China Steel Technical Report, No. 28, pp.58－62, (2015)

Innovative Operation Strategies for Improving Energy Saving in a Cooling Tower System

YING TSOU*, CHUN-CHENG CHANG* and SHI-SHANG JANG**

**New Material Research & Development Department, China Steel Corporation*
***Department of Chemical Engineering, National Tsing Hua University*

In cooling towers, the replacement of traditional single-speed fans with Variable-Frequency Drive (VFD) fans or two-speed fans can achieve significant energy saving. However, concerns regarding frequent on/off switching and the lack of a well-devised controller discourage the widespread implementation. In this study, a temperature zone setting method is proposed to replace the traditional point setting method on fan control strategy. We also developed a multi-fans control strategy. Additionally, the highest allowed temperature of output water in the process is set as the upper limit of a temperature zone in order to further conserve energy. Both strategies are comprehensively analyzed for a virtual cooling tower that uses operational data from an existing VFD-fan-based cooling tower system at CSC. The results of on-site implementation show energy savings of 38% for a 0.75 °C zone without increasing the on/off switching frequency. The proposed strategies were further verified by an on-line field experiment. The proposed strategies can be universally and easily applied to any existing cooling tower with significant energy conservation.

Keywords: Cooling tower, Variable-frequency drive, Zone setting control

1. INTRODUCTION

Cooling towers are a commonly utilized device of industrial plants, especially in energy-intensity sectors such as the iron, steel, or petrochemical industries. A cooling tower dissipates heat to the atmosphere through a combination of heat- and mass-transfer processes. Many studies in cooling towers have focused on design(1-3) and performance parameters(4,5) to improve the performance of cooling towers. Those results told us that any improvement in cooling tower operations would provide significant opportunity for energy conservation.

Variable-Frequency Drive (VFD) devices have been available for more than four decades, but were not applied to cooling tower fans until their prices fell sharply over the past decade(6-8). Recently, two-speed fans have been gradually replaced with VFD-fans. Practical concern is how to avoid frequent start/stop fan operation, which can cause sudden increases in stress due to the large inertia moment. This drawback prevented widespread implementation of cooling systems based on VFD-fans. The energy-saving potential of VFD-fans is more compelling and significant in large-scale, multi-cell systems used in energy-intensive industries (9,10). This study proposes two operational strategies to fully exploit the energy-saving potential represented by VFD-fan-based cooling tower systems.

Feedback control is not used in traditional cooling towers, due to a lack of operational choices. With improving affordability, VFD fans have gained popularity and gradually replaced two-speed fans in cooling towers. This provides a great opportunity to fully exploit the energy-saving potential of VFD technology by applying feedback control to ensure outlet water temperatures are maintained at set points. Nevertheless, frequent on/off switching of fans and the lack of a well-devised controller prevented industry from widely adopting this technology. As an alternative, rule based coded Programmable Logic Controllers (PLC) were used instead of the feedback controller. The control of the outlet water temperature at the highest allowable temperature is then compromised, as is the energy-saving potential associated with the introduction of VFD-fans. The shortfall is more apparent in a large-scale cooling tower system comprising multiple cells. Therefore, this study proposes two operational strategies to fully exploit the energy-saving potential of VFD-fan-based multi-cell cooling towers.

The content of this article includes five sections. Besides the introduction in Section 1, Section 2 presents the theoretical development and step-by-step implementation of the proposed strategies. The strategies will be modeled using operational data acquired from an existing cooling tower with variable-fan cooling in

Section 3, and the virtual cooling tower is established by this model. The proposed strategy validation, implementation and on-line experiments are documented in Section 4. The final section presents a brief summary of the findings.

2. OPERATIONAL STRATEGIES

Section 2.1 describes the effects of a larger “approach value” on energy savings during fan operation. Section 2.2 details the implementation and theoretical development of zone setting Proportional-Integral (PI) controllers.

