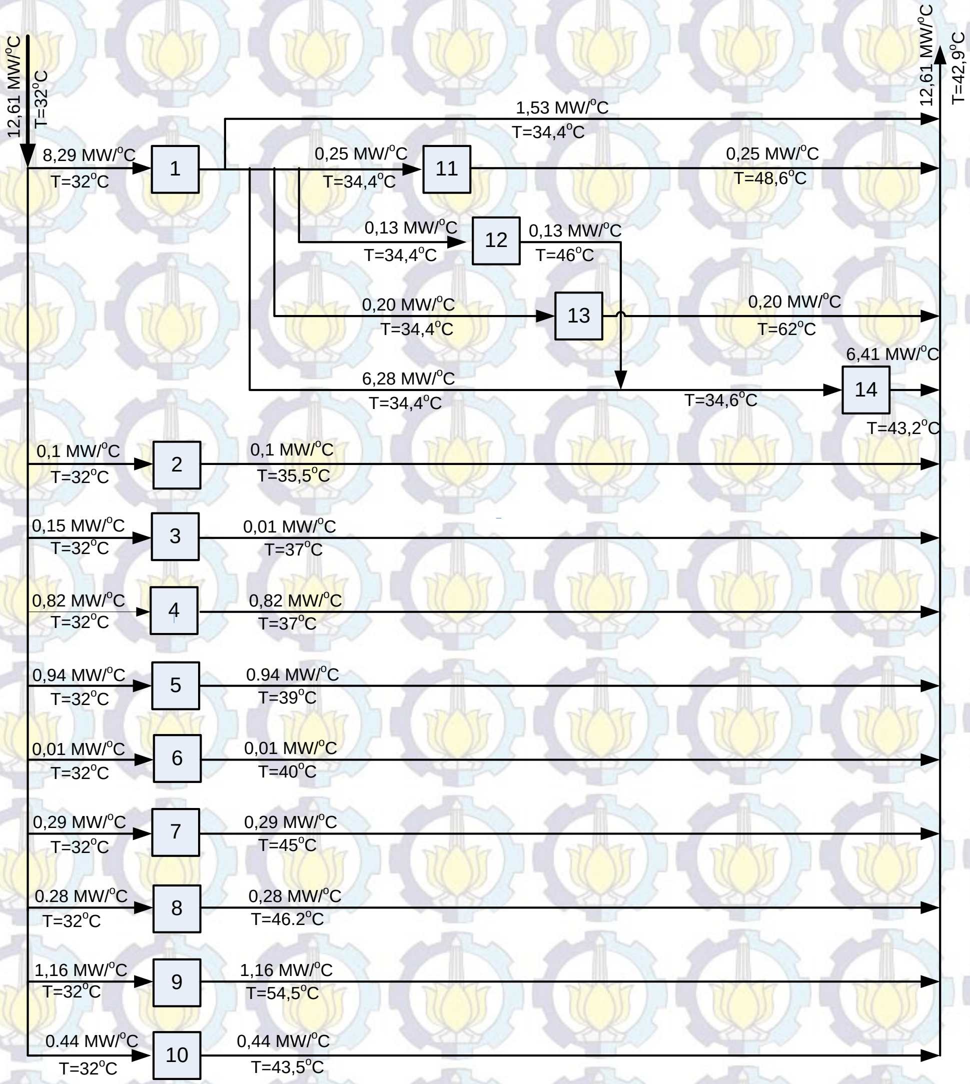


Figure 6: The Optimization of Cooling Water Network by Water Pinch Method

Figure 6 shows that the water reuse can design to four pieces of HE. Water demand of four HE can be met from HE1 or HE 127-C. Outlet temperature of HE1 was still lower than other HE, so it can be reused. Recalculation of the water demand can be done by calculating the new mcp. If the outlet temperature remains, then the mcp is reduced, because Q is fixed. Temperatures returned to the water tower increases from 38.72 ^{o} C to 42.9 ^{o} C.

