Efficiency improvement of cogeneration system using statistical model

Tianhong Pan, Dongliang Xu, Zhengming Li, Shyan-Shu Shieh, Shi-Shang Jang

A R T I C L E   I N F O
Article history:
Received 18 June 2012
Received in revised form 27 November 2012
Accepted 31 December 2012

Keywords:
Cooling tower (CT)
Turbine generator (TG)
Approach
Statistical model
Local model network (LMN)

A B S T R A C T
In order to improve the efficiency of the cogeneration system which integrates turbine generator (TG) and cooling tower (CT), a real-time optimum operation strategy of fans is proposed. First the statistical models of TG and CT are developed off-line by using the local model network (LMN) algorithm. Then the optimal outlet temperature of cooling water ($T_{cw,\text{out}}$) is calculated by solving the optimization problem which maximizes the net power output of cogeneration system. Based on the calculated $T_{cw,\text{out}}$, a statistical linear model is employed, which characterizes Approach of CT. Finally, based on the proposed Approach model, an optimum operation mode table for the six fans is established. In order to decide optimum mode for fans, the factors such as different climatic conditions are also incorporated. Using the optimum operation table, a real-time operation mode of fans can be achieved. The performance of the proposed method is similar to the previously developed LMN method (about 85–95% as demonstrated in Table 3) while requiring a very low computational cost. The proposed method is also advantageous because the field operators can understand the physical meaning of operation. This algorithm can be easily implemented into the existing distributed control system making it a very good option for on-line implementation.

1. Introduction
Energy efficiency is an important issue in the industrial processes, especially in many older and inefficient facilities. Efforts to manage and continuously improve energy efficiency can save the energy cost significantly. Furthermore, it can be considered as a key solution to reduce the greenhouse gas emissions. Among those energy utilizing industries, improvement of the energy efficiency in a power generation system is of great importance because electricity has become the main source of energy in daily life and industrial plants. Compared with the generation of electricity in a thermal power station or the production of heat with a boiler, the cogeneration system can simultaneously generate the electricity and heat. This makes it popular in the industrial community; in particular, energy-intensive industries, such as oil refineries, chemical plants, paper mills and mining operations etc. Besides, the fuel efficiency in the cogeneration systems is higher than an individual electricity plant or a thermal station. It is reported that in a plant consisting of the cogeneration system, the net energy production increases from 30–35% to 80–90% under the same operational conditions. Moreover, it has less emission of hazardous material to the atmosphere. Thus the cogeneration system results in significant cost savings and further reduces environmental contaminations, which has caught much attention in the recent years [1].

A typical cogeneration system consists of boiler, turbine generator (TG), condenser and cooling tower (CT). The efficiency of each unit is vital in the overall operation of the system. In the past decades, a great deal of work has focused on enhancing the efficiency of each of these individual parts of the cogeneration system. Chuang and Sue [2] proved that increasing the vacuum degree in condenser could gain more electrical power output. Zhao and Cao [3] also demonstrated that optimizing back pressure of condenser improved the energy efficiency. Huang and Edwards [4] altered the auxiliary to decrease the back pressure of condenser improving the thermal efficiency. Besides optimal operation on condenser, improvement in the thermal efficiency on CT has also gained considerable attention. Giorgia et al. [5] proposed an optimization model accounted for a cooling tower, a network of pipelines and heat exchangers. The model included the objective of minimizing the operating costs and improving the thermal efficiency of CT by optimizing the fan speed, water removal flow rate and valve positions at the heat exchanger branches. Panjeshahi and Ataei [6] and Daley [7] found optimal design methods of the cooling system. Yao and Lian [8] obtained that the energy saving was likely to reach as high as 10% by applying the optimal model to the cooling system. Moreover, selecting a suitable filling material is another key strategy to improve the thermal efficiency of CT. Goshayshi
and Missenden [9] found that mass transfer performance of rough corrugated packing was increased by 1.5–2.5 times the smooth packing packing values. Ashwini [10] studied the changes of efficiency, weight of film and influence of cooling water temperature in a power station in India that was using polyvinyl chloride. Reuter and Kröger [11] developed a linear upwind computational model and an Eulerian FLUENT model to evaluate fill performance characteristics from test data and to model fill performance in cooling towers, respectively. Some scientists [12–14] described some of the deterioration problems of asbestos-cement cooling tower fill and tried to find new filling materials to replace it. Comparison among the different filling materials can be found in [15–17]. Nenad and Perti [18] performed a series of experiments to test efficiency of different filling materials in a cooling tower. The mentioned work either focused on analysis of several factors which affected the performance of condenser, or adding/improving the auxiliaries of CT. However, realizing these improved strategies interrupts the normal operation of the cogeneration system, which is not possible in the real plant. On the other hand, the implementation will increase the additional cost of power plant. To tackle the dilemma, Pan et al. [19] proposed an optimal method to maximize the net power output via integrated operation of TG and CT. In this work, a linear model is developed which facilitates the computation of finding the optimum operation mode of fans in the cogeneration system. In Section 2, a description of a typical cogeneration system is given, followed with the objective statement of this paper. A linear model of CT is proposed based on the physical meaning of Approach in Section 3. Further in Section 4, some off-line study experiments are conducted to show the differences between the proposed algorithm and LMN proposed by Pan et al. Finally, conclusions are drawn for the utilization of the optimal Approach in Section 5.

