Analysis of Cooling Water Systems in a Petroleum Refinery

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An important area in process integration is the development of methodologies to minimize water and energy use in industry. More than 20 % of the energy consumption in industry is associated with cooling and heating water. This paper presents analysis and optimization of a re-circulating cooling water system, with the aim to satisfy any supply conditions for the cooling tower. The part of the atmospheric crude oil distillation unit was chosen for analysis and synthesis of cooling water systems by the Kim and Smith design (KSD) method. The load of the cooling tower and the cost related to the cooling water system could be reduced by modifying the configuration of the heat exchanger network. In this paper, the KSD methodology for a developed heat exchanger network is expanded with the principle based on the heuristic algorithmic water sources diagram procedure (WSD) to synthesize the mass exchange network.

These procedures are advantageous compared with other methodologies since hand calculation is used, a very useful feature for process engineers. The cooling water network was synthesized, leading to a 40 % reduction in cooling tower load, and consequently, lower operating costs and water consumption.

Key words:
cooling tower, heat exchanger network, cooling water, composite curve

Introduction

The traditional cooling water system can be regarded as an integrated system consisting of three main components: cooler network, cooling tower, and circulation water pump. The central unit of such system is the cooling tower in which hot water is cooled by air and returned to the process. A simplified diagram of such system is shown in Fig. 1.

Since 2001, there has been intensive research in the area of integrated design of cooling water systems in the chemical and petrochemical industries. For better cooling tower performance and increased cooling tower capacity, modification of the cooling water network is very important[1]. An extensive report on recirculating cooling water systems has already been provided by many authors. Smith et al. developed and described a grass root design method[2] and distributed system for effluent cooling[3]. Optimum design of cooling water systems for energy and water conservation[4,5] was performed for the rejection of waste heat to the environment. Progress in development of cooling water systems has expanded and a comprehensive simulation model of a recirculating cooling system has been developed to account for the interaction between the cooling tower performance and the heat-exchanger network configuration[6]. Castro et al. synthesized a cooling water system with multiple cooling towers[8]. The objective was to minimize the total annual cost.

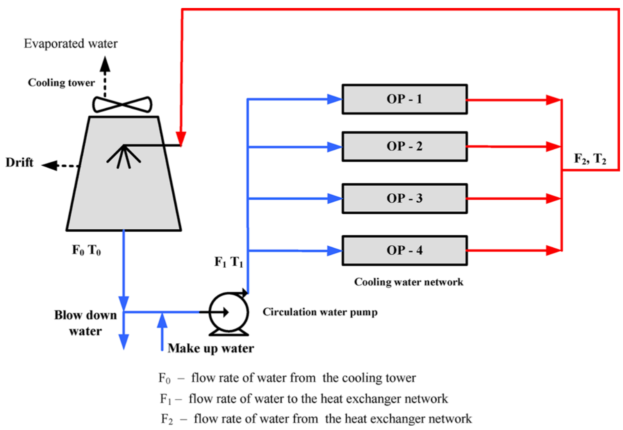

Fig. 1 – *Closed loop cooling water system*

Cooling water requirements of an oil refinery depend on processes in which the water is used for cooling, and on the complexity of the cooling water network configuration. The majority of designs in refineries still employ networks of water coolers that operate in parallel, which implies that heated cooling water is collected to form one or several streams,

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which are sent to the cooling tower regardless of their temperature. Moving from parallel to the series arrangement of cooling water network increases the efficiency of the cooling tower, decreases the temperature differences in the cooling water heat exchangers, and increases the pressure drop through the cooling water network. Water cooling in the processing industry contributes significantly to operating costs, so minimizing external cooling requirements through heat integration is essential for increasing profitability.

Recirculating cooling water systems

The chemical processing industry, including petroleum refineries, often uses closed-loop cooling water systems to supply the necessary cooling water. Several studies on recirculating cooling water have been reported in the literature varying from insight based on pinch analysis[7,10,16] to mathematical based optimization approaches[15,17,18]. A few authors use mathematical modelling techniques, which involve superstructure optimization in situations where multiple cooling water sources are involved[9,11]. In practice, there are systems with multiple cooling towers. A mathematical optimization technique for debottlenecking cooling water systems characterized by multiple cooling towers with different supply temperature was presented in several previous papers[8,15,17].

