

OPTIMIZE THE SCHEDULE OF CHILLER PLANT BY HARMONY SEARCH ALGORITHM

Chun-Wei Chen

Huizhou University, 46 Yanda Road, Huizhou, Guangdong, P.R. China 516007

ABSTRACT: Setting and adjusting each component operating status of the conventional chiller plant is usually based on human judgment or control of Proportional-Integral-Differential (PID) based on pressure, temperature variables. Due to the lack of scientific, systematic and optimum logic basis, it is difficult to optimize the operation of chiller plant and control the excessive energy consumption with these methods. This study employs the Harmony Search Algorithm (HSA) to determine the optimum operation of each component within the plant to obtain the most energy-saving operation for maximum operation efficiency of the chiller plant, according to the actual required cooling capacity at load side, actual performance and operation condition of each component. The results reflect that the HSA can obtain the optimum solution and increase the Coefficient of Performance (COP) of the original chiller plant by 6.25%.

Keywords: chiller plant, energy optimization, schedule, harmony search algorithm, coefficient of performance

INTRODUCTION

The chiller plant is the area where the air conditioning system produces chilled water. Its components are made up of chillers, the chilled water pumps, the condenser water pumps, and the cooling towers. The chiller plant is equivalent to the human heart in producing and supplying a cooling source (chilled water) to achieve refrigeration effect of the building's interior. The chiller plant must be designed to meet a range of cooling capacity needs, particularly in Taiwan, which has four distinct seasons and "cooling for area" needs to adapt to various changes. The chiller plant must operate in a permissible range by changing operation points so as to provide different cooling capacities, eventually satisfying different needs. Therefore, in common designs, multiple components are used to produce the required cooling capacity in a 'flexible' manner. The chiller plant provides the whole building or factory with an ample cooling source supply (chilled water), and therefore consumes an enormous amount of electricity (accounting for 60~70 percent of total air conditioning electrical consumption; 25~40 percent of total building electricity) [1].

Traditionally, the operation of chiller plant's components is controlled only by experience or proportional-integral-derivative (PID) controllers of chilled water temperature or pressure; the direct digital control (DDC) is used for setting and adjusting the operational status of each component in the plant. Due to the lack of scientific, systematic and optimum logic basis, it is difficult to optimize the operation of the chiller plant and control the excessive energy consumption with these methods. An advanced control method requires the establishment of an appropriate chiller plant model by which the dynamic action of the plant can be resolved and based on which the optimum control strategy can be designed to maintain the plant at the optimum operating point.

Based on the above considerations, this study proposes a new control mode to maximize the operation efficiency of the chiller plant, i.e. energy usage efficiency by using the HSA for system optimization technology, considering the actual required cooling capacity at load side as the basis of operation adjustment of all components in the plant and considering actual performance and operation condition of each component. The model will determine the optimum operation mode (schedule) for each component with its optimization logic and algorithm so as to achieve the optimum COP of the chiller plant when the cooling capacity of area is satisfied.

OPERATION SCHEDULE FOR ENERGY OPTIMIZATION OF CHILLER PLANT

Energy Optimization Control Mode of Chiller Plant [2][3][4]

The optimum operating strategy goal of the chiller plant is to control the operational status of each component so as to maximize the COP after the plant runs for satisfies all operating restrictions. From the mathematical perspective, this control can be described as a system optimization control mode. Fig. 1 is a diagram of a typical chiller plant operation.

