CHEMICAL ENGINEERING TRANSACTIONS

VOL. 70, 2018

A publication of AIDIC

The Italian Association
of Chemical Engineering
Online at www.aidic.it/cet

Guest Editors: Timothy G. Walmsley, Petar S. Varbanov, Rongxin Su, Jiří J. Klemeš

ISBN 978-88-95608-67-9; **ISSN** 2283-9216

DOI: 10.3303/CET1870082

Optimization of Cooler Networks Considering Different Types of Cooling

Haitian Zhang[a], Xiao Feng[a,]*, Yufei Wang[b], Zhen Zhang[c]

[a]School of Chemical Engineering & Technology, Xi'an Jiaotong University, Xi'an, Shaanxi, P.R. China
[b]School of Chemical Engineering, China University of Petroleum, Beijing, P.R. China
[c]Process Division, Hualu Engineering & Technology Co., LTD., Xi'an, Shaanxi, P.R. China
xfeng@mail.xjtu.edu.cn

As an important part of a heat exchanger network (HEN), a cooler network has a crucial effect on energy conservation and economy of the whole process. However, most researches considered only the circulating water cooling system (CWS) in recent years, with ignorance of the actual situation that the application of air coolers has been widespread in practical industries. In this paper, cooler networks with different types of cooling are optimized. Under the overall consideration of energy, water and total cost, on the basis of lectotype of cooling types among dry air coolers (DAC), spray air coolers (SAC) and water coolers, a superstructure based on mathematical model is established, with the minimum total annual cost as the objective function. A case study has revealed that the model makes optimization results more accordant with industrial practice, which provides a reasonable direction for cooler network synthesis in the field of process industries.

1. Introduction

Heat exchanger network (HEN) synthesis is an integral part to the energy integration and chemical process synthesis, which is directly linked to the rational utilization of energy and operational expenses in the process industry (Abu Bakar, et al., 2017). It aims to obtain the optimal HEN structure with the minimization of total cost as objective, in the premise that the hot stream reaches the required temperature after cooled down by the HEN (Escobar and Trierweiler, 2013).

A HEN mainly consists of a heat recovery network with heat transfer between hot and cold process streams, a heater network and a cooler network. Since the cooler network is considered as one of the most important parts in a HEN, during the last two decades, a considerable number of researches have been proposed for optimization of cooler networks. In current studies on HENs, most researchers replaced optimizing cooler networks by cold utilities; besides, investigates on cooler networks mostly focus on cooling water networks.

Aiming at optimization in some aspects including heat transfer and water consumption, Kim and Smith (2001) developed a systematic methodology for the design of cooling networks, with consideration of all the components affecting cooling performance. Taking into account the increase of concentration ratio of circulating water, Panjeshahi and Ataei (2008) optimized cooling water networks for the purpose of reducing energy and water consumption, by way of a novel technique called the integrated ozone treatment cooling system design based on pinch analysis and mathematical programming, producing the optimization results with minimum cost and environmental impact, as well as maximum energy and water conservation as objective functions. Picón-Núñez et al. (2012) brought forward a design procedure to add new coolers into an existing water cooler network, in view of both thermo-hydraulic effects and fouling caused by the crystallization of soluble salts. Besides, Shenoy and Shenoy (2013) put forward the unified targeting algorithm and nearest-neighbours algorithm which could be applied to optimize cooling water networks in the proposition that the heat duty was translated into supply-demand relationship between inlet and outlet. In addition, Luo et al. (2016) optimized both the heat exchanger network and utility system simultaneously combined with steam condensate and boiler feedwater. Moreover, Liu et al. (2018) considered cooling water as a special cold stream that needs to be optimized, and then made use of a modified stage-wise superstructure for the integration of both the HEN and the cooling water system.

Please cite this article as: Zhang H., Feng X., Wang Y., Zhang Z., 2018, Optimization of cooler networks considering different types of cooling , Chemical Engineering Transactions, 70, 487-492 DOI:10.3303/CET1870082

When it comes to cooling devices, in addition to cooling water systems, air-cooled heat exchanger can be extensive used in the actual situation. Different kinds of cooling methods are suitable for their appropriate cooling flows accordingly, which contributes to improving the extent of optimization and perfection of cooler networks. Considering different cooling types in the optimization of cooler networks is more consistent with industrial application. However, there is none of relevant literature found on cooler networks in consideration of various cooling methods.

