Optimal detailed design for integral cooling water systems

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Abstract

A cooling water system is used in industrial processes to cool down hot process streams from their supply conditions to target temperatures. A cooling water system is comprised of three major components, namely a cooling tower, a heat exchanger network (HEN), and a pumping system; these elements have strong interactions with each other and therefore must be optimized simultaneously to yield an optimal cooling water system.

This paper presents a mixed-integer non linear programming model for the optimal design of integral cooling water systems. The model includes a superstructure for the HEN component of the system that allows arrangements of coolers in series and/or in parallel, and also allows the bypass of fresh water and/or previously-used water to improve the performance of the cooling network. The optimization of HEN coolers is made simultaneously to take into consideration from the synthesis stage the interactions between the pumping effects and the heat transfer coefficients that determine their transfer areas. The model considers as objective function the minimization of the capital costs for the cooling tower, HEN coolers and pumps, as well as the operating costs due to the fan of the tower, pumping requirements and water makeup. One example problem is presented to show the application of the proposed method.

Introduction

Cooling water systems are used to treat hot process streams in the process industries. The cooling water system is constituted by three major components, namely the cooling tower, the heat exchanger network and the pumps; these elements have strong interactions with each other and therefore must be optimized simultaneously to yield an optimal cooling water system (see Figure 1).

Published works on cooling water systems have not carried out a simultaneous optimization that considers all of its components.[1,2,3,4,5,6,7,8,9,10,11] In addition, all previous methodologies have ignored the optimization for the total cooling water system considering the capital and operating cost simultaneously. This paper proposes a new mathematical model for the synthesis of cooling water systems that simultaneously considers the cooling tower, the cooling network and the pumping system. The model takes into account the capital and operating costs simultaneously, as well as the geometrical and operational constraints for the cooling tower and coolers. The methodology considers pumping effects in the cooling system through the heat exchangers detailed design. The objective function for the model consists in the minimization of the capital costs for the cooling tower, coolers and pumps, and the operating costs for the fan of the tower and the pumps, as well as the cost for the makeup cooling water.

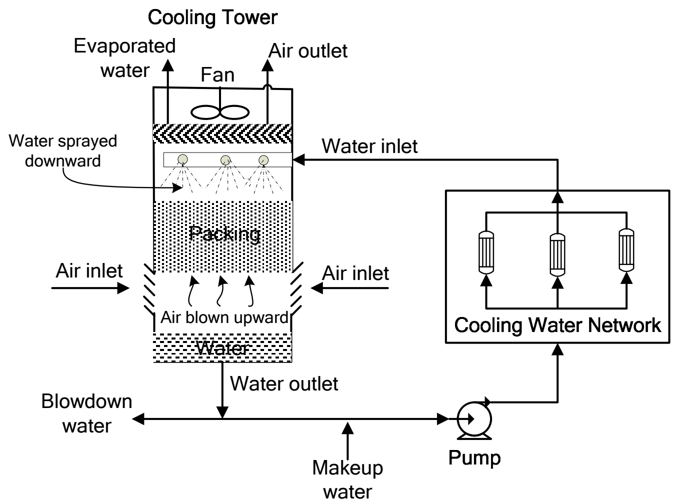

Figure 1. Cooling water system

Model formulation

A superstructure is proposed that considers the interactions between the cooling tower, the cooling water network and the pumping effects (Figure 2). Only one cooling tower is needed, and the cooling water network allows arrangements in parallel, in series and their combinations to get an optimum cooling water network. Also, the superstructure considers the pumping effects in the heat exchangers design. The cooling tower, the heat exchanger units and the pumping design are optimized simultaneously to synthesize the overall cooling water system.