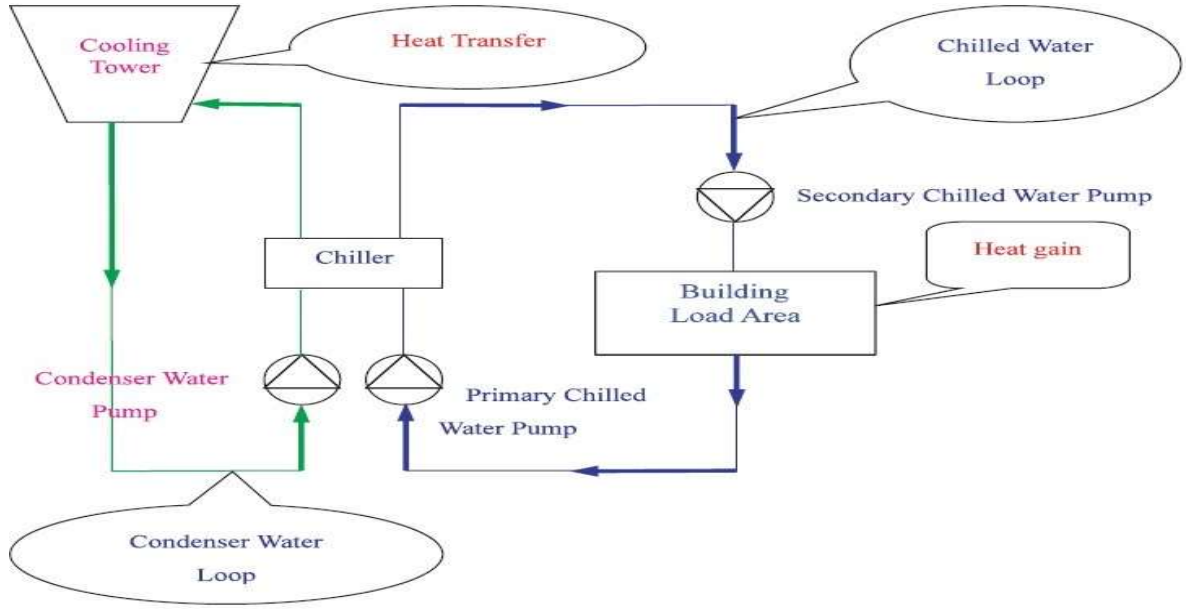


Fig. 1: Operating Diagram of a classic Chiller Plant. [2]

This study proposes a new control mode ‘energy optimization control mode of chiller plant’ based on this operation framework to maximize operation (energy) efficiency of the chiller plant, by employing the mathematical programming and considering the cooling capacity actually requested by the area and true operating performance and operation conditions of each component as demand restrictions. On this basis, the operational status of each component in the plant is optimized, thus achieving the optimum operation performance. The mathematical model is established as follows [2][3][4]:

A. Objective Function

$$\begin{aligned} \text{Max. COP} = Q \times & \left[\sum_{i=1}^n CH_i \times f_{kw}(OLR_{CH,i}) + \sum_{i=1}^n PCP_i \times f_{kw}(OLR_{PCP,i}) + \sum_{i=1}^n SCP_i \times f_{kw}(OLR_{SCP,i}) \right. \\ & \left. + \sum_{i=1}^n CWP_i \times f_{kw}(OLR_{CWP,i}) + \sum_{i=1}^n CTF_i \times f_{kw}(OLR_{CTF,i}) \right]^{-1} \end{aligned} \quad (1)$$

B. Constraints

$$\sum_{i=1}^n CH_i \times f_{RT}(OLR_{CH,i}) \geq Q \quad (2)$$

$$\sum_{i=1}^n PCP_i \times f_{LPM}(OLR_{PCP,i}) \geq L_{\text{Chilled Water}} \quad (3)$$

$$\sum_{i=1}^n SCP_i \times f_{LPM}(OLR_{SCP,i}) \geq L_{\text{Chilled Water}} \quad (4)$$

$$PCP_i \times f_{LPM}(OLR_{PCP,i}) \geq L_{CH,i,\text{Chilled Water}} \quad (5)$$

$$L_{\text{Chilled Water}} = 55 \times Q \times (C_{\text{Chilled Water}})^{-1} \times (\Delta T_{\text{Chilled Water}})^{-1} \quad (6)$$