For a cooler network after heat recovery between processes streams in a HEN, this work firstly focuses on the optimization of cooler networks in different cooling types. A superstructure based mathematical model is proposed, with the objective function as the minimum total annual cost. Meanwhile, the lectotype among different types of cooling devices including air cooling and water cooling is taking into consideration. That is to say, cooling methods in cooler network will be selected from the dry air cooler (DAC), spray air cooler (SAC) and water coolers. It is beneficial for directive significance on synthesis of networks which not only more accord with industrial practice but also have better economic performance.

2. Superstructure of a cooler network

After heat recovery is finished, a cooler network needs to be optimized. The structure of a cooler network that takes the minimum total annual cost as the objective function will be obtained, on account of the condition that streams can be cooled down to required temperature by the cooler network. In this paper, the selection of cooling types involves the DAC, SAC and circulating cooling water system (CWS).

First of all, it is necessary to build up the superstructure of a cooler network. The superstructure is based on the following assumptions: One stream exchanges heat with cooling medium only once; in other words, all coolers are in one-to-one correspondence with streams to be cooled down. Series-parallel connection combinations can be applied to CWSs. But air coolers including DACs and SACs connect in parallel. Additionally, a fan is used to meet demand for flowrate of cooling air to all air coolers. Moreover, parallel connection is suitable for the water-spray system of the SAC, while its rest spray water after evaporation can be reused.

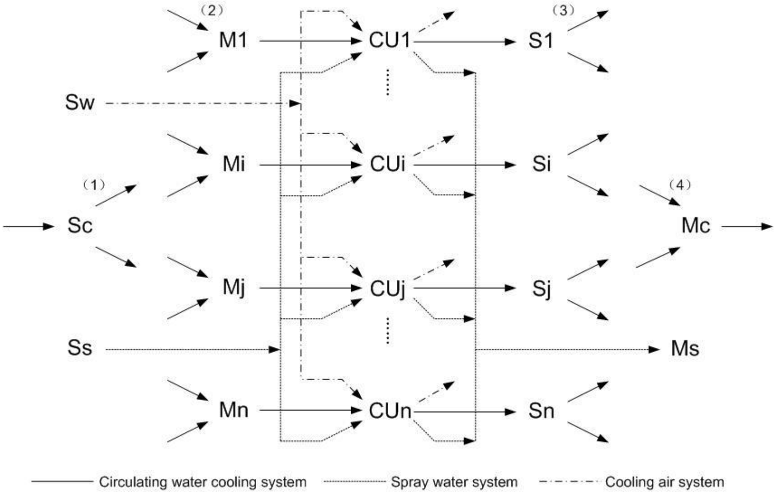

Figure 1: Superstructure of a cooler network

Figure 1 illustrates the superstructure of a cooler network. On the entry node of cooling air (Sw), the fan provides cooling air for paralleled air coolers; likewise, on the entry node of spray water (Ss), the spray water system can supply paralleled SACs with spray water via spray water pump. After rising in temperature, cooling air is directly discharged from coolers, while surplus spray water after evaporation makes its way to the exit node of spray water (Ms). The condition of CWSs is relatively complex, described as follows.

(1) On the splitting node (Sc), circulating cooling water is delivered from the cooling tower to every water cooler.

(2) On the entry node of water cooler j (Mj), circulating cooling water is received from the cooling tower and other water coolers.

(3) On the exit node of water cooler j (Sj), circulating cooling water after heated is discharged into the cooling tower or other water coolers;

(4) On the mixed node (Mc), circulating cooling water from water coolers is accepted and returns to the cooling tower.

According to the assumptions above, for any cooler in the cooler network, the cooling air can exist singly in the corresponding situation of the DAC; the cooling air and spray water might attain sufficient concurrence on condition of the SAC. Nevertheless, it is impossible that the circulating cooling water coexists with cooling air, under the corresponding circumstance of the CWS. The concrete relationship is demonstrated in Figure 2.