Usually, a closed-loop cooling water system is arranged in a parallel configuration, as presented in Figure 1. In such a configuration, all the hot cooling water, regardless of its temperature, is collected and mixed upon exiting a process. This leads to decreased temperature and increased flow rate of the hot cooling water through the cooling tower, which lowers the heat transfer driving force. Since not all processes require cooling water at the lowest available temperature, as encountered in the cooling-tower's outlet, a cooling water system can possibly be arranged in a serial configuration. Such a configuration enables reuse of the cooling water, leading to lower required flow rate and higher water temperature in the cooling system, providing greater driving forces for heat transfer and lower operating costs.

Figure 2 shows the cooling water system of a typical refinery in a parallel configuration. It can be seen that after it has been used in different refining processes, the cooling water is collected and routed to cooling towers.

Cooling requirements in a refinery depend on the processes using cooling water and on the integration level of the heat exchanger network. In this study, a closed-loop cooling water system of a refinery is analysed to prove that the cooling tower load can be reduced by different configuration of the heat exchanger network using the KSD (*Kim & Smith Design*) graphical method, expanded by the principle based on the

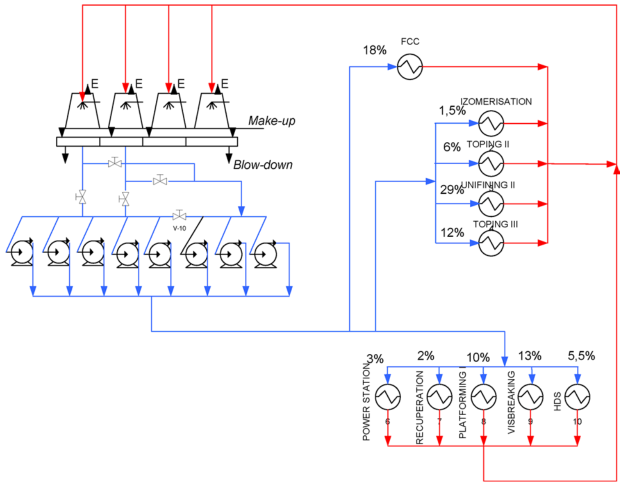

Fig. 2 – *Typical flow of cooling water in refineries*

water sources diagram (WSD)[13]. The combination of these two methods is advantageous because it is easy to apply in different process features, and all calculations can be done by hand. The method generates flow sheet and information acceptable and understandable for process engineers in practice. Mathematical programming knowledge of applied mathematics as well as the knowledge of how to mathematically describe the process. The mathematical models include a variety of functions, equations and formulas that are not real-world-engineer-friendly. Kim and Smith have developed and applied a graphical technique for maximization of cooling tower performance through minimization of supply water to the cooling water network. The KSD graphical method[2] utilizes limiting profiles of cooling water flows through heat exchangers to construct the composite curve. By determining pinch temperature and heat load, flow heat capacity (CP) is calculated with minimal water flow-rate through the cooling tower.

The minimal water flow rate through the cooling tower is determined in three steps. The first step is to determine feasible operating envelope of a cooling water system from cooling water composite curve, taking into consideration practical limits of the system. The second step is to explore the feasible operating envelope determined in the first step, to determine the minimal cooling water flow rate. The last step is cooling water network synthesis.

Cooling water composite curve

Figure 3 shows the feasible region for targeting the water supply of a recirculating cooling system. The cooling water network can be changed within the feasible operating envelope. The feasible area is determined by minimal water flow rate (maximal reuse) and maximal water flow-rate (parallel configuration)[4,5,6]. When determining the feasible area, several practical issues should be considered: the cooling water system cannot