2. Plant and optimal objective revisit

2.1. Plant description

In this work, a typical cogeneration system is considered as presented by Pan et al. [19]. The cogeneration system comprises of two identical, parallel power generation systems (named TG6 system and TG7 system), a CT with six fans, a condenser and two heat exchangers (LP1 and LP2). The details are shown in Fig. 1.

The high-pressure steam is generated from a boiler and introduced into TG to produce electricity. Then the low-pressure steam comes out from TG and flows into condenser to be condensed as feed water. Feed water is heated up through the LP1 and LP2, on its way to the boiler again. Thus the individual components TG, condenser and CT are closely connected. The condenser in the cogeneration system is usually operated in a vacuum condition. As a thumb rule, when the condenser achieves lower back pressure, the TG produces more electricity. This paper uses cooling water (CW), the most popular but not the only medium to condense exhaust steam in the condenser. CW becomes warm by absorbing heat in a condenser, and then it becomes cold when releasing heat in a CT. A higher degree of vacuum is achieved when absorbing heat in a condenser. CW enters in a condenser. In other words, cooler CW will drive the generation system to produce more electricity. In practice, the outlet temperature of CW is controlled by a set of fans. Different operation modes of fans result in different CW temperatures. Detailed description of the cycle operation of the integrated system was given by Pan et al. [19].

### Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{cw,in}$</td>
<td>Inlet water temperature of cooling tower ($^\circ$C)</td>
</tr>
<tr>
<td>$T_{cw,out}$</td>
<td>Outlet water temperature of cooling tower ($^\circ$C)</td>
</tr>
<tr>
<td>$T_{wb,in}$</td>
<td>Wet bulb temperature of inlet air to the cooling tower ($^\circ$C)</td>
</tr>
<tr>
<td>$m_{cw,in}$</td>
<td>Inlet water mass flow rate of cooling tower (kg/h)</td>
</tr>
<tr>
<td>$m_{cw,out}$</td>
<td>Outlet water mass flow rate of cooling tower (kg/h)</td>
</tr>
<tr>
<td>$m_{air}$</td>
<td>Mass flow rate of air (kg/h)</td>
</tr>
<tr>
<td>$m_{air}^D$</td>
<td>Mass flow rate of dry air (kg/h)</td>
</tr>
<tr>
<td>$T_{air,in}$</td>
<td>Dry bulb temperature of inlet air to the cooling tower ($^\circ$C)</td>
</tr>
<tr>
<td>$T_{air,out}$</td>
<td>Dry bulb temperature of outlet air from the cooling tower ($^\circ$C)</td>
</tr>
<tr>
<td>$\bar{T}_{air,in}$</td>
<td>Relative humidity of inlet air to the cooling tower (%)</td>
</tr>
<tr>
<td>$\bar{T}_{air,out}$</td>
<td>Relative humidity of outlet air to the cooling tower (%)</td>
</tr>
<tr>
<td>$E_{wb}$</td>
<td>Saturation vapor pressure of wet ball saturated air at the temperature $T$ (MPa)</td>
</tr>
<tr>
<td>$E_{db}$</td>
<td>Saturation vapor pressure of dry ball saturated air at the temperature $T$ (MPa)</td>
</tr>
<tr>
<td>$W_F$</td>
<td>Power consumption of cooling tower fans (kW)</td>
</tr>
<tr>
<td>$W_{TG6}$</td>
<td>Power production of TG6 (kW)</td>
</tr>
<tr>
<td>$W_{TG7}$</td>
<td>Power production of TG7 (kW)</td>
</tr>
<tr>
<td>$h_s$</td>
<td>Air enthalpy at cooling tower entrance (kJ/kg)</td>
</tr>
<tr>
<td>$\bar{h}_L$</td>
<td>Enthalpy of the saturated air at the temperature $T$ (kJ/kg)</td>
</tr>
<tr>
<td>$c_{P,L}$</td>
<td>Specific heat of water at constant pressure (kJ/kg$^\circ$C)</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>Humid heat (kJ/kg$^\circ$C)</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>Latent heat (kJ/kg)</td>
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### Subscript