2.1 Larger approach strategy

Two kinds of temperature differences are indexed for the design and operation of tower systems, namely, the range and approach. The temperature difference between water entering and leaving the cooling tower is called the range. The range is determined using the heat load and water flow rate, rather than by the thermal capability of the cooling tower. The difference between the outlet water temperature and the wet-bulb temperature of inflowing air is termed the approach.

At steady state, the heat load and water flow are constant and thus, the range is also constant. Subsequently, the enthalpy driving force increases as the outlet water temperature increases. Taking the selected cooling tower as an example, the operational conditions are assumed as follows: input water temperature of 35.0°C, air temperature of 25.4°C, relative humidity of 75%, and ratio of liquid to air flow rate of 2.02. If the output water temperature is 31.5°C, then the operation line is AB and the driving force is the average distance between line AB and line A’ B’, as shown in Fig.1.

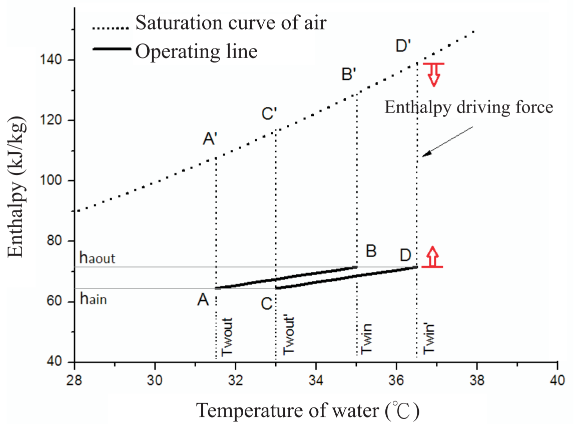

Fig.1. Driving force diagram for the studied cooling tower.

If the output water temperature is maintained at 33.0°C, then the operation line shifts to the line CD; the driving force becomes the average distance between line CD and line C’ D’, which is larger than the previous case. Operations with a large driving force consume less energy.

For the operation of an existing cooling tower, a large driving force requires a large approach and as indicated in Fig.1, a high outlet water temperature. Equipped with feedback control, a cooling tower with variable-speed fans can be automatically operated at the highest allowable outlet temperature.

2.2 Temperature zone control strategy

For a feedback control system, two process variables must be identified: the controlled (CVs) and manipulated (MVs) variables. In a VFD-controlled cooling tower, operators adjust the fan operating frequency (Hz), which in turn determines the fan speed and controls the outlet water temperature. Given the relationship between fan operating frequency (Hz) and power requirement, the power necessary to achieve the desired outlet water temperature can be calculated. Hence, outlet water temperature and fan power are considered as CV and MV respectively. In the following feedback controller, the objective is to reduce the error to zero:

$$e_{k=}\, y_{sp,k} - y_k \;\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

where K is the sequence index, e_k is the error term on the kth run, y_k is the measured value of the CV at the kth run, and y_{sp} is the set point of the CV.

The discrete PI control algorithm is considered the most appropriate, given its flexibility, computational simplicity, cost effectiveness, and transparency. The goal of feedback control is to maintain the measured value of the CV at its set point.

In this study, the measured value of the CV can be lower than the set point during periods of cold weather. When this occurs, the integral term accumulates until the controller output eventually fails. The velocity form of PI control is chosen in order to avoid this problem for the proposed temperature control. This approach inherently resolves anti-reset windup, because the summation of errors is not explicitly calculated. The velocity form of the formula for discrete PI control is described in Eq.(2).

$$P_{k+1=}P_k+K_c+[(e_k-e_{k-1})+(\triangle t/\tau_I)e_k] \;\ldots\ldots\ldots\ldots\ldots (2)$$

Here, P is the value of the MV, namely the power requirement of fan set; K_c is the controller gain; τ_I is an adjustable parameter and is referred to as integral time; $\triangle t$ is the sampling period, and K_c and τ_I are determined by a data-driven estimation.