$$\sum_{i=1}^n CWP_i \times f_{LPM}(OLR_{CWP,i}) \geq L_{\text{Condenser Water}} \quad (7)$$

$$CWP_i \times f_{LPM}(OLR_{CWP,i}) \geq L_{CH,i,\text{Condenser Water}} \quad (8)$$

$$L_{\text{Condenser Water}} = 66 \times Q \times (C_{\text{Condenser Water}})^{-1} \times (\Delta T_{\text{Condenser Water}})^{-1} \quad (9)$$

$$\sum_{i=1}^n CTF_i \times f_{CMM}(OLR_{CTF,i}) \geq F_{\text{Outside Air}} \quad (10)$$

$$F_{\text{Outside Air}} = 66 \times Q \times V \times (C_{\text{Air}})^{-1} \times (\Delta T_{\text{Air}})^{-1} \quad (11)$$

$$SCP_i \times (f_M(OLR_{SCP,i}) - H_{Chilled\ Water}) \geq 0 \quad (12)$$

$$CWP_i \times (f_M(OLR_{CWP,i}) - H_{Condenser\ Water}) \geq 0 \quad (13)$$

$$CH_i = PCP_i = CWP_i \quad (14)$$

$$\sum_{i=1}^n CTF_i = n, \text{ (when } Q \neq 0) \quad (15)$$

$$\sum_{i=1}^n CH_i + \sum_{i=1}^n PCP_i + \sum_{i=1}^n SCP_i + \sum_{i=1}^n CWP_i + \sum_{i=1}^n CTF_i = 0, \text{ (when } Q = 0) \quad (16)$$

$$OLR_{Min.} \leq OLR_{CH,i} , OLR_{PCP,i} , OLR_{SCP,i} , OLR_{CWP,i} , OLR_{CTF,i} \leq OLR_{Max.}, \text{ (when the value of } CH_i , PCP_i , SCP_i , CWP_i , CTF_i \text{ is } 1) \quad (17)$$

$$OLR_{CH,i} , OLR_{PCP,i} , OLR_{SCP,i} , OLR_{CWP,i} , OLR_{CTF,i} = 0, \text{ (when the value of } CH_i , PCP_i , SCP_i , CWP_i , CTF_i \text{ is } 0) \quad (18)$$

$$0 \leq Q \leq Q_{Max.} \quad (19)$$

$$CH_i , PCP_i , SCP_i , CWP_i , CTF_i \in K \quad (20)$$

$$OLR_{CH,i} , OLR_{PCP,i} , OLR_{SCP,i} , OLR_{CWP,i} , OLR_{CTF,i} \in R \quad (21)$$