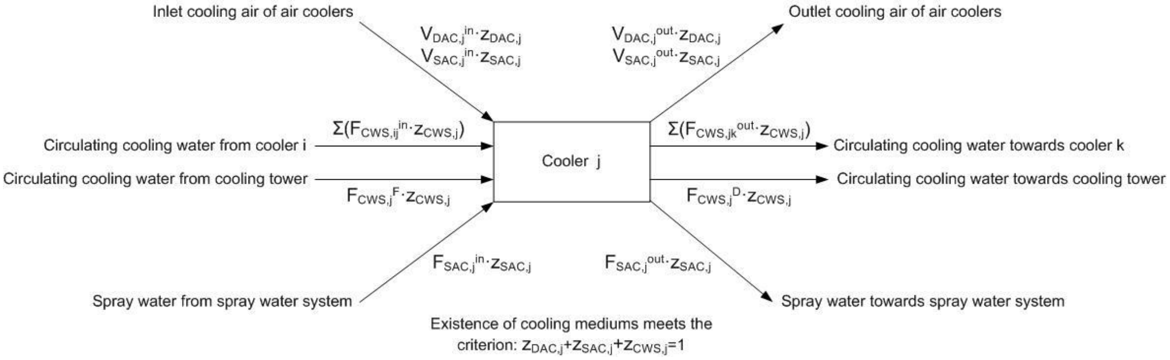

Figure 2: Inlet and outlet situations of air and water in a typical unit of a cooler network

The objective function is to minimize the total annual cost of the cooler network, which is stated as follows:

$$\min\left(\sum_{j=1}^{n}\left(C_{DAC,j}\cdot z_{DAC,j}+C_{SAC,j}\cdot z_{SAC,j}+C_{CWS,j}\cdot z_{CWS,j}\right)+\left(\sum_{j=1}^{n}\left(I_{DAC,j}\cdot z_{DAC,j}+I_{SAC,j}\cdot z_{SAC,j}+I_{CWS,j}\cdot z_{CWS,j}\right)\right)\Big/a\right) \tag{1}$$

where

$$C_{DAC,j}=N_{DAC,j}\cdot p_e,\ j\in CU \tag{2}$$

$$C_{SAC,j}=\left(N_{SAC,j}+P_{SAC,j}\right)\cdot p_e+We_{SAC,j}\cdot p_w,\ j\in CU \tag{3}$$

$$C_{CWS,j}=P_{CWS,j}\cdot p_e+We_{CWS,j}\cdot p_w,\ j\in CU \tag{4}$$

The subject restraints are listed as follows:
(1) The overall energy balance equation is presented as Eq(5).

$$\begin{aligned}&\left(\rho_a\cdot V_{DAC,j}^{in}\cdot c_a\cdot t_{DAC,j}^{in}+Q_{DAC,j}\right)\cdot z_{DAC,j}+\left(\rho_a\cdot V_{SAC,j}^{in}\cdot c_a\cdot t_{SAC,j}^{in}+F_{SAC,j}^{in}\cdot T_{SAC,j}^{in}+Q_{SAC,j}\right)\cdot z_{SAC,j}\\&+\left(F_{CWS,j}^{F}\cdot T_{CWS,j}^{F}+\left(\sum_{i\in P;i\neq j}F_{CWS,ij}^{in}\right)\cdot T_{CWS,i}^{out}\right)\cdot z_{CWS,j}+Q_{CWS,j}\cdot z_{CWS,j}=\rho_a\cdot V_{DAC,j}^{out}\cdot c_a t_{DAC,j}^{out}\cdot z_{DAC,j}\\&+\left(\rho_a\cdot V_{SAC,j}^{out}\cdot c_a\cdot t_{SAC,j}^{out}+F_{SAC,j}^{out}\cdot T_{SAC,j}^{out}\right)\cdot z_{SAC,j}+\left(F_{CWS,j}^{D}+\sum_{i\in P;j\neq k}F_{CWS,jk}^{out}\right)\cdot T_{CWS,j}^{out}\cdot z_{CWS,j},\ j\in CU\end{aligned} \tag{5}$$

(2) The total mass balance of inlet and outlet cooling mediums including circulating cooling water, spray water, and cooling air in view of cooler j is formulated as follows:

$$V_{DAC,j}^{in}=V_{DAC,j}^{out},V_{SAC,j}^{in}=V_{SAC,j}^{out},\ j\in CU \tag{6}$$

$$F_{SAC,j}^{in}=F_{SAC,j}^{out}+We_{SAC,j},\ j\in CU \tag{7}$$

$$F_{CWS,j}^{F}+\sum_{i\in P;i\neq j}F_{CWS,ij}^{in}=F_{CWS,j}^{D}+\sum_{i\in P;i\neq j}F_{CWS,jk}^{out},\ j\in CU \tag{8}$$