Superstructure Optimization of Cooling Water Network by Mathematical Model

Cooling water network optimization was created by using Lingo 8.0. Superstructure is the optimization of all the alternative structures that may be obtained from all existing stream. Constraints are inlet temperature, outlet temperature, mcp and Q were made in accordance with the design in Table 2. The superstructure optimization result of the cooling water network can be seen in Figure 7.

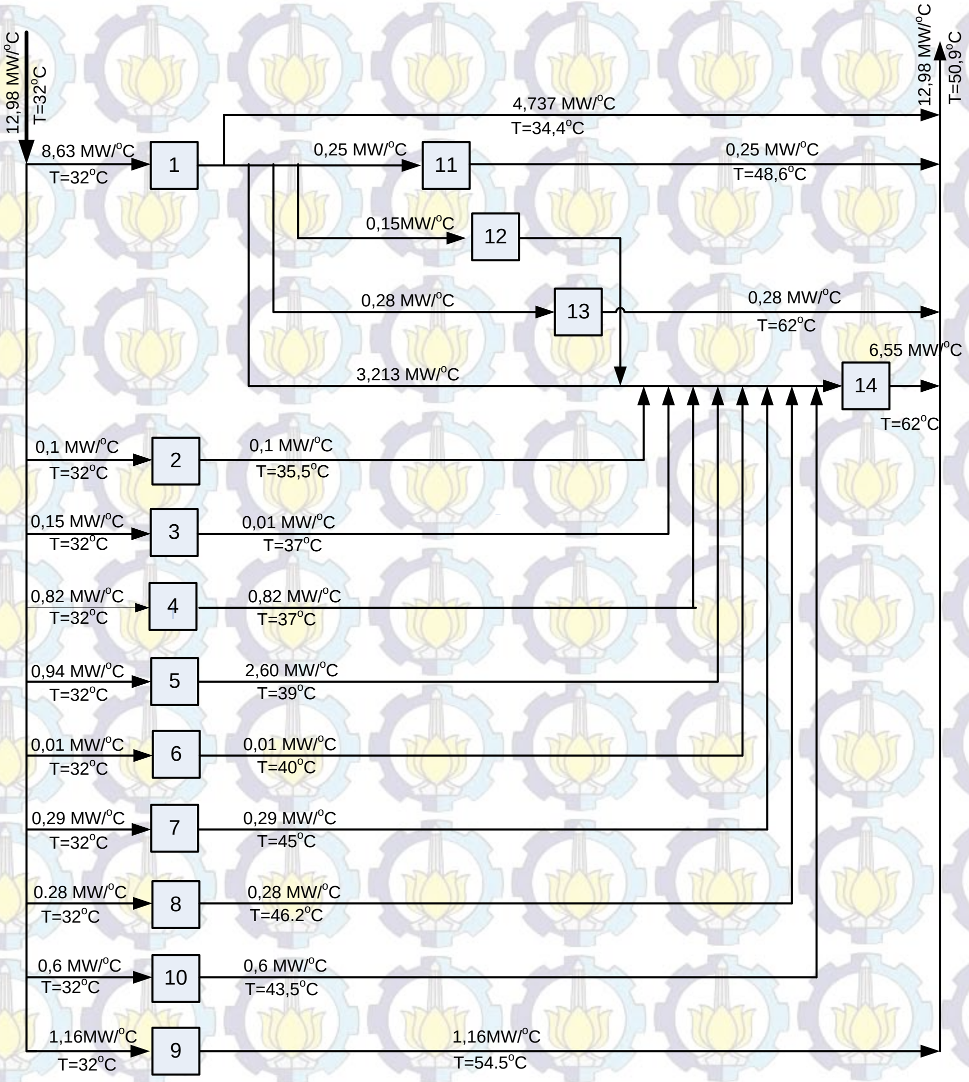


Figure 7: The Optimization of Cooling Water Network by Superstructure Optimization

Superstructure optimization using a mathematical model results obtained a water demand of 12.98 MW/°C. A reduction in water demand was 35.7%. This is 1.8% lower than the water pinch method result. In the superstructure optimization, there is an outlet temperature still eligible for reuse in HE 14. The returned water temperatures increases from 38.72 °C to 50.9 °C.