Equation (1), sets the model to pursue maximum COP for the chiller plant, and the plant's energy efficiency is defined as cooling capacity in energy consumption. Equation (2), sets the chillers' operating capacity not to be lower than the chiller plant's cooling capacity with the hypothesis that cooling capacity (Q) is a known value. Equations (3) and (4), set the value of chilled water supplied by the primary (and secondary) chilled water pumps not to be lower than the chilled water flow rate needed by the chiller plant during cooling capacity (Q). In addition, the usage equation (6) found in other literatures [3,4] computes the value of $L_{Chilled\ Water}$. Frequently, in the actual operation of a chiller plant, $C_{Chilled\ Water}$ is a known fixed value while $\Delta T_{Chilled\ Water}$ is a known set value [4]. Furthermore, equation (5), sets the value of chilled water supplied by the primary chilled water pump to the chiller not to be lower than the flow rate of chilled water needed by the chiller under the said operating load ratio (OLR). Equation (6) computes the value of $L_{CH,i,Chilled\ Water}$ while the Q here shows operating capacity of the chiller under a different operating load ratio (OLR). In equation (7), the value of condenser water supplied by the condenser water pumps is set not to be lower than the condenser water needed by the chiller plant during cooling capacity (Q). Here equation (9) computes the value of $L_{Condenser\ Water}$ [3,4]. In the formula, $C_{Condenser\ Water}$ is a known fixed value while $\Delta T_{Condenser\ Water}$ is a known set value [4]. Equation (8), sets the value of condenser water supplied by the condenser water pump to the chiller not to be lower than the flow rate of condenser water needed by the chiller under the said operating load ratio (OLR). Here equation (9) computes the value of $L_{CH,i,Condenser\ Water}$ while the Q here shows operating capacity of the chiller under a different operating load ratio (OLR). Equation (10), sets the volume of outside air supplied by the cooling tower fan not to be lower than the volume of outside air needed by the chiller plant during cooling capacity (Q). Here equation (11) computes the value of $F_{Outside\ Air}$ [3,4]. Measuring for V (specific volume of air) is not usually easy in the equation. However, the corresponding V value can be derived by measuring the two values of dry bulb temperature (°C) and its relative humidity (%), and by the psychrometric chart analysis. C_{Air} is a known fixed value while the study hypothesizes ΔT_{Air} is a known set value [4]. Equation (12), sets the head of the chilled water supplied by the secondary chilled water pump not to be lower than the set head, $H_{Chilled\ Water}$ is a known value. Equation (13), sets the head of the condenser water supplied by the condenser water pump not to be lower than the set head, $H_{Condenser\ Water}$ is a known value. Equation (14), is based on the actual operating condition of the chiller plant and sets the chiller and the corresponding start-stop condition of its primary chilled water pump and condenser water pump to be the same. Equation (15), is based on the actual cascading characteristic of the cooling tower fan and sets all fans in operation when the cooling capacity (Q) of the chiller plant is not 0, allowing condenser water for entering the cooling tower to obtain uniform heat dispersal. Equation (16), is based on the actual operating condition of the chiller plant and sets all components to stop operating when cooling capacity (Q) of the chiller plant is 0. This equation prevents the model from operating when Q is 0. Equation (17), sets the operating load ratio (OLR) of the components for operating between the lowest and highest operating load ratio. $OLR_{Min.}$ and $OLR_{Max.}$ are all known values. Equation (18), sets the operating load ratio (OLR) of the components for not operating is 0. Equation (19), sets the range of numerical values for the chiller plant's cooling capacity (Q), Q_{Max} as a known value and shows highest cooling capacity of the chiller plant (which is frequently its installed capacity). Equation (20), defines numerical values of the start-

stop status of chiller plant components. K is set with values of 0, 1 for the individual component. This means that each component has a K set. Value 1 means that the component starts to operate while value 0 means that the component does not start to operate. Equation (21), defines numerical values of the operating load ratio (OLR) of each of the chiller plant's components. R is set with numerical values of all possible operating load ratios for the individual component. This means that each component has an R set.

Equations (1)-(21) decide the most appropriate operating status (including the start-stop status and operating load ratio of the component) for chiller plant each component for providing cooling capacity (Q). Moreover, it optimizes chiller plant operation and maximizes energy efficiency.

Search Algorithm for Mode Solution Optimization [5][6]

Harmony Search Algorithm has been proposed by Geem et al.(2001). It is a meta-heuristic algorithm based on a population that models the effort of catching harmony among the sounds of musical instruments. The pitch of a musical instrument determines its harmony quality. Similarly, for an optimization problem, the fitness function determines the importance of decision variables. If the musician gets good harmony, she/he will record it in her/his memory. Likewise, if the algorithm achieves better fitness value, it stores this value in harmony memory. Using these similarities, Harmony Search Algorithm has been designed for optimization problems. Due to its random-based operators, Harmony Search Algorithm is an intuitive method that is fast to operate and easy to design.