In order to reduce the number of on/off events, the temperature zone control strategy is adopted in this work. When the measured outlet temperature is outside the temperature zone, the target is set as the zone mid-value; the target is set to the present outlet temperature when its value is within the zone i.e..

$$\begin{cases} e_k = T_{sp} - y_k \text{ , } T_k > T_{UL} \\ e_k = T_{sp} - y_{k}, \text{ , } T_k < T_{LL} \\ e_k = 0 \text{ , } T_{LL} \le T_{sp} \le T_{UL} \end{cases} \quad \text{........................ (3)}$$

where T_{UL} and T_{LL} are the upper and lower limit values, respectively; and T_{sp} is the set point temperature, i.e. T_{sp} (T_{UL} + T_{LL})/2. The three values have the following relationship: The power requirement can be calculated using Eq.(3). If the outlet temperature remains within the target zone, no adjustments are necessary and so the power requirement remains constant.

3. VIRTUAL PLANT ESTABLISHMENT

This study uses real operational data of CSC's #300k cooling tower system from an eight-day period in late March, 2014 to model the energy-saving effect of the proposed strategies. During that period, average daily energy consumption was 1334.6 kWh, and statistics for cooling water and air properties are shown in Table 1. The air temperature and humidity data reflect the typical spring season in Taiwan.

Table 1 Ambient air and cooling-water data used to model a virtual plant

	Tw,in (°C)	Tair (°C)	H (%)	Tw,out (°C)
Max.	36.6	31.9	94.6	32.9
Min.	32.6	18.8	52.3	30.2
Average	34.7	25.4	74.6	31.6
Standard Deviation	0.7	3.2	7.8	0.5

The model estimates outlet water temperature for the selected cooling tower, which is a function of inlet water temperature, air temperature, relative humidity, water flow rate, and air flow rate. The following Eq.(4) is obtained from linear regression of the first seven days data in Fig.2, and functions as the virtual cooling tower system:

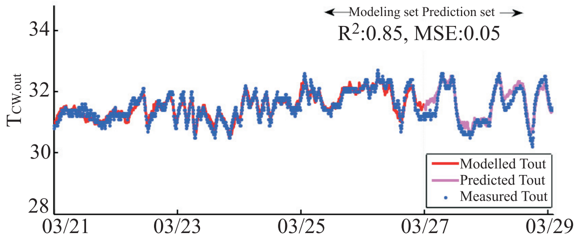

Fig.2. Modeled sets of the virtual plant.

$$T_{w,out} = 0.54\times T_{w,in,1} + 0.21\times T_{w,in,2} + 0.63 \times T_{w,in,3} + 0.92\times H - 0.01\times P + 0.02 \quad \text{........................(4)}$$

where $T_{w,in,1}$, $T_{w,in,2}$, and $T_{w,in,3}$ are the temperatures of each inlet water stream; T_{air} is air temperature; H is relative humidity; and P is total power consumption of the cooling tower fans.

Figure 2 shows the modeled and prediction results. Besides the data from the first seven days are implemented as the modeled set, the data of the last day are used as the prediction set. The model gives an R^2 value of 0.85 and the Mean Square Error (MSE) of the prediction set is 0.05. The results indicate that the model can accurately represent a cooling tower system to examine the implementation of the proposed operational strategies.

To validate the proposed strategies, the virtual plant must be equipped with a PI feedback controller, which replaces the rule-based PLC used in the existing system. The construction of the proposed control loop is described in Section 2. To reduce on/off switching of the fans, this PI feedback controller must adopt hybrid operations that combine rule- and equation-based operations. When ambient air temperature is low, partial startup of the four-fan set can sufficiently cool the water. Once all fans are required i.e., power requirement exceeds 55.36 kW, the Eq.(5) is executed:

$$f = 12.1+0.006p^3 - 0.12p^2 + 0.4p \quad \text{........................(5)}$$

where f is the operated frequency and p is the power requirement.

In equation , the MV (i.e. power requirement) is calculated automatically in the controller. The proportional and integral parameters, K_c andτ_I, of the controller in the virtual system are calculated via the data-driven method. K_c and τ_I are obtained as 42.62 and 0.52 respectively. The heat load of the process is assumed to be constant during the studied period.