(3) The inlet and outlet temperature requirements of cooler j are as follows:

$$t_{DAC,j}^{in} \le t_{DAC,j}^{out},\ j \in CU \tag{9}$$

$$t_{SAC,j}^{in} \le t_{SAC,j}^{out}, T_{SAC,j}^{in} \le T_{SAC,j}^{out},\ j \in CU \tag{10}$$

$$T_{CWS,j}^{in} \le T_{CWS,j}^{in,\max}, T_{CWS,j}^{out} \le T_{CWS,j}^{out,\max},\ j \in CU \tag{11}$$

$$5 \le T_{CWS,j}^{out} - T_{CWS,j}^{in} \le 15,\ j \in CU \tag{12}$$

With regard to Eq(12), since the temperature difference of water coolers between inlet and outlet is about 8~10 °C in industrial practice, the sliding interval of temperature is relaxed to 5~15 °C.
(4) The restrictive condition of binary variables on existence of cooling mediums is shown as Eq(13).

$$z_{DAC,j} + z_{SAC,j} + z_{CWS,j} = 1,\ j \in CU \tag{13}$$

3. Lectotype of coolers and model solution

For cooler selection, the DAC, SAC and CWS are considered as candidates for corresponding coolers. In the software called Aspen Exchanger Design and Rating (EDR), the model of the DAC originates from the module of Air Cooled Exchanger, while the module of Shell & Tube Exchanger offers the model of the CWS. As for the SAC whose calculation is based on the DAC, its spray water is sprinkled onto the surface of heat transfer tubes, leading to more evaporative heat dissipation; meanwhile, the water film over the interface of heat transfer results from the spray water, which contributes to the improvement of heat transfer efficiency. The related design and calculations of coolers can refer to literature (Lai and Zhang, 2009) and literature (Zhang, et al., 2017) in order to calculate the operational cost.
This paper solves the model of the cooler network through the software called GAMS, while the lectotype of coolers depends on corresponding binary variables. The optimization of the cooler network in the case study is obtained in virtue of Baron solver, while the solution to the total annual cost of the cooler network as objective function is implemented.

4. Case study: optimization of a cooler network

The optimization of a cooler network is to gain the optimal network structure with minimum total cost, on the basis that all the streams reach their own required temperatures. The double-declining-balance method is applied to the depreciation of coolers (Ibarra, 2013). The working hours in a year is taken as 8,000 hours. The operational annual cost mainly consists of industrial electricity cost spent by both fans and pumps, as well as fresh water cost spent by both spray water and circulating cooling water.

Table 1: Optimization results of the cooler network

Serial numbers of coolers	Corresponding streams	Flowrates of streams (kg/s)	Heat duty (kW)	Selection of coolers	Equipment cost ($)	Total annual cost ($/y)
1	H4	7.09	750	SAC	3.13×10^4	--
2	H6	2.33	781	CWS	1.99×10^4	--
3	H7	7.02	1,638	DAC	5.32×10^4	--
4	H8	6.98	1,906	CWS	2.80×10^4	--
5	H11	7.12	1,050	SAC	3.78×10^4	--
6	H12	5.64	313	DAC	2.56×10^4	--
7	H14	4.73	850	SAC	2.76×10^4	--
8	H15	16.54	1,944	SAC	2.96×10^4	--
9	H17	2.27	800	CWS	1.98×10^4	--
10	H18	4.81	450	SAC	1.63×10^4	--
11	H20	7.97	1,054	SAC	3.13×10^4	--
12	H21	2.33	200	DAC	1.29×10^4	--
The network	--	--	--	--	--	2.29×10^5

The case from literature (Pettersson, 2005) is adopted in this paper. Since only the data on heat capacity flowrate of streams are mentioned in the literature, while the selection of coolers needs to know the data on flowrates of streams, it is assumed that streams in the cooler network is water, and then the cooler network is optimized in line with the proposed model.

According to the data in Aspen EDR, the power cost per kilowatt-hour is taken as \$ 0.06. In addition, the cold utility cost is 15 $\$\cdot kW^{-1}\cdot h^{-1}$; in other words, the price of fresh water is taken as 1.2933 $\$\cdot m^{-3}\cdot h$, which refers to literature (Yerramsetty and Murty, 2008).

