Optimizing technology of chilled water system simulator for an industrial plant FAB
(Fabrication)

Eiji Urabe¹, Yongsung Park¹, Jeonghun Gwak¹
Jin-Hong Kim², Young-Sub Kim², Hyeong-Gon Jo², Cheol-Soo Park²
¹Semiconductor Infra Laboratory Samsung C&T, Seoul, SOUTH KOREA
²Department of Architecture and Architectural Engineering College of Engineering Seoul National
University, Seoul, SOUTH KOREA

Abstract
Chilled water system accounts for large amount of energy in an industrial plant FAB. The system is complicated and
has many operating parameters. It is not easy for the site operators to search the optimum operation point and
parameters in order to reduce energy of the whole system.
Conventionally, a single equipment has been analysed for
the system optimization. Some limited interrelationships
have been analysed try-and-error based. In this study, we
studied all parameters and interrelationships in the system
and made each equipment calculation model. Then we
applied a method of mathematical optimization
(Generalized reduced gradient (GRG)) to solve
interrelationships of all equipment. As a result of applying
optimization on this study, it is estimated that the energy
consumption of the chiller system can be reduced by 10
to 20%.

Highlights
Pump performance can be calculated by a third-degree
equation and a forth degree equation.
Chiller COP shows its highest value around the part load
factor of 70-80%. Forth-degree equation estimates the
value accurately.
Condensed water temperature from Cooling Tower with
full speed FAN condition can be calculated by NTU
dependent.
Pipe system performance can be calculated by a second-
degree equation.
GRG (Generalized Reduced Gradient) method solves
interrelationships between all equipment in the system and
provides the optimized result.

Introduction
Typical example of a chilled water system in an industrial
plant FAB is shown in Figure 1. It includes several
chillers, chilled water pumps, condensed water pumps, air
conditioner coils and pipe network systems. The system
used for this study has five cooling towers, nine chillers,
nine chilled water pumps, and five condensed water
pumps.
All parameters of all equipment are organically linked
each other. It is easy to determine an optimum operation
parameter for a single equipment (or single group of
equipment). But if a parameter is adjusted to reduce
energy of a single equipment, it increases energy of other
equipment at the same time. This situation makes the
issue complicated. There are some major examples. (a)
Lower temperature of condensed water reduces energy of
chillers and increases energy of cooling towers (fans). In
addition, heat recovery heating coils will lose their
performance (decrease heating capacity). (b) Higher
temperature of chilled water reduces energy of chillers
and increase energy of chilled water pumps (chilled water
flow rate of cooling coils is required to increase). (c)
Lower flow rate of condensed water reduces energy of
condensed water pumps and increases energy of chillers.
(d) System load can be shared by multiple equipment such
as chillers and pumps. The operating number changes
their part load factor (or speed of variable speed drive
(VSD(Variable Speed Drive)) if applicable) which relates
to energy efficiency of each equipment. According to the
energy efficiency curve characteristics, their energy will
go up or down.

Figure 1: Example of a chilled water system in an
industrial plant FAB

The purpose of this study is to show how to express the
operating conditions of all equipment and system interrelationships with mathematical formulas by using
appropriate parameters. In addition, this study shows how
to apply a method of mathematical optimization in order
to solve all interrelationships of all equipment in terms of
energy saving (for example electric power).
MATHEMATICAL CALCULATION MODEL

Each calculation model indicates how to calculate energy of each equipment by using appropriate parameters. We developed mathematical calculation models for all equipment based on manufacturer data, conventional academic knowledge & studies (ASHRAE Journal (June 2012), Winter Simulation Conference (2022)), algorithm of other simulation software and operation data of some actual sites.

Pump calculation model
For pump operation, the basic calculation model is described by a third-degree equation for pump pressure (head) and a fourth-degree equation for efficiency (equation 1, 2).

\[
\begin{align*}
\text{Head} &= a_4 \times L^3 + a_3 \times L^2 + a_2 \times L + a_1 \\
\text{Head} &= \text{Pin} - \text{Pout} \\
\text{Eff} &= b_4 \times L^3 + b_3 \times L^2 + b_2 \times L + b_1 \times L
\end{align*}
\]

Where, **Head**: pump pressure difference, \(\text{Pin, Pout}\): pump pressure, \(a_1-a_4, b_1-b_4\): factors, \(L\): flow rate, \(\text{Eff}\): pump efficiency.

\[\text{Head} = \text{Pin} - \text{Pout}\]

\[\text{Eff} = \frac{\text{Pwp}}{\text{Effm}}\]

\[\text{Pwp} = \frac{\text{Lv} \times \text{Headv}}{\text{Effv} \times \text{Effm}}\]