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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</thead>
<tbody>
<tr>
<td>CW</td>
<td>Cooling water</td>
</tr>
<tr>
<td>D</td>
<td>Dry</td>
</tr>
<tr>
<td>G</td>
<td>Dry air mass flow rate (kg/h)</td>
</tr>
<tr>
<td>L</td>
<td>Low power heat exchanger</td>
</tr>
<tr>
<td>WP</td>
<td>Power production of TG7 (kW)</td>
</tr>
<tr>
<td>OA</td>
<td>Optimal operation mode of fans</td>
</tr>
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</table>

### Superscript

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>g</td>
<td>Ground</td>
</tr>
</tbody>
</table>

### Abbreviation

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CT</td>
<td>Cooling tower</td>
</tr>
<tr>
<td>DCS</td>
<td>Distributed control system</td>
</tr>
<tr>
<td>IOTCS</td>
<td>Integrated ozone treatment cooling system</td>
</tr>
<tr>
<td>LMN</td>
<td>Local model network</td>
</tr>
<tr>
<td>TG</td>
<td>Turbine generator</td>
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</tbody>
</table>
2.2. Problem statement

As discussed in the previous section, in a real cogeneration system, the optimal operation mode of six fans is a key factor in the balance between power consumption (CT) and power generation (TG). The main purpose of this paper is to gain the maximum net power output which is simultaneously determined by three factors: $W_{TG6}$, $W_{TG7}$ and $W_F$. Thus we can formulate the optimization problem as follows:

$$\text{max} J = \max \{ W_{TG6} + W_{TG7} - W_F \}$$

s.t. $W_{F,\text{min}} \leq W_F \leq W_{F,\text{max}}$  \hspace{1cm} (1)

where $W_{TG6}$ and $W_{TG7}$ are power production of TG6 and TG7 respectively, $W_F$ is power consumption of fans, which is determined by the revolution number of fans.

In the selected plant, the CT unit has 6 fans. Each fan has 3 operating options, namely, close, low speed and high speed. Due to the restriction of turn-down ratio, the fan set usually operates in one of the following seven modes: six low-speed $(C0_L6_H0)$, five low-speed and one high-speed $(C0_L5_H1)$, four low-speed and two high-speed $(C0_L4_H2)$, three low-speed and three high-speed $(C0_L3_H3)$, two low-speed and four high-speed $(C0_L2_H4)$, one low-speed and five high-speed $(C0_L1_H5)$, six high-speed $(C0_L0_H6)$. The $W_{TG6}$ and $W_{TG7}$ mentioned in Eq. (1) are determined by the degree of vacuum in condenser as well as the magnitude of steam from boiler. $W_F$ determines the outlet temperature of CW $(T_{cw,\text{out}})$ which directly connects the vacuum of condenser. Therefore, when the cooler CW enters in the condenser, the higher degree of vacuum is achieved; however, the consumption of $W_F$ is greater. In order to tackle this dilemma in the operation, we design an optimal strategy to maximize electricity gain with the minimum consumption. The key point is to find out the optimal output temperature of CW. Unlike the method proposed by Pan et al. [19], an optimum operation table based on Approach to achieve the electricity gain is presented in this paper. The details are discussed in the subsequent sections.