Design of Make-up Water Reduction

In addition to the cooling water network optimization that can reduce cooling water demand, another thing that needs to be done is to reduce make-up water demand simultaneously, because in general the make-up water is the greatest water demand in the industry.

There are several potential sources of reuse water. The first is condensate, which is fullfil the standard quality of cooling water. The second is blowdown. This water can cause fouling and incrustation, because it is concentrated at the recycling used. Therefore, to obtain the water quality that can be reused, the water from this blowdown should be treated.

Blowdown water quality are as follows, pH of 8.85; colloidal Silica as SiO_2 140 mg / l; Suspended Solid 10 mg / l and COD of 3.5 mg / l (Zeng et.al, 2009). Chemicals are usually contained in the condensate is sulfate (3-10 mg/l), nitrate (0.4 to 15 mg / l as N), nitrite (1-8 mg / l as N), and total suspended solid 10 mg / l, while the organic material was not detected from burning natural gas (Harrold and Baumann, 1985).

Removal efficiency using a sand filter with a residence time of 6 hours for turbidity, suspended solid and colloidal sand greater than 90%, while for the COD is greater than 65% (Ahack et.al, 2009 and Mulligan et.al, 2009). A sand filter can eliminate nitrate significantly. According to Aslan (2005), nitrate was not detected in the effluent produced and according to Ahack et.al, (2009) nitrate removal efficiency achieved was 99%.

Optimization results with mathematical models show that the returned water temperatures was 50.9 ^{o} C, which must be reduced to 32 ^{o} C. It means that there were water losses because of evaporation amounting to 3.4% of recycle water, blowdown was 1% and drift loss *was* 0.3%.

The amount of water returned to cooling water tower after optimization is 11,136.3 tons/hour, which means the loss of water due to evaporation was 378.6 tons/hour. Blowdown is 111.4 tons/hour and drift loss is 33.4 tons/hour, and therefore the make-up water required is 523.4 tons/hour. Existing make-up water demand was 907.62 tons/hour. Therefore a reduction of make-up water was 384.2 tons/hour or 42.3%. To minimize water demand, effluent condensate and *blowdown* were treated simultaneously using a sand filter. Quantity of blowdown to be treated is 111.4 tons/hour and the effluent condensate is 412 tons/hour. There is water demand to operate wastewater treatment plant. To fullfil this demand, the processed water added was as much as 10%, so the quantity of water that will be processed increases to 575.8 tons/hour. The effluent condensate to meet the make-up water demand amounted to 464.5 tons / hour.

From the above data, given the blowdown characteristics as following, the total solid 150 mg/l, COD 3.5 mg/l and the effluent condensate as follows, suspended solid 10 mg/l and nitrate 10 mg/l. Characteristic of blowdown and condensate effluent mixture to be as follows: total suspended solid 37 mg/l; COD 0.7 mg/l, and nitrate 8 mg/l. From these qualities it can be seen that the main problem is suspended solid.

Given that the sand filter can reduce TSS on average 90%, COD by 65% and nitrate by 90%. TSS concentration entering into the cooling water system to be 3.7 mg/l, COD at 0.1 mg/l and nitrate at 0.8 mg/l. Quantity of suspended solid is caught in a sand filter is 33.3 mg / l and that flowed into the reservoir of 3.7 mg / l.

Given that a maximum concentration of suspended solid entering HE network is 10 mg/l, then the concentration of suspended solid from the cooling tower back to the HE network increases to 10.5 mg/l. The optimization result of water demand on the cooling water system can be seen in Figure 8.