Figure 2: Example of a pump

Recently, VSD is installed in each pump to reduce energy. VSD speed affects dramatically pump pressure and efficiency. VSD speed ratio, \(R\), calculated in equation 3, is important. The flow rate is proportional to \(R\). The pressure is proportional to the square of \(R\). So the basic calculation model is updated as equation 4 and 5 using \(R\).

\[R = \frac{\text{Nv}}{\text{No}}\]

\[\text{Lv} = \text{L} \times R\]

\[\text{Headv} = R^2 \times \text{Head}\]

\[\text{Effv} = R^2 \times \text{Eff}\]

Figure 3: Pump head curve based on flow rate and \(R\)

Figure 4: Pump efficiency curve based on flow rate and \(R\) (VSD speed ratio)

Chiller calculation model
There are many discussions about the parameters which affect the chiller operation. In this study, the part load factor, temperature of chilled water and condensed water and the flow rate of condensed water are considered as main parameters. We made a calculation model step by step base using these parameters.

**Figure 5: Example of a chiller**

First, chiller manufacturers basically provide a performance curve of chiller electric power at given part load factor and temperature of condensed water. Figure 6 shows a sample performance data from a manufacturer (Chiller cooling capacity = 2500USRT, Chilled water design temperature = 13 to 18degC, Condensed water design temperature = 32 to 37degC, Design electric power = 70-80% of part load factor).
Chiller electric power increases as increase of the part load factor & temperature of condensed water. This performance curve looks like simple and linear line. But, if we convert it into chiller efficiency value of COP by using equation 7, the curve is no longer simple nor linear line, but delicate curved surface.

Figure 7 shows the convert result from the electric power in Figure 6 to COP. This curved surface of COP shows its highest value around the part load factor of 70-80%. This characteristic is very important to find the optimum chiller operation point. So we have been careful with the accuracy of the calculation model.

For example, “Energyplus” (widely known energy simulation software) uses a second degree equation about it. After several trial calculations, we decided to use a forth degree equation to increase its accuracy (equation 8, 9, 10). Figure 8 shows the comparison between manufacturer’s data and the calculation result of our model. Only at lower part load condition (less than 300kW), its tolerance exceed 5%. But we considered that it is acceptable because such lower part load operation seldom occurs during actual operation.

\[ Fpl = a_1 + a_2 x P_l + a_3 x P_l^2 + a_4 x P_l^3 + a_5 + P_l^4 \]  
\[ Fcd = b_1 + b_2 x T_{cd} + b_3 x T_{cd}^2 + b_4 x T_{cd}^3 + b_5 x T_{cd}^4 \]  
\[ P_{wc} = Fpl x Fcd \]  
\[ FL_{adj} = FL x Kadj \]  
\[ Kadj = A x B \]

Where, \( Fpl \): Effect of part load factor, \( a_1-a_5, b_1-b_5 \): factors, \( Fcd \): Effect of condensed water temperature, \( T_{cd} \): Condensed water temperature.

Second, it is common sense that higher temperature of chilled water reduces energy of chillers. But it is difficult to get exact data from manufacturers. According to our studies, the rising 1degC affects 3-5% increase of chiller efficiency. ASHRAE Standard 90.1(2019) suggests an adjustment factor (Kadj) based on temperature of chilled water & condensed water as equation 11. Kadj also provides similar result to our studies. So we decided to utilize this factor for our calculation model.

\[ F_{pl} = a_1 + a_2 \times P_l + a_3 \times P_l^2 + a_4 \times P_l^3 + a_5 + P_l^4 \]  
\[ F_{cd} = b_1 + b_2 \times T_{cd} + b_3 \times T_{cd}^2 + b_4 \times T_{cd}^3 + b_5 \times T_{cd}^4 \]  
\[ P_{wc} = F_{pl} \times F_{cd} \]  
\[ F_{L_{adj}} = F_{L} \times Kadj \]  
\[ Kadj = A \times B \]

Where, \( F_{pl} \): Effect of part load factor, \( a_1-a_5, b_1-b_5 \): factors, \( F_{cd} \): Effect of condensed water temperature, \( T_{cd} \): Condensed water temperature.

Figure 9 shows an example calculation result by using Kadj. In the result, the electric power ratio based on chilled water temperature is modelled as equation 12.

\[ R_{ch} = a_1 + a_2 \times T_{ch} \]  

Where, \( R_{ch} \): Electric power ratio, \( a_1, a_2 \): factors, \( T_{ch} \): leaving temperature of chilled water.
Third, recently most of chillers can apply variable flow rate of condensed water. But, the data of its effect is seldom provided from manufacturers. After our studies, we decided to use a sample data from a manufacturer which indicates a relation between electric power ratio and flow rate ratio (Figure 10). According to the data, the effect is relatively small from 80 to 100 % of the flow rate ratio. But the electric power ratio significantly increases less than 60% of the flow rate ratio. We made third degree equation as equation 13.

\[ R_{cd} = c_1 + c_2 \times R_{Lcd} + c_3 \times R_{Lcd}^2 + c_4 + R_{Lcd}^3 \]  
(13)

Where, \( R_{cd} \): Electric power ratio, \( R_{Lcd} \): Ratio of condensed water flow rate, \( c_1-c_4 \): factors.