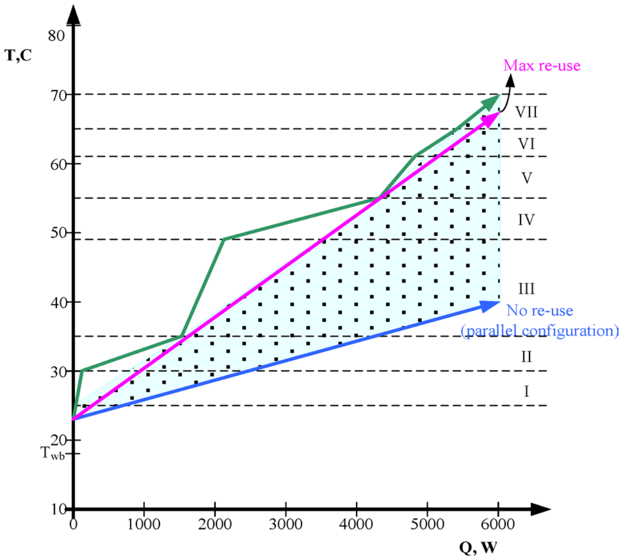

Fig. 3 – *Composite curve with feasible operating envelope*

operate above the temperature of the returning hot water because it might cause fouling problems, corrosion and problems with the cooling tower's packing.

Case study

The applicability of the proposed methodology for designing a recirculating cooling water network is demonstrated on part of the atmospheric crude oil distillation unit in a local refinery. The analysed parallel cooling water system had eight heat exchangers, with total cooling water flow rate of 311 t h^{-1}. The central unit in this system is the cooling tower with a water temperature of 23 °C at the exit. After passing through heat exchangers, it is collected and returned to the cooling tower at about 40 °C.

The current state of the cooling water system is given in Tables 1 and 2. Table 1 shows the flow rates of the recirculating cooling water, together with inlet and outlet temperatures. The temperature, flow rate, and cooling duty are given in Table 2.

Table 1 – *Current state of the analyzed system*[14]

Heat exchanger	Process stream	Flow rate t h^{-1}	Flow rate CW, m^3 h^{-1}	$T_{in,CW}$ °C	$T_{out,CW}$ °C
E-1	gas	7.06	7	23	39
E-2	gasoline	75.20	75	23	39
E-3	petroleum	41.90	32	23	39
E-4	light gas oil	107.80	90	23	44
E-5	naphtha	24.10	27	23	39
E-6	LPG	8.60	12	23	34
E-7	top splitter	23.80	37	23	34
E-8	bottom splitter	49.60	32	23	39

Table 2 – *Process stream data for this example*[14]

Heat exchanger	T_{Hin} °C	T_{Hout} °C	T_{Cin} °C	T_{Cout} °C	CP, kW °C^{-1}	Q, kW
E-1	70	40	25	55	4.27	128
E-2	70	40	25	55	46.8	1405
E-3	64	40	25	49	24.5	587
E-4	80	45	30	65	62.6	2190
E-5	75	40	35	70	14.4	504
E-6	60	35	30	55	6.0	150
E-7	66	35	30	61	15.2	471
E-8	60	40	35	55	29.5	590
						Σ = 6025

The data for cold streams in Table 2 (columns 4 and 5) are estimated with the same temperature difference between the inputs and outputs of hot and cold streams. For maximum reuse at serial configuration, T_{Cout} is increased by an average of 15 °C in relation to the data of Table 1 (last column), actual data for a parallel configuration.

Characteristics of the cooling tower

The inlet temperature of the hot water in the cooling system must be < 70 °C. The wet bulb temperature and the ambient temperature are taken at average values T_{WB} = 18 °C and T_{amb} = 25 °C.

Construction of composite curve

The design of cooling water network is based on the cooling water composite curve, which represents overall limiting conditions of the entire network. A composite curve is constructed using data in Tables 1 and 2, with aim of maximal reuse of water (Figure 4 a and b).