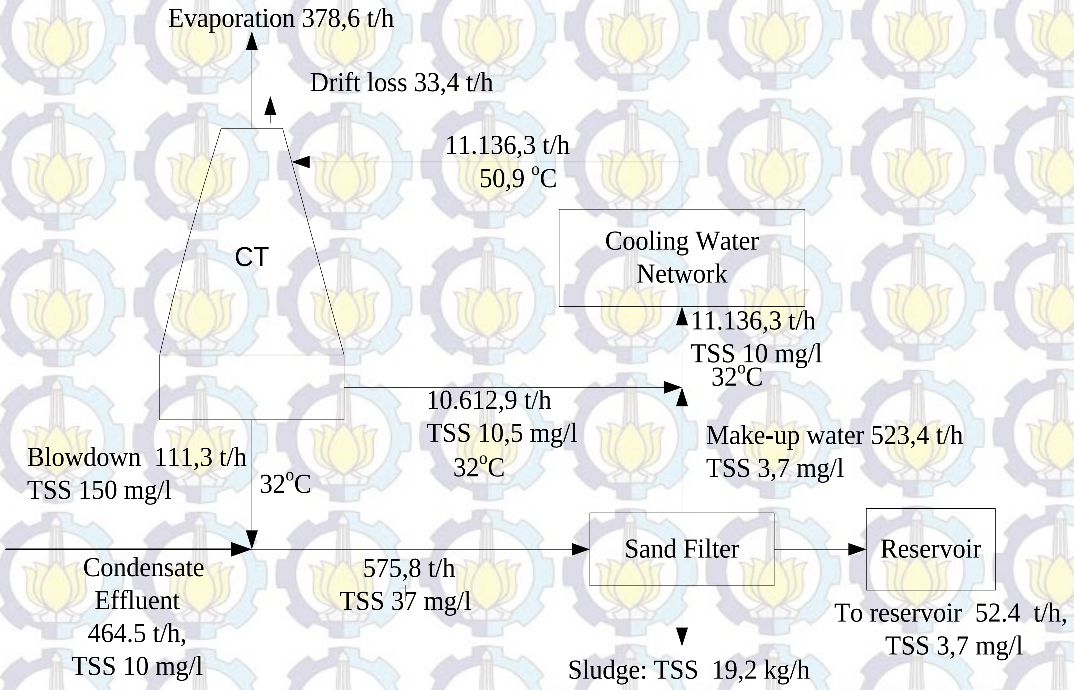


Figure 8: Water Demand of Cooling Water System

CONCLUSION

Using Water Pinch Analysis one can obtained a water demand of 12.61 MW / ^oC, or a water demand reduction of 37.6% of the existing condition. If one use Superstructure optimization a water demand of 12.98 MW/$^{\circ}C$ can be obtained or a water demand reduction by 35.7%. If the make-up water can be filled withreplaced by effluent from the blowdown and condensate, the overall cooling water systems can reduce water demand 40.6% by water pinch analysis and 38.9% by superstructure optimization.

NOTATION LIST

A: heat transfer area (m $^{2)}$

B: *blow down* flow rate (kg / hr)

CP: *Heat capacity flow rate* (MW / $^{\circ}$C)

Cp : *Heat capacity* (kJ/kg. ^{o} C)

CT : *Cooling Tower*

CW: *Cooling water*

E : *Evaporation loss* (kg/hr)

C_E = evaporation factor (0.75 - 1)

e : effectifness

$F_{o:}$ inlet flow rate to the CW *Network* (kg / hr)

$F_{1:}$ outlet flow rate from CT (kg / hr)

$F_{2:}$ inlet flow rate to CT (kg / hr)

G: dry air flow rate (kg / sm $^{2)}$

M: *make-up* water flow rate (kg / hr)

Q: Heat duty (MW)

$Qi_{in:}$ Inlet heat duty of each HE (MW)

$Qi_{out:}$ Outlet heat duty of each HE (MW)

T: Temperature (^{o} C)

$T_{1:}$ The outlet temperature (^{o} C)

T_{2} : The temperature outside the network (^{o} C)

$T_{iout:}$ outlet temperature of each HE $^{(o}$ C)

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