3. Methods

3.1. Performance index of cooling tower

The characteristics of CT can best be explained on the driving force diagram as shown in Fig. 2. The lower line (i.e. the straight line) is the operation line, which results from an overall energy balance on the fluid streams entering and leaving the tower. It also represents the enthalpy of saturated air $(h_a)$ as a function of the water temperature. The upper curve (i.e. the equilibrium curve) represents the enthalpy of water $(h_w)$. Thus, the enthalpy difference between the equilibrium curve and the operating line $(h_w - h_a)$ provides the driving force for the cooling process.

Three common terms named Merkel equation, Range and Approach, are used to describe the performance of the CT. Usually, the manufacturer can provide the tower’s design characteristic curve, which is obtained through experimental test under specified design parameters. Long term usage, changes of packing, fouling etc. may affect the characteristics of CT. In order to get the real-time performance of CT, several methods for the analysis of CT are available. Johannes and Detlev [20] critically evaluated the heat rejected and water evaporated in mechanical and natural draft cooling towers by employing the Merkel, Poppe, and e-number-of-transfer-units (e-NTU) methods of analysis respectively, at different operating and ambient conditions. Jaber and Ralph [21] also developed the e-NTU design method for cooling towers. The most used thermodynamic characteristic of the cooling tower $KAV/L$ is determined by Merkel’s integral, which is shown as follows:
\[
\frac{K_aV}{L} = \int_{T_{cw,in}}^{T_{cw,out}} \frac{C_{pw}}{H_w - H_b} dT_{cw}
\]

where \( T_{cw,in} \) is the input temperature of CW.

On the other hand, the temperature difference between \( T_{cw,in} \) and \( T_{cw,out} \) defines the Range of CT:

\[
\text{Range} = T_{cw,out} - T_{cw,in}
\]

Regarding the optimal operation of CT, Stout and Leach [22] studied the various fan control modes, namely, single-speed, two-speed, and variable-speed, under different ambient conditions. They concluded that the Range of a CT was a key index for conserving fan power especially in colder climates. Besides the Range, Braun and Diderrich [23] proposed to maintain a constant Approach, i.e., temperature difference between the outlet CW temperature from CT and inlet wet-bulb temperature of ambient air \( T_{wb,in} \).

\[
\text{Approach} = T_{cw,out} - T_{wb,in}
\]

To find the wet-bulb temperature of the inlet air in Fig. 2, move horizontally (adiabatically) from the bottom of the operating line to the equilibrium curve (the interface is saturated). At this temperature, air saturated with water has the same enthalpy as the steam at equilibrium (the interface is saturated). At this temperature from CT and inlet wet-bulb temperature of ambient air \( (T_{wb,in}) \).

\[
\text{Approach} = T_{cw,out} - T_{wb,in}
\]

The wet bulb temperature of the air stream can be calculated by Eq. 10.

Further, the airflow rate in the cooling tower \( m_{air} \) is directly correlated with the fans’ revolution rate which is determined by power consumption \( (W_f) \). Thus, the power consumption of the fans can be used to approximate the airflow rate.

Note that \( m_{air} \) can be reformulated as:

\[
W_f = f(m_{air})
\]

Approach is affected by many other factors, it is not advisable to keep Approach as low as possible [25]. The optimal value of Approach will be different when the conditions change. In general, the best Approach varies from 3 °C to 8 °C. Panjeshahi and Ataei [6] performed an analysis of a cooling water system using IOTCS for minimizing the total cost and conservation energy. They took Approach into consideration as an important factor. After the optimization, the minimum Approach value was 5 °C. They also concluded that the Approach was more important than the flow rate and the range in achieving a high driving force for cooling. This is reason that the driving force becomes more limiting as the Approach becomes narrow. Therefore a suitable method, i.e. the optimal linear operation line, should be developed to control Approach.