The water line began at temperature of 23 °C, and pinch point was found at 55 °C. Targeted minimal cooling water flow capacity is calculated from the heat transferred to the pinch point and the temperature at the pinch point, using the following equation:

$$CP_t = \Delta Q_{pinch} / \Delta T_{pinch}$$

$$CP_t = \frac{5093.1}{55-23} = 159.16\ \text{kW °C}^{-1}$$

Required targeted minimum amount of water from the tower is calculated as:

$$F = \frac{159.16\ \text{kW °C}^{-1}}{4.183\ \text{kJ kg}^{-1}\ \text{°C}^{-1}} = 38.05\ \text{kg s}^{-1} = 136.96\ \text{t h}^{-1}$$

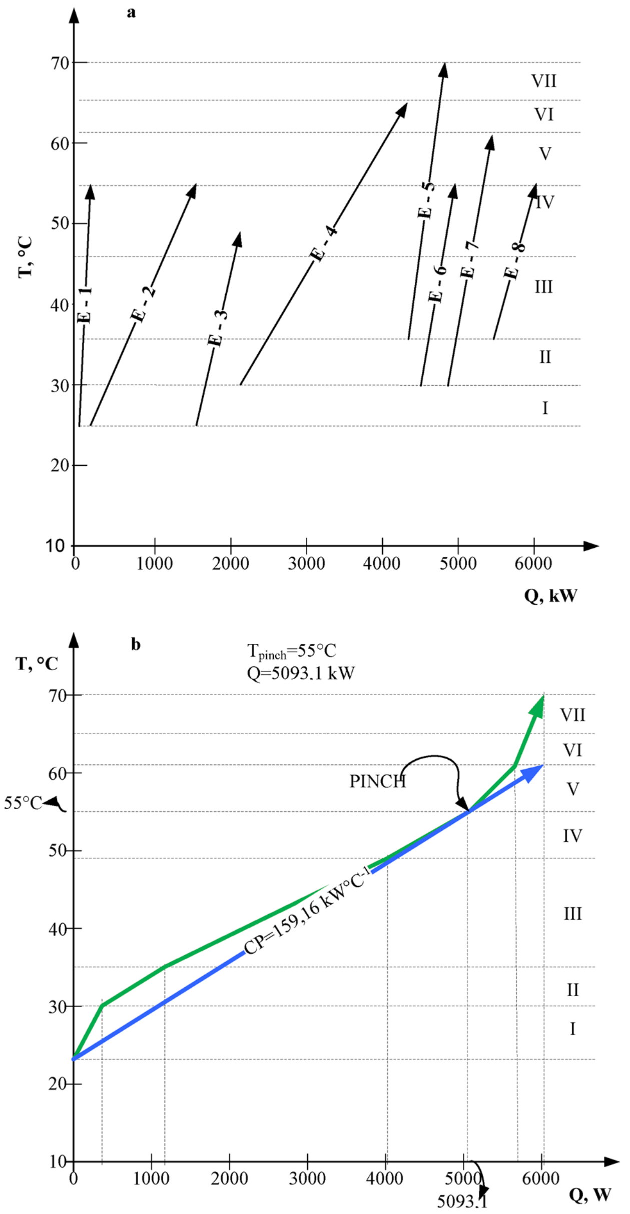

Fig. 4 – *Cooling water composite curve and targeting for maximum reuse*

Since operating costs are proportional to cooling water flow rate, minimal cooling water in this case is optimal.

Cooling water network synthesis

The cooling water network was synthesized using target minimum water flow rate of 136.96 t h^{-1} and flow capacity of 15.16 kW °C^{-1}.

Temperature intervals are sorted in order of increasing water temperature. The procedure was developed by combining the KSD methodology and WSD principles.

For synthesis, the following steps are required:

Step 1. Divide the problem into temperature intervals, which are limited by single external cooling water source (cooling tower water at 23 °C) and the internal water sources at various temperatures (Figure 5).