In Fig. 2, the flow diagram of Harmony Search algorithm is given. As shown in the figure, the algorithm starts with the creation of the parameters and the harmony memory (HM) according to the problem parameters. The HM is initially filled with random values that are compatible with the parameter boundaries. At the same time, the objective function appropriate for the problem is determined. At this stage, if it is a constrained optimization problem, a method is chosen related to how the constraint function will be effected on the objective function. Then, a new harmony is generated in three ways. These ways are harmony memory consideration rate (HMCR), pitch adjustment rate (PAR) and random selection. If the obtained new harmony is better than anyone in HM, the new harmony is stored instead of the worst harmony in HM. Unless the termination conditions are met, the process of creating new harmony and if necessary, the process of updating the HM is repeated.

In this study, the maximum iteration of HSA is set to 10,000, HMS (Harmony Memory Size) is 100, HMCR (Harmony Memory Consideration Rate) is 0.95, Min PAR (Pitch Adjustment Rate) is 0.3, Max PAR (Pitch Adjustment Rate) is 0.95, Min bandwidth is 0.0001, and Max bandwidth is 1.0.

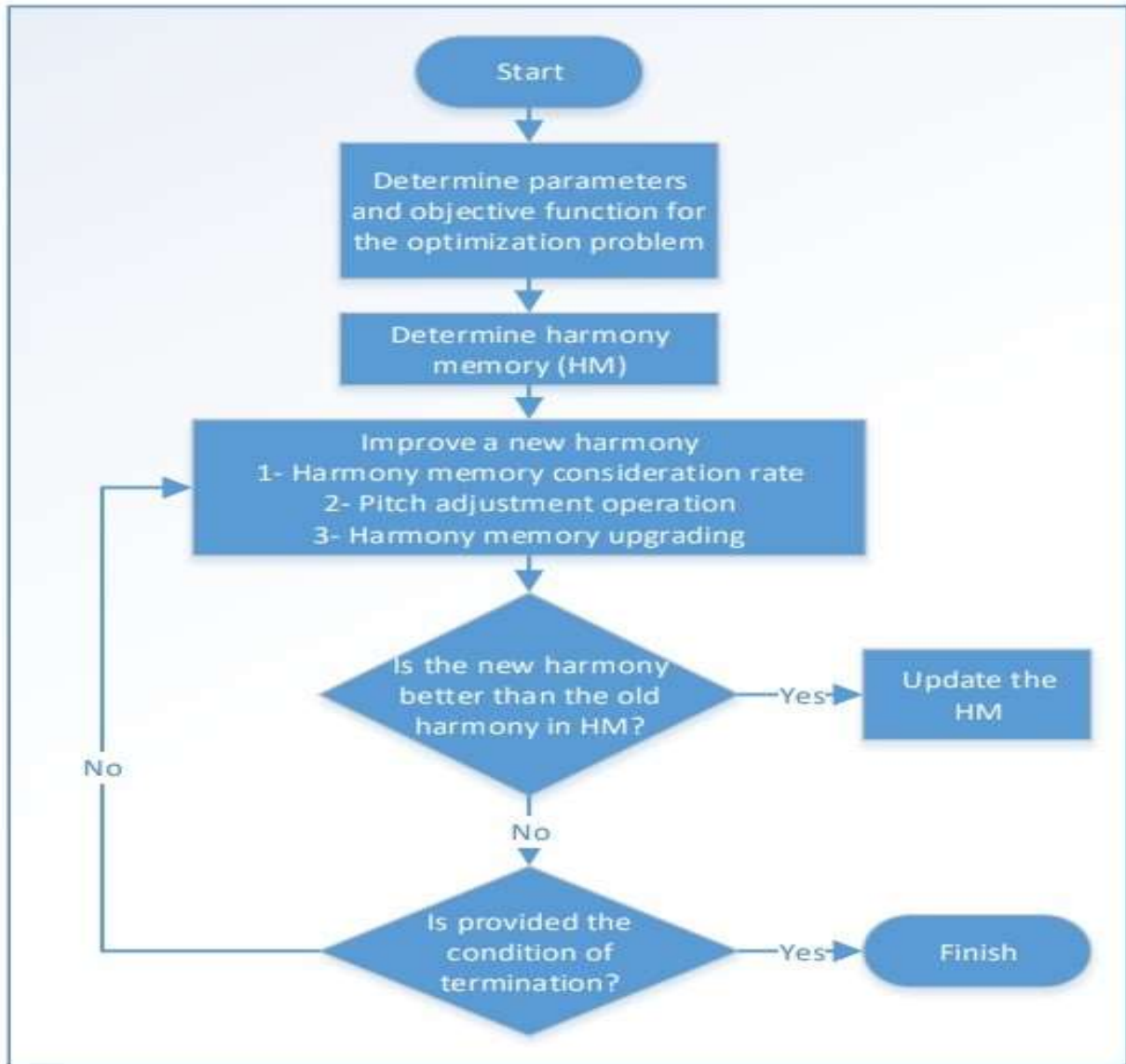


Fig. 2: The flowchart of Harmony Search Algorithm. [5][6]

CASE ANALYSIS AND RESULTS

The example of this study is an installed capacity 400RT for chiller plant from office-building. It includes two centrifugal chillers, two centrifugal primary chilled water pumps, two centrifugal secondary chilled water pumps, two centrifugal condenser water pumps, and series four centrifugal cooling tower fans. In addition, the needed chilled water and condenser water of number 1 and 2 chiller located in this chiller plant are supplied by chiller number 1's primary chilled water and condenser water pumps, and chiller number 2's primary chilled water and condenser water pumps. The chilled water supply temperature is 8(°C) while the condenser water inlet temperature to chiller is 30(°C). For other more detailed specifications of the components and their operating conditions, please see Tab. 1.