Finally, we update equation 10 to calculate chiller electric power by equation 12 and 13 as indicated in equation 14.

\[ P_{wc} = F_{pl} \times F_{cd} \times R_{cd} \times R_{ch} \]  
(14)

Where, \( P_{wc} \): Electric power of a chiller

### Cooling tower calculation model

First, we made calculation model to estimate the outlet condensed water temperature from a cooling tower at given outdoor wet-bulb temperature. As described above, the outlet condensed water temperature provides large impact to the chiller energy.

Figure 12 graphically shows the condition of cooling tower operation with water temperature and air condition (enthalpy). The hatched area in the figure relates to \( NTU \) (number of transfer unit) as calculated in equation 15. It closely relates to cooling ability of a cooling tower. Even if the outdoor air condition (wet-bulb temperature) changes, the area of hatched area keeps same value (same \( NTU \) value). Once \( NTU \) at design condition is calculated, the outlet water temperature at any outdoor wet-bulb temperature can be calculated by the design \( NTU \) as equation 16.

\[ NTU = \int \frac{Tw_{out}}{Tw_{in}} \frac{cp_{w} \times dTw}{hs} \]  
(15)

\[ h = hin + \frac{L}{G} \times (Tw - Tw_{out}) \]  

\[ \int \frac{Tw_{out}}{Range+Tw_{out}} \frac{cp_{w} \times dTw}{hs} = NTU_{design} = 0 \]  
(16)

Where, \( Tw_{out} \): outlet water temperature, \( Tw_{in} \): inlet water temperature, \( cp_{w} \): specific heat of water, \( hs \): enthalpy of saturating water, \( h \): enthalpy of induction water, \( hin \): enthalpy of outdoor air, \( L \): Water flow amount, \( G \): Air flow amount

Figure 13 shows comparison between operation data of a sample cooling tower and the calculation result of our model. Same trend is shown in both of the operation data and the calculation model that outlet temperature of condensed water decreases as outdoor wet-bulb goes down. This trend is considered as cooling tower “operation curve”.

\[ y = -0.0383x + 1.4985 \]  
(6.4)

\[ y = -4.815E-06x^3 + 1.237E-03x^2 - 1.065E-01x + 4.092E+00 \]  
(6.6)

\[ k = 0.93 \]  
(6.8)

\[ k = 0.92 \]  
(7.0)

\[ k = 0.91 \]  
(7.2)

\[ k = 0.89 \]  
(7.4)

\[ k = 0.85 \]  
(7.6)

\[ k = 0.81 \]  
(7.8)

\[ 0.90 \]  
(10)

\[ 0.92 \]  
(11)

\[ 0.94 \]  
(12)

\[ 0.96 \]  
(13)

\[ 0.98 \]  
(14)

\[ 1.00 \]  
(15)

\[ 1.02 \]  
(16)

\[ 1.06 \]  
(18)

\[ 1.08 \]  
(19)

\[ 1.10 \]  
(20)

\[ 11 \]  
(21)

\[ 12 \]  
(22)

\[ 13 \]  
(23)

\[ 14 \]  
(24)

\[ 15 \]  
(25)

\[ 16 \]  
(26)

\[ 0.5 \]  
(27)

\[ 1.1 \]  
(28)

\[ 1.2 \]  
(29)

\[ 1.3 \]  
(30)

\[ 1.4 \]  
(31)

\[ 10 \]  
(32)

\[ 11 \]  
(33)

\[ 12 \]  
(34)

\[ 13 \]  
(35)

\[ 14 \]  
(36)

\[ 15 \]  
(37)

\[ 16 \]  
(38)

\[ 0 \]  
(39)

\[ 0.2 \]  
(40)

\[ 0.4 \]  
(41)

\[ 0.6 \]  
(42)

\[ 0.8 \]  
(43)

\[ 1 \]  
(44)

\[ 1.2 \]  
(45)

\[ 1.4 \]  
(46)

\[ 0 \]  
(47)

\[ 50 \]  
(48)

\[ 60 \]  
(49)

\[ 70 \]  
(50)

\[ 80 \]  
(51)

\[ 90 \]  
(52)

\[ 100 \]  
(53)
The dotted rectangular shape in the Figure 13 does not follow the “operation curve”. The reason is that the speed of the cooling tower fans is controlled based on given set-points (outlet temperature of condensed water). Of course, it affects electric power of the fans. Second, we assumed that the electric power relates to the approach ratio between the actual operation and our calculation model as indicated in equation 17. Of course, the equation would better be restudied according to the method of fan control such as on/off, pole change (two speed motors) and VSD.