Model for the cooling water network. The model for the cooling water network is based on the one previously reported by Ponce-Ortega et al.[11]

Coolers design equations. When a heat exchanger is needed in the cooling network, a detailed design must be considered to take into account the pumping effects simultaneously. To model this situation, a generalized disjunctive programming model is developed. When the exchanger exists, the set of equations for the detailed design is applied rigorously; otherwise the optimization variables involved are set as zero, as follows:

$$\begin{bmatrix} z_{i,k} \\ \text{Apply exchanger design equations} \end{bmatrix} \vee \begin{bmatrix} \neg z_{i,k} \\ \text{Set designvariables as zero} \end{bmatrix} \quad i \in HPS, k \in ST$$

The equations used for the detailed heat exchangers design include two compact relationships that relate the pressure drops for the heat transfer area and the film heat transfer coefficients for the shell side and the tube side. The compact expression for the shell side is based on the Kern method.[12] Also, the model includes equations for the calculation of the velocities of the fluids, the log-mean temperature difference using Chen's approximation[13], the global heat transfer coefficient and the heat transfer area. The big-M formulation is used to model this disjunction.

Layout and equivalent diameter. The equivalent diameter for the heat exchanger units is needed for the calculation of the shell side heat transfer coefficient, and it depends on the arrangement of the tubes. To model this situation the following disjunction is proposed,

$$
\left[\begin{array}{c}
z_{i,k} \\
De_{i,k} Dt_{i,k} = \dfrac{4\left(a_{i,k}^{layout1} Lpt_{i,k}^{2} - a_{i,k}^{layout2} \pi \, Dti_{i,k}^{2} / 4\right)}{\pi} a_{i,k}^{layout3} 1000 \\
\left[\begin{array}{c}
Y_{TRI_{i,k}}^{layout} \\
(\text{triangular}) \\
C_{AT_{i,k}} = 0.866 \\
a_{i,k}^{layout1} = 1 \\
a_{i,k}^{layout2} = 1 \\
a_{i,k}^{layout3} = 1
\end{array}\right] \vee
\left[\begin{array}{c}
Y_{SQU_{i,k}}^{layout} \\
(\text{square}) \\
C_{AT_{i,k}} = 1 \\
a_{i,k}^{layout1} = 0.435 \\
a_{i,k}^{layout2} = 0.5 \\
a_{i,k}^{layout3} = 2
\end{array}\right]
\end{array}\right] \vee
\left[\begin{array}{c}
\neg z_{i,k} \\
De_{i,k} = 0 \\
C_{AT_{i,k}} = 0 \\
a_{i,k}^{layout1} = 0 \\
a_{i,k}^{layout2} = 0 \\
a_{i,k}^{layout3} = 0
\end{array}\right] \quad i \in HPS, k \in ST
$$