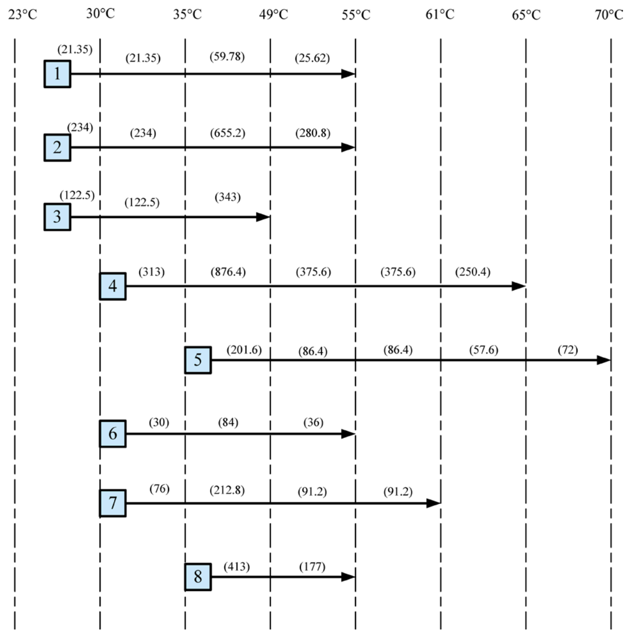

Fig. 5 – *Cooling water streams with transferred heat in bracket*

Step 2. Represent each operation by an arrow from the respective inlet to outlet temperature. This particular system consists of 7 intervals.

Step 3. For each temperature interval, the total number of streams, the number of streams using external cooling water source, and the number of internal water sources must be determined. For every stream in an interval, new flow capacities and transferred heat are calculated by the following equation.

$$CP_{exw/inw} = \Delta Q_{k,j} / \left(T_j - T_{j-1}\right)$$

where $CP_{exw/inw}$ is flow capacity external water source or internal water sources, T_j and T_{j-1} are interval temperature, $\Delta Q_{k,j}$ is transferred heat between intervals for each stream.

The development of a cooling water network is shown in Figures 6–13. Final network diagram with *pinch* point is shown in Figure 11.

By adding the required flow capacities for each stream utilizing an external source, the flow capacity for the cooling tower is obtained at 159.16 kW °C^{-1}, corresponding to the targeted water flow rate obtained from the composite curve. *Pinch* point is at 55 °C. The flow capacities of the cooling tower were changed (blue lines in Figure 13) from 159.16 kW °C^{-1} to 92.2 kW °C^{-1} (62.6 + 14.4 + 15.2). The new network configuration with reduced cooling tower load is shown in Figure 14.