Tab. 1: Specifications of Chiller Plant

Component	Capacity	Head	OLR _{Min}	OLR _{Max}
(I) Chiller				
CH ₁	200 (RT)	-	40 (%)	100 (%)
CH ₂	200 (RT)	-	40 (%)	100 (%)
(II) Primary Chilled Water Pump(Constant Speed Pump)				
PCP ₁	2200 (LPM)	15 (M)	100 (%)	100 (%)
PCP ₂	2200 (LPM)	15 (M)	100 (%)	100 (%)
(III) Secondary Chilled Water Pump(Variable Speed Pump)				
SCP ₁	2250 (LPM)	35 (M)	40 (%)	100 (%)
SCP ₂	2250 (LPM)	35 (M)	40 (%)	100 (%)
(IV) Condenser Water Pump(Constant Speed Pump)				
CWP ₁	2750 (LPM)	30 (M)	100 (%)	100 (%)
CWP ₂	2750 (LPM)	30 (M)	100 (%)	100 (%)
(V) Cooling Tower Fan(Variable Speed Fan)				
CTF ₁	5000 (CMM)	-	40 (%)	100 (%)
CTF ₂	5000 (CMM)	-	40 (%)	100 (%)
CTF ₃	5000 (CMM)	-	40 (%)	100 (%)
CTF ₄	5000 (CMM)	-	40 (%)	100 (%)
Operating Condition (Parameter) of Chiller Plant			Set Value	
(1)	C _{Chilled Water}		1 (Kcal/Kg-°C)	
(2)	ΔT _{Chilled Water}		5 (°C)	
(3)	C _{Condenser Water}		1 (Kcal/Kg-°C)	
(4)	ΔT _{Condenser Water}		5 (°C)	
(5)	C _{Air}		0.24 (Kcal/Kg-°C)	
(6)	ΔT _{Air}		5 (°C)	
(7)	H _{Chilled Water}		28 (M)	
(8)	H _{Condenser Water}		22 (M)	
(9)	Q _{Max}		400 (RT)	
(10)	V		not fixed value, needs to be decided upon by the condition of outside air (dry bulb temperature, relative humidity)	

This study uses on-the-spot investigation to obtain data for parameters and functions of this model needing input. This study also uses actual measurements combining the statistical regression method to establish operating performance function of each component. This study uses FORTRAN programming language for the “energy optimization control mode of chiller plant” framework to write its operating and solving program.