4. VALIDATION OF THE PROPOSED STRATEGIES

Two short term field experiments were conducted to demonstrate the validity of the proposed strategies. Considering of the maximum allowable temperature of water in outlet (32.5°C) and some tolerant value, we conducted the first experiment by the traditional (precise target) feedback control with a set point of 32°C to verify the large approach strategy control, and was run from 10:35 to 15:50 on a day in late spring. During the experimental period, average air temperature was 27.2°C, relative humidity was 57.9% and wet-bulb temperature was 21.1°C.

Figure 3 clearly shows that the traditional feedback control keeps adjusting the fans' power, and after one or two cycles, the outlet temperatures gradually converge to the set point. Figure 3 shows corresponding temperature and power profiles for the simulated rule-coded PLC operation that was run at the same time. At 12:35, the outlet temperature dropped below 31.5°C, causing one of the fans to be turned off. During this period, the average power level was 47 kW, while that for the original PLC operation would be 55 kW. The energy saving was about 14.5% by applying the large approach strategy. However, the proposed control method involves 11 on/off operation, compared with 1 for the original PLC operation. Observably, the large approach strategy had the shortcoming of much more on/off switching cycles than original operation.

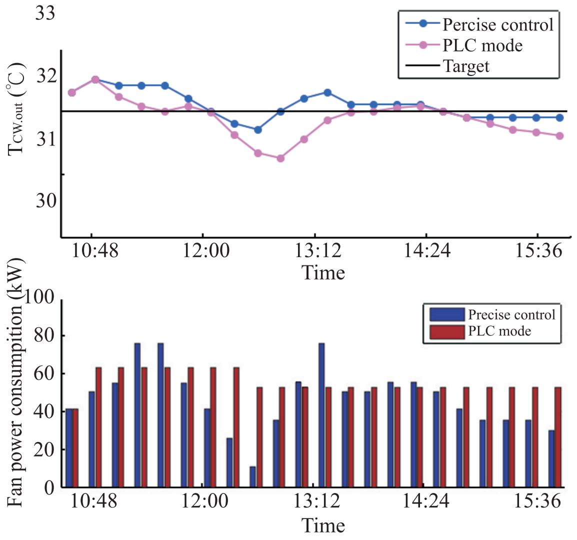

Fig.3. Field experiment using precise feedback control with set point of 32°C.

To overcome the shortcoming of large approach strategy with point setting control, the zone setting strategy was employed. The second field experiment was run from 9:45 to 13:15 on the next day, using PI feedback control with a 0.5°C zone as described in Section 2. During the experimental period, average air temperature was 31.0°C, relative humidity was 59.3%, and wet-bulb temperature was 24.5°C. The target temperature zone was set between 32.0°C and 32.5°C. Figure 4 shows that the temperature dropped below the lower bound of the zone interval; at 10:30, the fan frequencies decreased with resulting energy consumption of 55.3 kW. The temperature remained below the lower zone boundary; at 10:34, one fan turned off, and the frequency of the other increased from 35 to 40 Hz, with resulting energy consumption of 50.4 kW. At 11:00, the temperature remained below the lower bound of the zone interval; the frequency of the one operational fan decreased from 40 to 35 Hz, with resulting energy consumption of 44.8 kW. At 11:30, the temperature exceeded the lower bound and the same fan increased frequency from 35 to 40 Hz. In summary, the fan operation was only adjusted when the temperature dropped below the lower limit; otherwise, it remained unchanged. The experimental period involved 14 fan adjustments, with only 1 on/off operation. The outlet water temperatures were controlled around the target region.