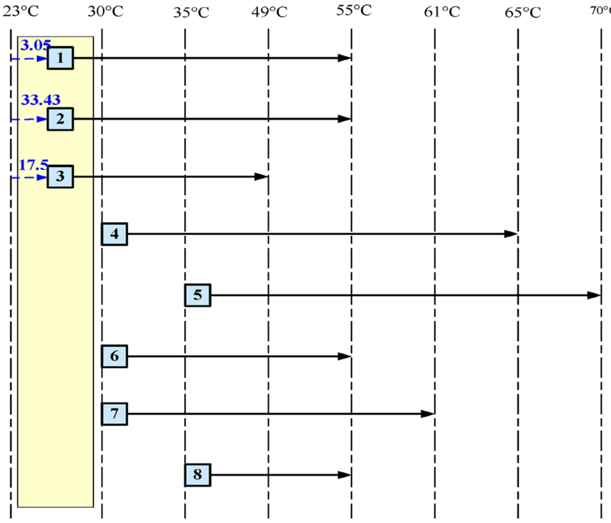

Fig. 6 – *Calculation CP for interval 1*

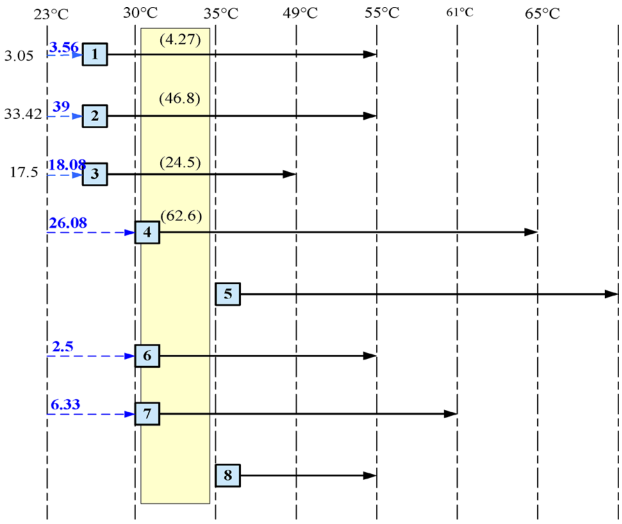

Fig. 7 – *Calculation CP for interval 2*

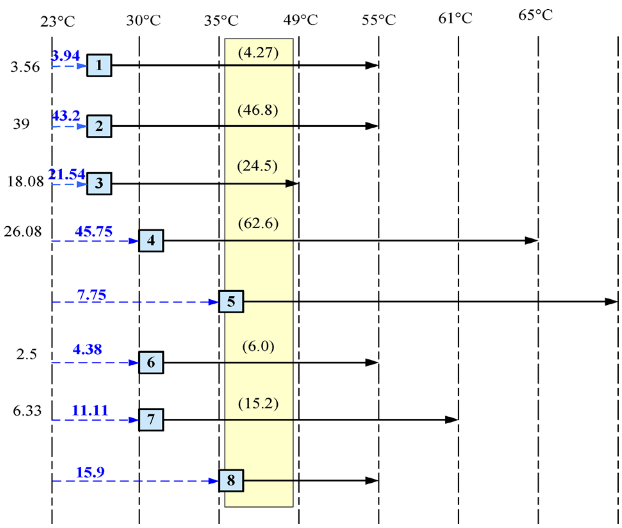

Fig. 8 – *Calculation CP for interval 3*

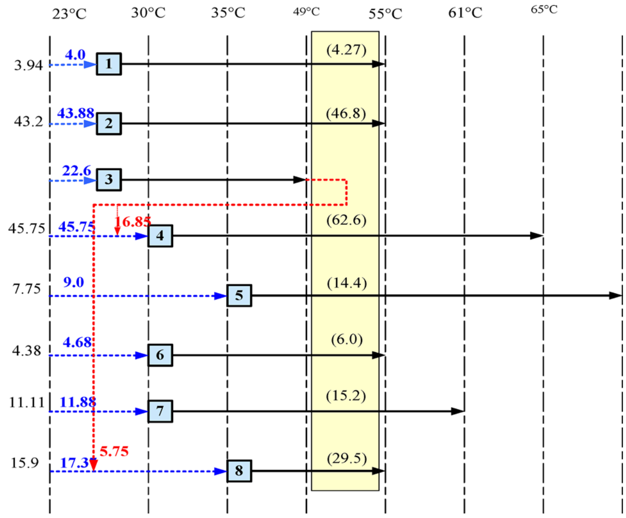

Fig. 9 – *Calculation CP for interval 4*

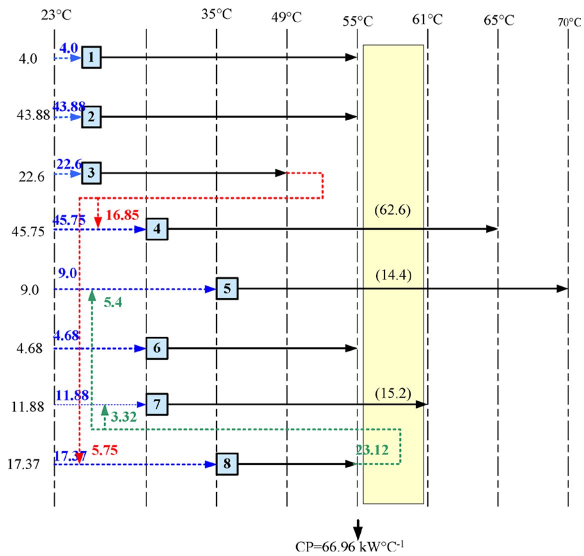

Fig. 10 – *Calculation CP for interval 5*

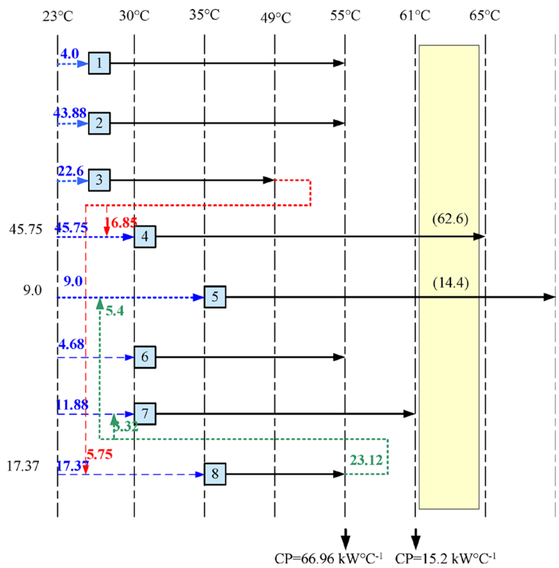

Fig. 11 – *Calculation CP for interval 6*

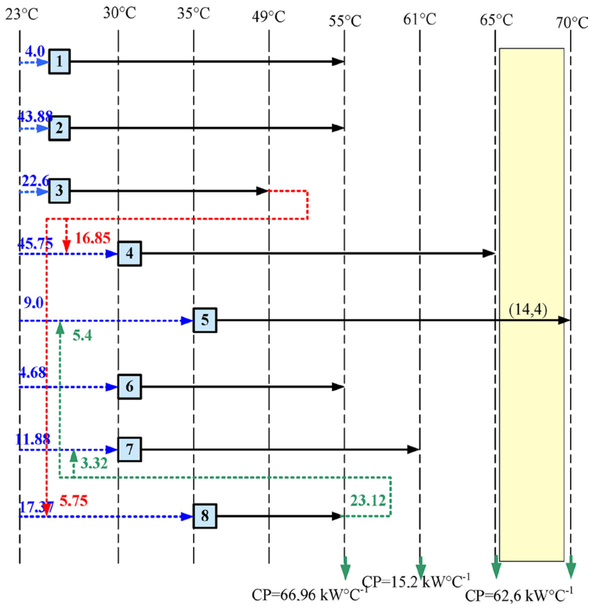

Fig. 12 – *Calculation CP for interval 7*

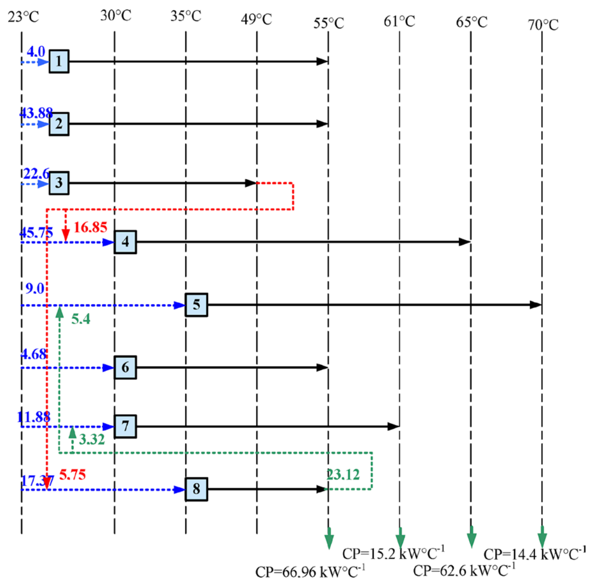

Fig. 13 – *Final network diagram*

Operating costs and detailed system analysis

Operating costs are calculated using the following equation:

$$OC = 2.4094 \cdot 10^{-3}(PP) + 44(F_{air}) +$$
$$+ 110(F_{in}) + 2275.132(M) + 1138(B)^4$$

where PP is pumping power, F_{air} is tower air flow rate (t h^{-1}), M is make-up flow rate (t h^{-1}), B is blow-down flow rate (t h^{-1}) and F_{in} is cooling cooling tower water flow rate (t h^{-1}).

Table 3 – *Comparison base case and KSD design methods*

	F_2, t h^{-1}	T_2, °C	T_0, °C	E, t h^{-1}	B, t h^{-1}	M, t h^{-1}	OC 10^3 \$/year
Base case	305	40	23	7.93	3.97	11.9	151.51
KSD method	136.96	60.9	23	7.93	3.97	11.9	85.02

Cooling tower inlet flow rate of 305 t h^{-1}, as calculated from heat balance, is by 6 t h^{-1} lower than cooling water inlet flow rate, due to network losses.