The related parameters of the cooler network after heat recovery process between hot and cold streams are listed as the first four columns of Table 1. The data of the cooler network is put into the mathematical model mentioned above for the sake of total optimization. The optimization results are shown as the fifth column and the sixth column of Table 1.

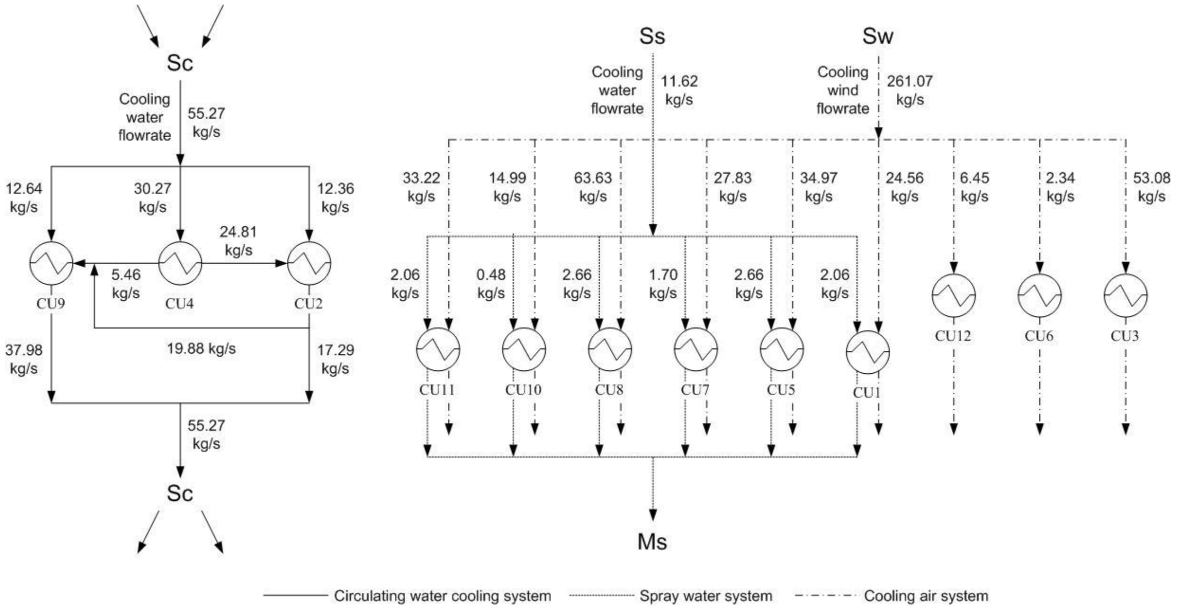

Figure 3: Optimized network in consideration of several cooling methods

The optimization results are illustrated in Figure 3. The total annual cost of the optimized cooler network is 2.29×10^5 \$/y. If only the CWS is applied to all the coolers, its total annual cost of the network is 3.62×10^5 \$/y.

The above results show that different kinds of cooling methods have their own characteristics, leading to their own suitable application to cool down streams under different temperature range in view of economic effects.

More concretely, air coolers have more edges in cooling streams at higher temperature, since on one hand, the operational cost of air coolers is lower than that of water coolers owing to almost zero cost of air, on the other hand, the specific heat capacity is much smaller than that of cooling water. The required temperature of streams cooled by air coolers need to be ordinarily about 15 °C higher than the temperature of ambient air. In this case, air cooler cannot be manipulated for cooling streams that have lower temperature. Besides, water coolers are more applicable to cooling down streams at lower temperature, especially around the temperature of ambient air. This is not to say that water coolers are incapable of cooling streams with higher temperature, but it is no more than much higher cost of coolers, which might bring about higher total cost of corresponding cooling network.

5. Conclusions

This paper studies optimization of a cooler network, in consideration of different cooling methods including air cooling and water cooling. The superstructure of a cooler network is built up, on the basis that the range of selection on cooling types mainly consists of the DAC, SAC and CWS. The optimization mathematical model of a cooler network with minimum total annual cost as the objective function is proposed, based on the lectotype of coolers. In the case study, compared with the cooler network applying water cooling entirely, the optimized cooler network using coolers from both water cooling and air cooling can effectively reduce the total cost of the cooler network, leading to a result more in accordance with the practical industry process.