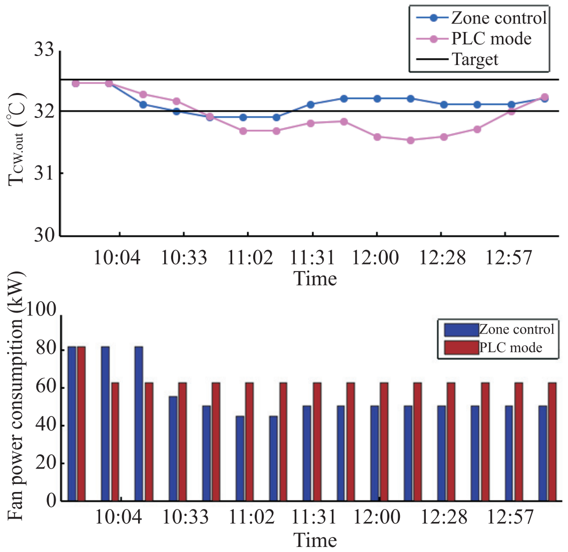

Fig.4. Experimental zone temperature control strategy.

Under the same ambient air conditions as the field experiment, the operations following the rule-coded PLC are documented in Fig.4. At 10:00, outlet water temperature was 32.5°C; according to the PLC rules, all fans turned on, with corresponding energy consumption of 63 kW. Subsequently, the temperature fluctuated slightly but never dropped below 31.5°C, and therefore all the fans remained on. Average energy consumption of zone control throughout this period was 56.3 kW, compared with 63 kW for the original PLC operation. The zone control case required 1 on/off operation, whereas the PLC scenario required none.

The second case showed that combine the proposed large strategy and zone setting control can really save energy without increasing much more on/off switching cycles than the original PLC operation.

The results of two months on-site implementation further showed that for the 0.75°C zone, daily energy consumption was 826.2 kWh, which was 62% of the original energy consumption and the 63 times of on/off cycle was much lower than the original mode (103 times). In other words, by employing a PI controller operating a temperature zone strategy, a VFD fan can achieve 38% energy saving in a cooling tower without increasing the frequency of on/off switching. It is worth saying that we can save energy by just applying the proposed strategies to the PLC system without installing any new hardware.

5. CONCLUSION

The replacement of traditional two-speed fans with VFD-fans in a cooling tower can significantly reduce energy use. Concerns of frequent on/off switching and the lack of a well-devised controller lead to conservative operations, which allow for further improvements in energy efficiency. In this work, a PI feedback controller with a temperature zone setting was proposed for an existing VFD-controlled cooling tower system to manage the outlet water temperature while reducing fan energy consumption and solving the problem of frequent on/off switching.

A successful on-site implementation verified the proposed strategies. The results showed that the original energy consumption can be reduced by 38% with a 0.75°C temperature zone without increasing on/off switching frequency. It is worth noting that the proposed strategies can be implemented without further investment or any additional hardware if the existing system is operated by a Distributed Control System (DCS). The cost of purchasing the additional hardware needed is still much lower than that of maintaining the original operating strategy, given the long-term economic benefits of energy saving, not to mention the reduction in CO_2 emissions. It was concluded that the proposed energy-saving strategies are very promising for further improvements in any VFD-fan-based cooling tower system.

REFERENCES

1. N. Milosavljevic and P. Heikkilä: Applied Thermal Engineering, 2001, vol. 21, pp. 899-915.
2. M. H. Panjeshahi et al.: Chemical Engineering Research and Design, 2009, vol. 87, pp. 200-209.
3. Zou Z et al.: Energy Conversion and Management, 2013, vol. 76, pp. 945-955.
4. F. W. Yu and K. T. Chan: Applied Energy, 2006, vol. 83, pp. 628-648.
5. T. H. Pan et al.: Energy Conversion and Management, 2011 vol. 52, pp. 1377-1385.
6. CTI 105-ATC (00) CTI Code Tower Standard Specifications for Acceptance Test Code for Water Cooling Towers: Cooling Technology Institute, 2000, pp. 67-69.
7. G. F. Cortinovis et al.: Energy Conversion and Management, 2009, vol. 50, pp. 2200-2209.
8. J. G. Wang et al.: Energy Conversion and Management, 2013, vol. 73, pp. 226-233.
9. N. Muntean, C. Volosencu and A. Hedes: The 9th WSEAS International Conference on International Conference on Automation and Information, Bucharest, Romania, 2008, pp. 184-189.
10. F. W. Yu and K. T. Chan: Applied Energy, 2008, vol. 85, pp. 931-950. □