New piping costs should be taken into consideration for a more accurate analysis. By reducing the cooling water flow rate, operating costs were reduced from 151,510 \$/year to 85,020 \$/year. Additional reduction in operating costs could be achieved by implementing air coolers. In this case, two air coolers that provide 260 kW of cooling power were inserted downstream of operation 3. After that modification, an additional internal source became available at 37.5 °C, with flow capacity of 22.58 kW °C^{-1}. Cooling water network was then developed using the same procedure, and the solution is given in Figure 15. By implementing air coolers, the total flow capacity was reduced to 144.6 kW °C^{-1}, and with it, the water flow rate to 124.4 t h^{-1}. The overall results are given in Table 4.

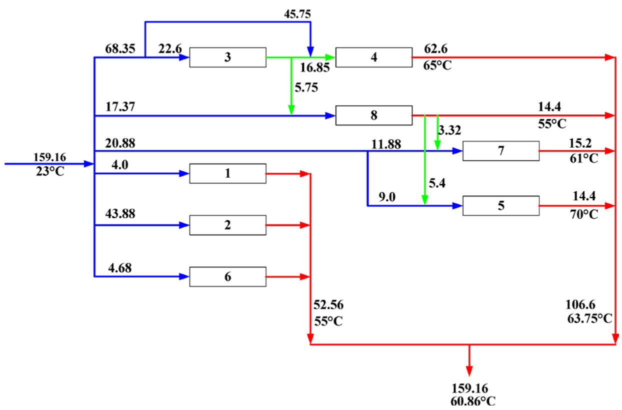

Fig. 14 – *Cooling water network design with target return temperature of 60.86 °C*

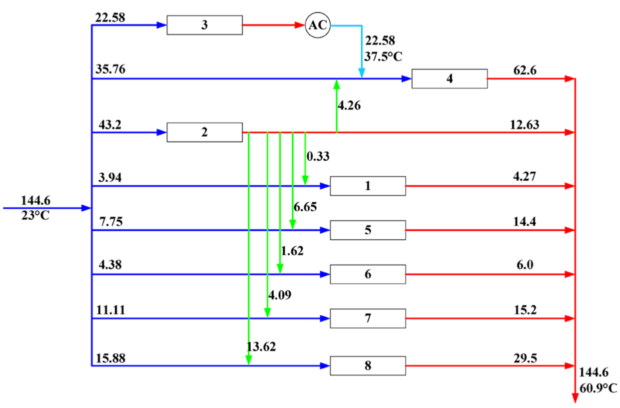

Fig. 15 – *Cooling water network after implementation of air-cooler*

Table 4 – *Comparison of different configurations of cooling water systems*

	F_2, t h^{-1}	T_2, °C	T_2, °C	E, t h^{-1}	B, t h^{-1}	M, t h^{-1}	OC $\cdot 10^3$ $/year
Base case	305.00	40	23	7.93	3.97	11.9	151.51
KSD method	136.96	60.9	23	7.93	3.97	11.9	85.02
With air coolers	124.40	60.9	23	7.22	3.6	10.8	82,75

Conclusion

By implementation of a serial cooling water system configuration, developed by using the KSD method expanded with principles based on the water source diagram, a significant reduction in operating costs has been achieved. This allows better cooling tower performance and increased cooling tower capacity. Additionally, the lower recirculation water flow rate and its higher temperature will benefit the heat transfer process in the cooling tower, further reducing operating costs. By introducing additional air coolers, besides reducing operating costs, fresh water consumption can also be reduced.

Nomenclature

CP – heat capacity flow rate, kW ºC^{-1}
OC – operating cost, $/year
Q – total heat load, kW
T_0 – outlet cooling water temperature of cooling tower, ºC
T_1 – inlet temperature of the heat exchanger network, ºC
T_2 – outlet temperature of the heat exchanger network, ºC
T_{amb} – ambient temperature, ºC

Abbreviations

FCC – Fluid catalytic cracking
HEN – Heat exchange network
KSD – Kim & Smith Design
WSD – Water Sources Diagram

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