3.2. Modeling for cooling tower

Based on the energy and mass balance [26], the outlet temperature of cooling water can be achieved by:

\[
T_{cw,out} = f(T_{cw,in}, T_{air,in}^{D}, H_{R,in}, W_f)
\]

where \( f \) is an unknown nonlinear function, \( H_{R,in} \) and \( T_{air,in}^{D} \) are the relative humidity and dry temperature of the air stream entering the cooling tower.

Substituting Eq. (5) into Eq. (4), Approach can be rewritten as:

\[
\text{Approach} = f(T_{cw,in}, T_{air,in}^{D}, H_{R,in}, T_{wb,in}, W_f)
\]

Note that \( T_{cw,in} \), \( T_{air,in}^{D} \), and \( H_{R,in} \) satisfy the following equation:

\[
E_{wb} = AP_h(T_{air,in}^{D} - T_{wb,in}) = \frac{H_{R,in}E_{wb}}{100}
\]

where \( E_{wb} \) represents the pure horizontal liquid surface saturation vapor pressure of the wet ball temperature, \( A \) is dry and wet table coefficient, \( P_h \) is atmospheric pressure and \( E_{wb} \) is the pure horizontal liquid surface saturation vapor pressure of the dry ball temperature. The wet bulb temperature of the air stream can be calculated by Eq. (7).

Further, the airflow rate in the cooling tower \( m_{air} \) is directly correlated with the fans’ revolution rate which is determined by power consumption \( (W_f) \). Thus the power consumption of the fans can be used to approximate the airflow rate.

\[
\begin{align*}
W_f &= f(m_{air}) \\
\frac{m_{air}}{C} &= \frac{m_{air}L_{F}}{C_s(T_{air,in}^{D} - T_{air,in}^{D}) + \lambda_0(H_{R,in} - H_{R,out})}
\end{align*}
\]

where \( \lambda_0 \) represents the latent heat and \( C_s \) is the humid heat. The water mass flow rate \( (m_{cw}) \) passing through the cooling tower is continuously monitored by a variable area flow meter. In this study, \( m_{cw} \) is assumed to be a constant because the evaporation water is negligible compared to \( m_{air} \).

The cooling tower of the China Steel Corporation located in Taiwan is shown in Fig. 3. The cooling tower has 6 units. On top of each unit, there is a large fan that draws the air through the fill, cools the water and exhausts the hot air to atmosphere. The thermocouples of dry and wet bulb temperature are used to measure the air stream leaving the cooling tower. Positions of these installed thermocouples are shown in Fig. 3. Through the experiments performed on 2010.4.15, 2010.5.9, 2010.5.26 and 2010.5.27, we found that all the air streams leaving the cooling tower were saturated under low speed and high speed of fans respectively. Figs. 4 and 5 show the details of measurement on 2010.4.15. This implies that the \( H_{R,out} \) is constant in this study and may be regarded as an offset in statistical modeling.

Therefore, \( m_{air}^{D} \) can be reformulated as:

\[
W_f = f(T_{cw,in}, T_{air,out}, T_{air,in}^{D}, H_{R,in})
\]

Rearranging Eq. (6) using Eqs. (7), (8), (9) and (10) yields:

\[
\text{Approach} = f(T_{cw,in}, T_{air,in}^{D}, H_{R,in})
\]

Rearranging Eq. (5) using Eqs. (8), (9) and (10) yields:

\[
T_{cw,out} = f(T_{cw,in}, T_{air,in}^{D}, H_{R,in})
\]

Then combining Eq. (11) and Eq. (12) yields:

\[
T_{cw,out}^{D} = f(T_{cw,in}, T_{air,in}^{D}, H_{R,in})
\]

As mentioned earlier, the LMIN algorithm was used to develop several local linear models corresponding to different operating regimes based on a divide-and-conquer strategy and the global output is obtained by summing local outputs. Based on the results of LMIN, the linear model of Approach is established by the statistical regression algorithm:

\[
T_{cw,out}^{D} = a_1T_{cw,in} + a_2T_{air,in}^{D} + a_3H_{R,in} + a_0
\]

The advantage of this method is that the on-line computational cost is reduced greatly. The optimal temperature of CW can be found through Eq. (14).
3.3. Build an optimal operation table

Based on different operation modes of fans and climate conditions, an optimal operation table is built to search for the temperature of CW. Further, the prediction model can be obtained using Eq. (13) by LMN method. This optimal table avoids any calculation for the prediction of the temperature of CW. This optimum table can be constructed using the following equations:

\[
T_{cw, out}^{(i)} = b_1^{(i)} T_{cw, in} + b_2^{(i)} T_{air, in} + b_3^{(i)} H_{R, in} + b_4^{(i)}
\]

where \( i = 0, 1, \ldots, 6 \) means the seven operation modes of fans.