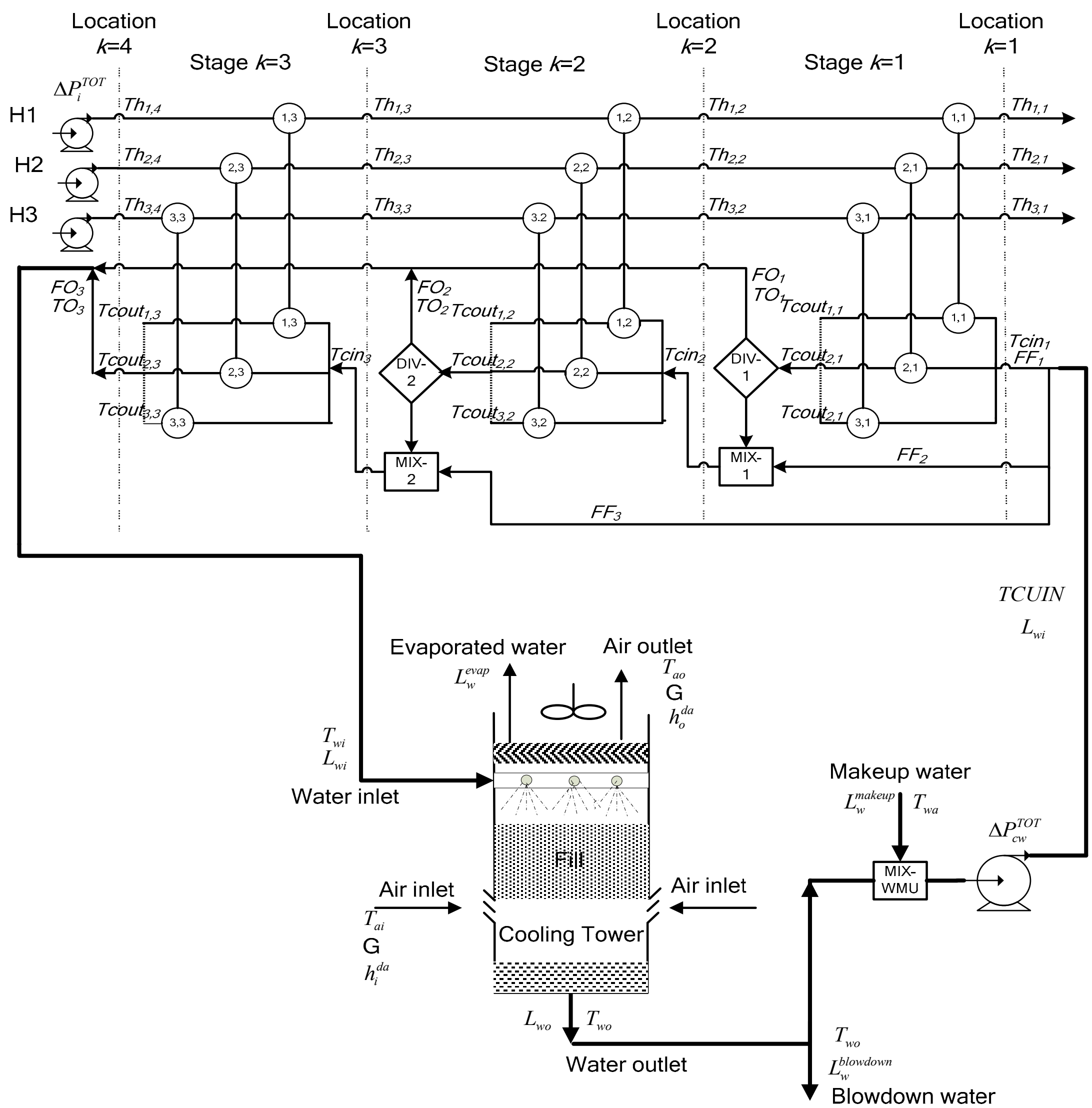

Figure 2. Superstructure for the cooling system.

Tube size. The model must select the optimum tube size from standard dimensions when the heat exchanger exists. Therefore, the following disjunction is proposed,

$$\left[\begin{array}{c} z_{i,k} \\ \left[\begin{array}{c} Y^{tube}_{1_{i,k}} \\ Dt_{i,k} = 6.350 \\ Dti_{i,k} = 4.928 \\ Lpt_{i,k} = 7.938 \end{array}\right] \vee \ldots \vee \left[\begin{array}{c} Y^{tube}_{it_{i,k}} \\ Dt_{i,k} = \ldots \\ Dti_{i,k} = \ldots \\ Lpt_{i,k} = \ldots \end{array}\right] \vee \ldots \vee \left[\begin{array}{c} Y^{tube}_{IT_{i,k}} \\ Dt_{i,k} = 50.8 \\ Dti_{i,k} = 45.26 \\ Lpt_{i,k} = 63.5 \end{array}\right] \end{array}\right] \vee \left[\begin{array}{c} \neg z_{i,k} \\ Dt_{i,k} = 0 \\ Dti_{i,k} = 0 \\ Lpt_{i,k} = 0 \end{array}\right] \quad i \in HPS, k \in ST$$

Localization of the fluids. The model must select the optimal localization of the fluids inside of the heat exchangers in the shell or tubes sides. This situation is modeled using the following disjunction,

$$\left[\begin{array}{c} z_{i,k} \\ \left[\begin{array}{c} Y^{loc}_{1_{i,k}} \\ \text{hot fluid in the tubes} \\ \text{cold water in the shell} \end{array}\right] \vee \left[\begin{array}{c} Y^{loc}_{2_{i,k}} \\ \text{hot fluid in the shell} \\ \text{cold water in the tubes} \end{array}\right] \end{array}\right] \vee \left[\begin{array}{c} \neg z_{i,k} \\ \text{set all variables as zero} \end{array}\right] \quad i \in HPS, k \in ST$$