Fig. 3 reveals the comparison results of COP before and after optimization of components of 2022.09.01–2022.09.30 chiller plant. The average running COP prior to plant optimization is 3.77. However, after optimization with ‘energy optimization control mode of chiller plant’ established in this study, the simulated result reveals that the average COP increases to 4.00 with an average energy saving rate of 6.25%. It is under equivalent cooling capacity.

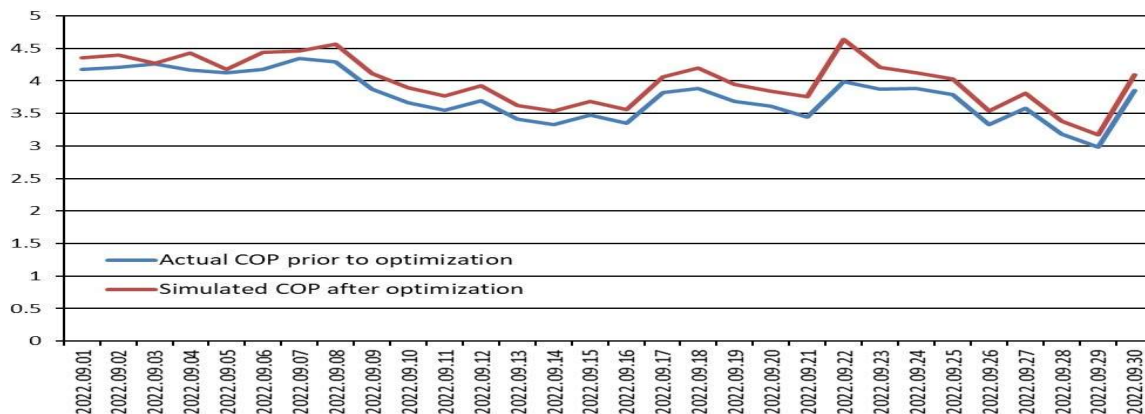


Fig. 3: COP comparisons before and after chiller plant optimization

CONCLUSIONS

According to the simulation results, we observe that these results are consistent with our expectations and constraints; therefore, mathematical modeling optimization and Harmony Search Algorithm (HSA) can greatly promote the operational performance of the chiller plant. The conclusions are as follows:

(I) The 'energy optimization control mode of chiller plant' with HSA can determine the optimum operational status of each component within the plant (including component start/stop status and operating load rate), without changing the existing component or influencing the cooling quality, i.e. maintaining an equal cooling ability, in order to obtain better energy efficiency.

(II) The new mode achieves a more exact match for actual chiller plant operation, and provides a more precise mathematical result when obtaining highly precise data on required parameters and functions of the new mode.

REFERENCES

- [1] Fu-Ann Lin. *Branch-and-Bound Method for Optimal Chiller Sequencing*. Master Thesis, Taiwan, 2003.
- [2] Chun-Wei Chen, Cheng-Wen Lee and Chia-Yon Chen. *To Enhance the Energy Efficiency of Chiller Plants with System Optimization Theory*. *Energy and Environment*. 2010, 21(5): 409- 424.
- [3] R.J. Dossat. *Principles of Refrigeration*. Wiley, U.S.A., 1991.
- [4] *ASHRAE Handbook of Liquid Chilling System*, American Society of Heating, Refrigeration and Air Conditioning Engineers, U.S.A., 2000.
- [5] Geem, Z. W., Kim, J. H., & Loganathan, G. V. (2001). *A new heuristic optimization algorithm: Harmony search*, *SIMULATION: Transactions of The Society for Modeling and Simulation*, 76(2), 60-68.
- [6] Geem Z. W. (2009). *Music-inspired harmony search algorithm*. Berlin, Germany: Springer.