The coefficients \( b_1^{(i)}, b_2^{(i)}, b_3^{(i)} \) and \( b_4^{(i)} \) can be calculated by the statistical regression algorithm using the historical data. Then seven different \( (T_{cw, out}^{(i)})_{i=1}^{6} \) are obtained under the same \( T_{cw, in}, T_{air, in} \) and \( H_{R, in} \) which are assembled in the optimal operation table.

3.4. Design of operation

In order to find the optimal operation mode of fans, a designed strategy combining off-line and on-line steps is presented as follows:

3.4.1. Design algorithm

Off-line procedure:

\[ \text{Step 1: Collect the operating data from DCS, which is representative of different operating conditions and climates.} \]
\[ \text{Step 2: Based on the method proposed by Pan et al. [19], an optimal } T_{cw, out} \text{ is calculated.} \]
\[ \text{Step 3: The optimal Approach model can be constructed using the optimal } T_{cw, out}. \]
\[ \text{Step 4: An optimum operation table based on different climates is built by using the Approach model.} \]
On-line procedure:

Step 5: When a new set of data includes \( T_{cw,in} \), \( T_{\text{air},in} \), and \( H_{\text{in}} \), required, a theoretically optimal \( T_{cw,out} \) is found in operation table.

Step 6: Comparing with the calculated value of \( T_{cw,out} \) using the different models under the different level of fans, a final optimal operation mode of fans is selected.

4. Experiment

4.1. Procedure to find the optimum operation mode of fans

The data were collected from one of CSC power plants from January, 2010 to December, 2010. The sampling frequency of the data is one sample per minute. Following the model identification algorithm depicted in Eq. (15), regression coefficients of the linear model, i.e. \( b_1, b_2, b_3, b_0 \), under different operation modes of fans are shown in Tables 1.

The statistical model of cooling tower give a good explanation of variance in the \( T_{cw,out} \), which is usually evaluated by the \( R^2 \) statistics. From Table 1, it can be seen that the regression coefficients sufficiently explain the variability (all the values of \( R^2 \) are greater than 99%).

Then the optimal operation problem is solved on-line for every new-coming sample by searching optimal operation table for fans. Some examples are shown in Table 2 including the predicted \( T_{cw,out} \) obtained by the optimal Approach model.

Based on the \( T_{cw,out} \) operation table, it is easy to judge whether it is necessary to adjust the operation mode of fans.

4.2. Experimental example

To demonstrate the validation of the proposed method, the proposed algorithm is compared with Pan’s method (see [19]) in Table 3. Although the efficiency of the integrated system of CT and TG using linear model reaches more than 85% of the efficiency using LMN, it has several advantages listed as follows:

1. It greatly reduces the on-line computational burdens.
2. The field operators can understand the physical meaning of operation.
3. It is easily implanted into the existing DCS.

On the other hand, the proposed method is also evaluated by the practical experiment conducted on March 31, 2010. The net power gained of turbine generators, the main steam change, the load change and the operation modes of fans are shown in Fig. 5.

The color maps of dry and wet bulb temperature under low speed and high speed of fan in different time (2010.4.15).

Table 1

The regression coefficients under different operation modes of fans.