Pressure drops constraints. Because the heat exchanger units for the hot process streams are placed in the superstructure in series, the total pressure drop for each hot process stream is calculated as follows,

$$\Delta P_i^{TOT} = \sum_{k \in ST} \Delta P_{i,k}^h, \quad i \in HPS$$

For the cold water there are combinations of arrangements in series and in parallel in the superstructure; therefore, we need to identify the biggest pressure drop in each stage of the superstructure because this is the one that must be consumed in each stage of the superstructure,

$$\Delta P_{cu_k}^{STAGE} \geq \Delta P_{i,k}^c, \quad i \in HPS, k \in ST$$

Multipass exchangers. Because of space limitation, the use of multipass heat exchangers is sometimes needed. In this case it is necessary to consider the selection of multipass or single pass exchangers, as shown in the following disjunction,

$$\left[\begin{array}{c} z_{i,k} \\ \left[\begin{array}{c} Y^{Npass1}_{i,k} \\ \text{Single pass exchanger} \end{array}\right] \vee \left[\begin{array}{c} Y^{Npass2}_{i,k} \\ \text{Multipass exchanger} \end{array}\right] \end{array}\right] \vee \left[\begin{array}{c} \neg z_{i,k} \\ \text{Set variables as zero} \end{array}\right], \quad i \in HPS, k \in ST$$

Interconnection between cooling network and the cooling tower. The following balances between the cooling network and the tower are needed.

Fresh cold water,

$$L_{wi} = \sum_{k \in ST} FO_k$$

Energy balance for the mixer in the last stage of the superstructure,

$$\sum_{k \in ST} \left(FO_k TO_k \right) = L_{wi} T_{wi}$$

The heat load for the cooling tower,

$$Q_{CT} = Cp_{cw} \left(L_{wi} T_{wi} - L_{wo} T_{wo} \right)$$

Energy balance in the makeup mixer,

$$L_w^{makeup} \left(T_{wa} - T_{wo} \right) = L_{wi} \left(TCUIN - T_{wo} \right)$$

Cooling tower. This work uses the equations proposed by Serna-Gonzalez et al.[17] to model the cooling tower performance.

Water Consumption. Makeup water is constantly added to the cooling tower basin to compensate the loss of water for evaporation, drift, and blowdown. The total makeup water is given by,

$$L_w^{makeup} = \frac{n_{cycles} L_w^{evap}}{n_{cycles} - 1}$$

where n_{cycles} is the number of cycles of concentration. A cycle of concentration is the ratio of the solid concentration in the circulating water to the solid concentration in the makeup water.

Feasible constraints. There are a set of geometrical and operational constraints for the heat exchanger units and the cooling tower.

Feasible constraints for the coolers. To get a practical cooler, several works have proposed a set of geometrical and operational constraints. These constraints must be applied when the cooler exists in the network, according to the following disjunction,

$$\begin{bmatrix} Z_{i,k} \\ \text{Feasible constraints for exchangers} \end{bmatrix} \vee \begin{bmatrix} \neg Z_{i,k} \\ \text{Set variables as zero} \end{bmatrix}$$

Feasible constraints for the cooling tower. There is a set of constraints to allow an efficient operation of the cooling tower, and another set of constraints to model the cooling tower.[14]

Objective function. The objective function is taken as the minimization of the total yearly cost for the cooling water system, given by the capital cost for the cooling tower, the capital cost for the heat exchangers that considers the number of shells needed when multipass exchangers are selected, the capital cost for the pumps required for the hot process streams and for the cooling water, the operational costs for the electricity needed to operate the fan of the cooling tower, the costs due to the makeup water, and the electricity costs needed to operate the pumps of the system. The objective function is then written as,