Acknowledgments

Financial support from the National Natural Science Foundation of China (21736008) is gratefully acknowledged.

Nomenclature

Parameters & variables

a	period of depreciation / y
C	total annual cost / $\$\cdot\mathrm{y}^{-1}$
c	specific heat / $\mathrm{kJ\cdot kg^{-1}\cdot {}^{o}C^{-1}}$
F	heat capacity flowrate of inlet and outlet water / $\mathrm{kW\cdot {}^{o}C^{-1}}$
I	installation cost / \$
N	fan power / kW
P	motor power of water pump / kW
p_e	price of industrial electricity / $\$\cdot\mathrm{kW}^{-1}$
p_w	price of fresh water/ $\$\cdot(\mathrm{m^{-3}\cdot h})$
Q	heat duty of a cooler/ kW
T	temperature of water / ${}^{o}\mathrm{C}$
t	temperature of cooling air / ${}^{o}\mathrm{C}$
V	flowrate of cooling air / $\mathrm{m^{3}\cdot h^{-1}}$
We	water consumption / $\mathrm{m^{3}\cdot h^{-1}}$
z	existence of a cooler
ρ	density / $\mathrm{kg\cdot m^{-3}}$

Subscripts & superscripts

a	air
CWS	circulating cooling water system
D	towards cooling tower
DAC	dry air cooler
F	from cooling tower
$i.j,k$	a cooler in the cooler network ($i \neq j \neq k$)
ij	from cooler i to cooler j
in	inlet
in,max	limiting inlet temperature
n	total quantity of coolers in the cooler network
out	outlet
out,max	limiting outlet temperature
SAC	spray air cooler

Sets

CU	set of coolers

References

Abu Bakar S.H., Hamid M.K.A., Wan Alwi S.R., Manan Z.A., 2017, A Simple Case Study on Application in Synthesizing a Feasible Heat Exchanger Network, Chemical Engineering Transactions, 56, 157-162.

Escobar M., Trierweiler J.O., 2013, Optimal Heat Exchanger Network Synthesis: A Case Study Comparison, Applied Thermal Engineering, 51, 801-826.

Ibarra V.C., 2013, The Straight-Line Depreciation Method Used by Selected Companies and Educational Institutions in the Philippines, Journal of Modem Accounting and Auditing, 7, 480-488.

Kim J.K., Smith R., 2001 Cooling Water System Design, Chemical Engineering Science, 56, 3641-3658.

Lai Z.P., Zhang R.K. (Ed.), 2009, Air Cooled Heat Exchanger, Beijing, China.

Liu F., Ma J., Feng X., Wang Y., 2018, Simultaneous Integrated Design for Heat Exchanger Network and Cooling Water System, Applied Thermal Engineering, 128, 1510-1519.

Luo X., Huang X., El-Halwagi M.M., Ponce-Ortega J.M., Chen Y., 2016, Simultaneous Synthesis of Utility System and Heat Exchanger Network Incorporating Steam Condensate and Boiler Feedwater, Energy, 113, 875-893.

Panjeshahi M.H., Ataei A., 2008, Application of an Environmentally Optimum Cooling Water System Design in Water and Energy Conservation, International Journal of Environmental Science & Technology, 5(2), 251-262.

Pettersson F., 2005, Synthesis of Large-Scale Heat Exchanger Networks Using a Sequential Match Reduction Approach, Computers & Chemical Engineering, 29, 993-1007.

Picón-Núñez M., Polley G.T., Canizalez-Dávalos L., Tamakloe E.K., 2012, Design of Coolers for Use in an Existing Cooling Water Network, Applied Thermal Engineering, 43(5), 51-59.

Shenoy A.U., Shenoy U.V., 2013, Targeting and Design of CWNs (Cooling Water Networks), Energy, 55(1), 1033-1043.

Yerramsetty K.M., Murty C.V.S. , 2008, Synthesis of Cost-Optimal Heat Exchanger Networks Using Differential Evolution, Computers & Chemical Engineering, 32(8), 1861-1876.

Zhang H., Feng X., Wang Y., 2017, Economic Analysis Based on Energy and Water Consumptions between Air-cooling and Water-cooling, Chemical Engineering Transactions, 61, 367-372.