<table>
<thead>
<tr>
<th>Fan’s mode</th>
<th>( b_1 )</th>
<th>( b_2 )</th>
<th>( b_3 )</th>
<th>( b_0 )</th>
<th>( R^2 ) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C0_L6_H0</td>
<td>0.510</td>
<td>0.243</td>
<td>0.0355</td>
<td>3.99</td>
<td>99.2</td>
</tr>
<tr>
<td>C0_L5_H1</td>
<td>0.499</td>
<td>0.242</td>
<td>0.0358</td>
<td>4.07</td>
<td>99.2</td>
</tr>
<tr>
<td>C0_L4_H2</td>
<td>0.492</td>
<td>0.241</td>
<td>0.0361</td>
<td>3.97</td>
<td>99.1</td>
</tr>
<tr>
<td>C0_L3_H3</td>
<td>0.488</td>
<td>0.240</td>
<td>0.0367</td>
<td>3.72</td>
<td>99.1</td>
</tr>
<tr>
<td>C0_L2_H4</td>
<td>0.486</td>
<td>0.240</td>
<td>0.0376</td>
<td>3.41</td>
<td>99.3</td>
</tr>
<tr>
<td>C0_L1_H5</td>
<td>0.481</td>
<td>0.240</td>
<td>0.0390</td>
<td>3.13</td>
<td>99.5</td>
</tr>
<tr>
<td>C0_L0_H6</td>
<td>0.473</td>
<td>0.241</td>
<td>0.0407</td>
<td>2.94</td>
<td>99.6</td>
</tr>
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Table 2

The optimal \( T_{cw,out} \) and the predicted \( T_{cw,out} \) under different fans’ modes.

<table>
<thead>
<tr>
<th>Related variables</th>
<th>( T_{cw,in} ) (°C)</th>
<th>( T_{\text{air},in} ) (°C)</th>
<th>( H_{\text{in}} ) (%)</th>
<th>( T_{cw,in} ) (°C)</th>
<th>( T_{cw,out} ) (°C)</th>
<th>Optimal ( T_{cw,out} ) (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>32.16</td>
<td>26.57</td>
<td>50.69</td>
<td>19.20</td>
<td>28.60</td>
<td>28.36</td>
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<td></td>
<td>39.14</td>
<td>27.10</td>
<td>70.10</td>
<td>22.80</td>
<td>32.90</td>
<td>32.40</td>
</tr>
<tr>
<td></td>
<td>45.95</td>
<td>28.80</td>
<td>78.95</td>
<td>26.60</td>
<td>37.47</td>
<td>37.04</td>
</tr>
<tr>
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</tbody>
</table>
Compared with the electricity generated by the main steams with high pressure, the net power gained by using adjusted mode of fans is small. To confirm the electricity gain that is really caused by the adjustments of fans, the following cases are considered (shown in Figs. 6 and 8):

**Case 1**: From window #1 to window #2, the load of TG7 changes, but the load of TG6 keeps constant. Therefore the TG6 is selected to evaluate the electricity gain.

**Case 2**: Similar to the stage from window #1 to window #2, the TG7 is selected to evaluate from window #2 to window #3.

**Case 3**: From window #3 to window #4, the TG6 and TG7 are all used to test for the electricity gain owing to the unchanged loads.

**Case 4**: From window #4 to window #5, the TG6 and TG7 are also used to test for the electricity gain owing to the unchanged loads.

---

### Table 3
Comparison of net output power using LMN and Approach.

<table>
<thead>
<tr>
<th>Date</th>
<th>LMN method (kW)</th>
<th>The proposed Approach (kW)</th>
<th>Percentage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>227.3</td>
<td>197.4</td>
<td>86.84</td>
</tr>
<tr>
<td>February</td>
<td>227.8</td>
<td>202.0</td>
<td>88.66</td>
</tr>
<tr>
<td>March</td>
<td>199.3</td>
<td>183.2</td>
<td>91.92</td>
</tr>
<tr>
<td>April</td>
<td>153.9</td>
<td>145.5</td>
<td>94.56</td>
</tr>
<tr>
<td>May</td>
<td>93.1</td>
<td>85.7</td>
<td>92.03</td>
</tr>
<tr>
<td>June</td>
<td>130.1</td>
<td>111.3</td>
<td>85.58</td>
</tr>
<tr>
<td>July</td>
<td>91.6</td>
<td>74.9</td>
<td>81.78</td>
</tr>
<tr>
<td>August</td>
<td>249.6</td>
<td>234.7</td>
<td>94.05</td>
</tr>
<tr>
<td>September</td>
<td>181.3</td>
<td>170.8</td>
<td>94.21</td>
</tr>
<tr>
<td>October</td>
<td>207.2</td>
<td>188.5</td>
<td>91.14</td>
</tr>
<tr>
<td>November</td>
<td>233.1</td>
<td>206.9</td>
<td>88.76</td>
</tr>
<tr>
<td>December</td>
<td>226.8</td>
<td>192.9</td>
<td>85.07</td>
</tr>
</tbody>
</table>