$$\begin{aligned}
\min TAC = {} & k_F \left[C_V^{CT} A_{CT} L_{fi} + C_G^{CT} ma_{mean} + C_0^{CT} \right] \\
& + k_F \left[\sum_{i \in HPS} \sum_{k \in ST} CF_i^{exc} z_{i,k} + \sum_{i \in HPS} \sum_{k \in ST} Ns_{i,k} C_i^{exc} \left(\frac{A_{i,k}}{Ns_{i,k}} \right)^{\beta} \right] \\
& + k_F \left[\sum_{i \in HPS} CF_i^{pump} + \sum_{i \in HPS} C_i^{pump} \left(\frac{\Delta P_i^{TOT} F_i^h}{\rho_i} \right)^{\gamma} \right] \\
& + k_F \left[CF_{cu}^{pump} + C_{cu}^{pump} \left(\frac{\sum_{k \in ST} \left(\Delta P_{cu_k}^{STAGE} \right) \sum_{k \in ST} \left(FF_k \right)}{\rho_{cu}} \right)^{\gamma} \right] \\
& + C_{pow} H_Y 3600 \Delta P_{CT} \\
& + C_{pow} \frac{H_Y}{\eta_{pump}} \left[\sum_{i \in HPS} \left(\frac{\Delta P_i^{TOT} F_i^h}{\rho_i} \right) + \frac{\sum_{k \in ST} \left(\Delta P_{cu_k}^{STAGE} \right) \sum_{k \in ST} \left(FF_k \right)}{\rho_{cu}} \right] \\
& + C_{water} H_Y 3600 L_w^{makeup}
\end{aligned}$$

where C_V^{CT}, C_G^{CT} and C_o^{CT} are constants for the capital cost of the tower, CF_i^{exc}, C_i^{exc} and β are parameters for the capital cost of the heat exchangers, CF_i^{pump}, C_i^{pump} and γ are parameters for the capital cost of the pump, C_{pow} is the unit cost for electricity and C_{water} is the unit cost for the makeup water.

Results and discussion

One example is used to show the application of the proposed model. The parameter H_Y was assumed as 8,500 hr/year, with an annualization factor 0.23 year^{-1}, and the coefficients for the capital cost function for the coolers as follows, CF_i^{exc} of $30,800, C_i^{exc} of $1,650 (where A is in m^2) and β of 0.65. The capital costs for the pumps are estimated as follows, CF_i^{pump} is set as $2,000, C_i^{pump} as $5 (where ΔP , *F* and ρ are in Pa, kg/s and kg/m^3, respectively) and γ as 0.68. The coefficients for the capital cost of the cooling tower are $1,097.5 and $31,185 for C_G^{CT} and C_o^{CT}, respectively. The electricity cost, C_{pow} , is $0.00005/W-hr and the efficiency for the pumps is 70%. The unit cost for the cold makeup water was taken as $1.5949 x 10^{-5}/kg. The efficiency for the fan of the cooling tower is 75%, and the number of cycles for the cooling water system is set as 4.

The following conditions were taken as a basis. The maximum allowable temperature for the cooling water is 50°C, the total pressure of the system is 101,712.27 Pa, the temperature for the air at the inlet conditions is 9.7°C, and the wet bulb temperature for the air at the inlet conditions is 8.23°C. The temperature for the makeup water was taken as 12°C.

The physical properties for the cooling water in the network are assumed as follows. The heat capacity is 4.187 kJ/(kg K), the viscosity 1x10^{-3} kg/(m s), the thermal conductivity 0.58 W/(m K), the density 998 kg/m^3 and the individual fouling factor 0.00015 (m^2 K)/W.

To solve the model, the solver DICOPT, implemented in the general algebraic modeling system (GAMS) was used.[15]

The stream data for the hot process streams are given in Table 1, and their physical properties are given in Table 2.