---

### Table 4
Result analysis for the experiment in March 31, 2010.

<table>
<thead>
<tr>
<th>Net power gained (kW)</th>
<th>t-Test for net power gained (p-value)</th>
<th>t-Test for steam change (p-value)</th>
<th>Electricity gain (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>110</td>
<td>0.042</td>
<td>0.601</td>
</tr>
<tr>
<td>Case 2</td>
<td>–60</td>
<td>0.072</td>
<td>0.025</td>
</tr>
<tr>
<td>Case 3</td>
<td>–10</td>
<td>0.080</td>
<td>0.339</td>
</tr>
<tr>
<td>Case 4</td>
<td>260</td>
<td>0.001</td>
<td>0.893</td>
</tr>
</tbody>
</table>

*The significance level is set as 0.05. If the p-value associated with the t-test is not small (p > 0.05), then the two group means are not different.*

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Figs. 6–9. Compared with the electricity generated by the main steams with high pressure, the net power gained by using adjusted mode of fans is small. To confirm the electricity gain that is really caused by the adjustments of fans, the following cases are considered (shown in Figs. 6 and 8):

**Case 1**: From window #1 to window #2, the load of TG7 changes, but the load of TG6 keeps constant. Therefore the TG6 is selected to evaluate the electricity gain.

**Case 2**: Similar to the stage from window #1 to window #2, the TG7 is selected to evaluate from window #2 to window #3.

**Case 3**: From window #3 to window #4, the TG6 and TG7 are all used to test for the electricity gain owing to the unchanged loads.

**Case 4**: From window #4 to window #5, the TG6 and TG7 are also used to test for the electricity gain owing to the unchanged loads.
Based on the Student’s t-test, the p-values are greater than 0.05 (see Table 4), which demonstrate that the steam in Case 1 and Case 4 do not change. So the electricity gain is produced by the operation of Fans.

In Case 2, although the electricity power changes, the value of steam also changes (p-value is 0.025, which is less than 0.05). Therefore it cannot be determined whether the change in the electricity power is caused by the fan speed or the steam. On the other hand, the TG load changes. All these factors would lead the net power gained to be negative.

It is interesting that the adjustment of fans cannot produce the electricity power in Case 3 (the load and steam is kept constant). In this case, the adjustment does not follow the design rule and is intentionally implemented by the field operator. This confirms the proposed optimal operation strategy for the fans is useful.

5. Conclusion

Based on Approach, a statistical linear model has been presented to achieve the electricity gain in the cogeneration system. As opposed to the previous on-line optimization algorithm using LMN models, the operation mode of fans is selected by searching the optimum operation table which has been established off-line using the proposed Approach model. Using a mathematical model and without making changes in the existing plant, the significant energy saving is accomplished. It is important that the presented method can be easily implemented into the existing DCS. The real experiments validate the proposed algorithm. It is also confirmed that the integrated system of CT and TG will produce more electricity by adjusting the operation mode of fans. Therefore, manufacturers apply this technique to increase the performance of cooling tower and can save both engineering effort and cost significantly.

Acknowledgments

The authors thank Dr. Swanand Khare from Department of Chemical & Material Engineering, University of Alberta, for helpful discussions to improve the presentation quality of the paper, Chan-Wei Wu and Jenq-Jang Ou from China Steel Corporation for scientific advice and technical support, and gratefully acknowledge the financial support provided by National Natural Science Foundation under Grant 60904053 and 61273142, Natural Science Foundation of Jiangsu under the Grant BK2011466, Key Technology R&D Program of Jiangsu under the Grant BE2011143, and Special Foundation for Six Talents by Jiangsu Province.

References