Table 1. Stream data for the Example

Stream	TIN [°C]	TOUT [°C]	FCP [kW/(m^2 K)]
H1	76.60	40.00	100.00
H2	82.00	60.00	60.00
H3	108.85	45.00	400.00
CU	10.00	-	-

Table 2. Physical properties for streams of the Example

Property	*Cp* [J/(kg K)]	μ [kg/(m s)]	*k* [W/(m K)]	ρ [kg/m^3]	*Rd* [(m^2 K)/W]
H1	2,454	2.4 x 10^{-4}	0.114	634	0.00015
H2	1,670	2.3 x 10^{-4}	0.23	780	0.00017
H3	2,680	2.1 x 10^{-4}	0.14	890	0.00016

After the application of the proposed methodology, the water system design shown in Figure 3 was obtained, with the coolers designs given in Table 3. In the optimal system design, the inlet temperature to the cooling network is 17.893°C; for the cooling network there is a parallel arrangement for coolers 1 and 2, foolowed by cooler 3 in series. The outlet temperature of cooling water for cooler 3 is the maximum allowable temperature. The cold water is then sent to the cooling tower.

Table 4 reports a summary of the costs obtained for the optimal design for the cooling water system. Notice that the main contribution to the total annual cost is the capital cost for the cooling tower, which accounts for 50.7%. The second contribution is the cost associated with the operation of the fan for the cooling tower (27.0%); the capital cost for the exchanger contributes with 17.6% of the total.

Table 4 also shows the results for the case when only a classical arrangement of coolers in parallel is allowed for the cooling network (which is achieved by setting the number of stages in the superstructure as one). In this case the total annual cost is 2.22% higher than the in the optimal configuration; this result is mainly due to an increase in the capital costs for the coolers.

Table 4 also reports the results for the case when the cooling tower and the cooling network are optimized sequentially. The optimal design for the cooling water system shows savings by 7.1% with respect to the sequential optimization process, mainly due to the reduction in the water makeup consumption.

Table 3. Designs for the coolers

Concept	Cooler 1	Cooler 2	Cooler 3
Q [kW]	3,660	1,320	25,540
Hot stream allocation	Tubes	Tubes	Tubes
LMTD [K]	35.481	50.019	37.311
F_T	1	1	1
ΔP_T [kPa]	0.175	0.165	0.377
ΔP_S [kPa]	7.691	7.691	16.316
A [m^2]	52.643	16.563	304.885
Dt [mm]	10.211	18.008	4.928
Dti [mm]	12.700	22.225	6.350
Lpt [mm]	15.875	27.781	7.938
Ds [m]	0.914	0.549	1.086
Lbc [m]	0.914	0.549	1.086
L_{TT} [m]	3.657	2.196	4.346
U [kW/(m^2 K)]	1.960	1.593	2.245
Ns	1	1	1
Ntp	1	1	1
Tube arrangement	Square	Square	Square
v_T [m/s]	2.176	1.674	2.500
v_S [m/s]	1.000	1.000	0.963

Table 4. Results comparison for Example 1

Cost	Simultaneous optimal design	Simultaneous design with in parallel cooling water network	Sequential design
Cooling tower capital cost [$/year]	127,462.914	127,462.914	138,210.023
Coolers capital cost [$/year]	44,222.850	48,748.490	46,909.650
Pumps capital cost [$/year]	2,269.802	2,464.469	2,187.345
Electricity fan cost [$/year]	67,811.467	67,811.467	66,224.223
Electricity pumps cost [$/year]	3,365.536	4,312.879	2,432.673
Makeup water cost [$/year]	5,989.807	5,989.807	13,066.278
Total annual cost [$/year]	251,122.376	256,709.206	269,030.193

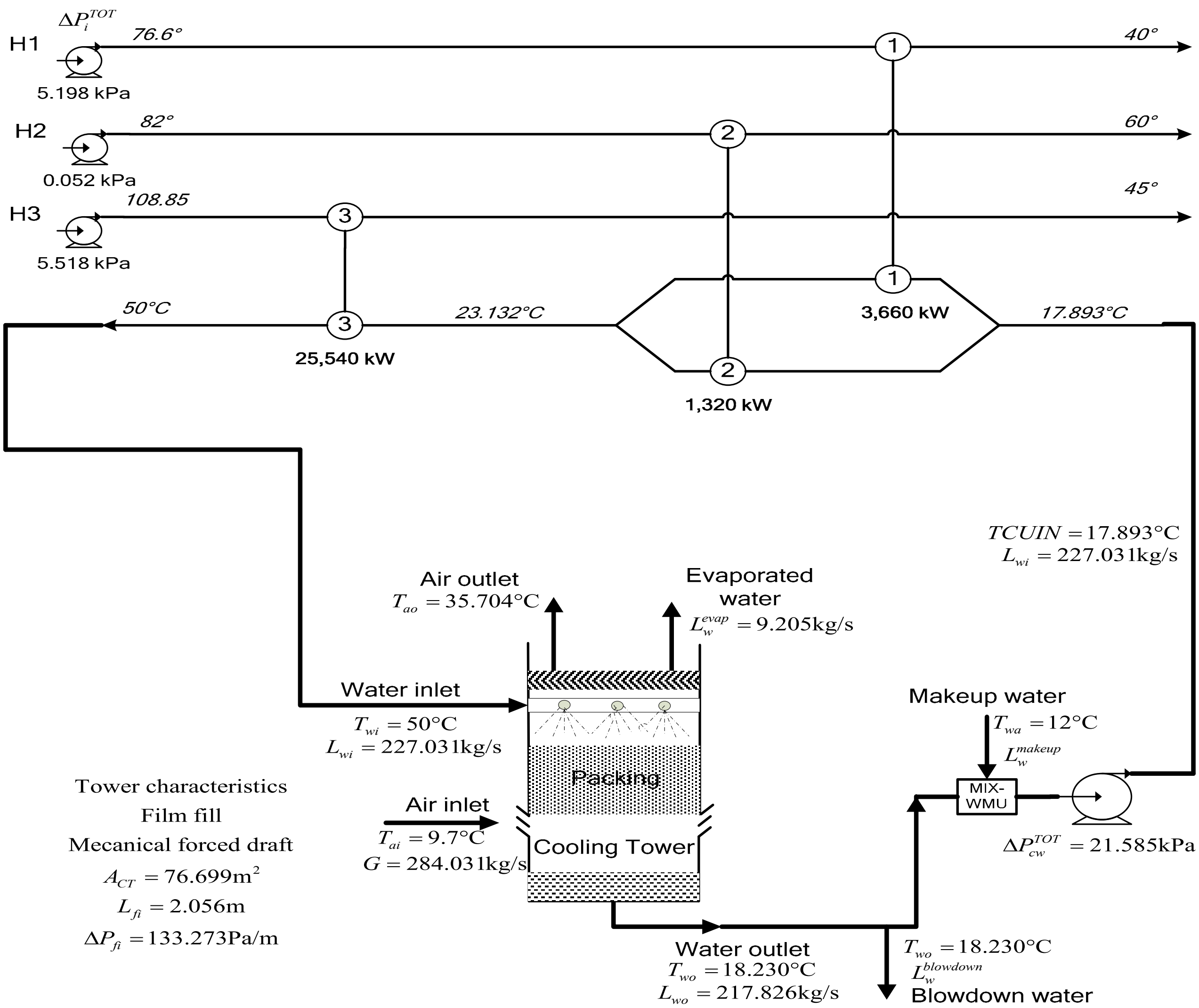

Figure 3. Optimal network for Example 1

Conclusions

An MINLP model for the optimal design of cooling water systems has been presented. The model takes into account the interactions between the components of the system, namely the cooling tower, the cooling network and the pumping system. A simultaneous optimization of the continuous and discrete variables associated with the overall cooling water system is carried out to get a minimum total annual cost for the system. The model considers the operational and geometrical constraints given by standard codes to get feasible designs for the units. A disjunctive programming model is formulated to model the discrete decisions for the system, which is then solved as an MINLP problem. This problem is highly nonlinear and nonconvex, so proper initialization process is needed to obtain a good solution.

The model has been applied to solve several example problems. In all of those problems, the maximum allowable temperature for the cooling water was reached; this result helps the cooling tower performance. In addition, the outlet temperature for the cooling water from the cooling tower is determined by the ambient conditions and the targets temperatures for the hot process streams. In the example problem here presented, the optimal network structure was relatively simple; no bypass for the cooling water was needed, and one cooler for each hot process stream was required. This solution differed form the ones obtained using simplified formulations that do not consider simultaneously the capital and operating costs.

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