Where, $P_{\text{wct}}$: electric power of cooling tower (fan), $P_{\text{wctdsg}}$: design value of electric power (fan), $T_{\text{woutmdl}}$: outlet water temperature calculation result, $T_{\text{wb}}$: wet-bulb of outdoor air.

**Pipe system calculation model**

The pipe system closely relates to operation of pumps and their energy through its pressure drop which includes all equipment connecting the pipe. The pump provides water pressure (pump head) to overcome the pipe system pressure drop and circulates the water. This situation is described as equation 18. The value indicated under the equation is a calculation result of a sample chilled water pipe system.

$$\text{Head} = dP_{\text{pipe}} + dP_{\text{fit}} + dP_{\text{eq}}$$  \hspace{1cm} (18)

Where, $\text{Head}$: pump pressure difference (pump head), $dP_{\text{pipe}}$: pipe loss, $dP_{\text{fit}}$: fitting loss (fitting means elbows, valves and etc.), $dP_{\text{eq}}$: equipment loss (equipment means chillers, coils and etc.).

$$dP_{\text{pipe}} = f \left[ \frac{L}{D} \right] \left[ \frac{\rho v^2}{2} \right]$$  \hspace{1cm} (19)

$$\frac{1}{\sqrt{f}} = 1.74 - 2 \log \left( \frac{2e}{D} + \frac{18.7}{Re \sqrt{f}} \right)$$

$$dP_{\text{fit}} = K \left[ \frac{\rho v^2}{2} \right]$$  \hspace{1cm} (20)


ASHRAE handbook fundamentals (2019) suggests to use popular equations (Darcy-Weisbach & Colebrook) in order to calculate $dP_{\text{pipe}}$ and $dP_{\text{fit}}$ as equation 19 and 20. There is “v2” in the both equations. It is very important and provide large impact to the pipe pressure drop. Because these pressure drops are proportional to the square of the water velocity.

Figure 14 shows the pressure drop of pipe & pipe fitting based on main pipe flow rate at a sample chilled water pipe system. At the maximum flow rate, the pressure drop indicates 373 kPa (104+269).

$$y = 2.071E-06x^2 + 3.321E-05x - 1.589E-01$$

At the minimum flow rate, it dramatically goes down to 133 kPa. Same situation is occurring in the actual sites. We decided to use equation 21 for the pressure drop of pipe & pipe fitting.

$$dP_{\text{pipe}} + dP_{\text{fit}} = a_1 L^2 + a_2 L + a_3$$  \hspace{1cm} (21)

Where, $L$: water flow rate, $a_1$-$a_3$: factors. About equipment pressure drop $dP_{\text{eq}}$, main equipment are chillers, coils and control valves of coils. Equation 22 shows a calculation result of a sample chilled water pipe system.

$$dP_{\text{eq}} = dP_{\text{chiller}} + dP_{\text{coil}} + dP_{\text{cvalve}}$$  \hspace{1cm} (22)

Where, $dP_{\text{chiller}}$: chiller loss, $dP_{\text{coil}}$: coil loss, $dP_{\text{cvalve}}$: control valve loss.
MATHEMATICAL OPTIMIZATION

In case of chillers, manufacturers often provide the pressure drop data based on its chilled water flow rate. Figure 15 shows a sample data from a manufacturer. The pressure drop increases proportionally to the chilled water flow rate. We decided to use equation 23 to calculate the pressure drop of chillers.

\[ dP_{\text{chiller}} = a_1 x L + a_2 \]  \hspace{1cm} (23)

Where, \( a_1, a_2 \): factors.

About coils and control valves of coils, we consider that it is better to keep constant (design) value. Because a great number of coils & control valves are connected in parallel and their operating condition would be decided by air side requirement. It is not easy to evaluate from views of chilled water system.

MATH BALANCE AND VARIABLES

Mass balance is also required to take under consideration. Flow rate of chilled water & condensed water must be kept same through chillers, chilled water pumps, cooling towers and condensed water pumps as equation 24, 25 and 26.

\[ LC_{\text{ch}} \times C_n = LP_{\text{ch}} \times P_{\text{ch}}n \]  \hspace{1cm} (24)

\[ LC_{\text{cw}} \times C_n = LP_{\text{cw}} \times P_{\text{cw}}n \]  \hspace{1cm} (25)

\[ LP_{\text{cw}} \times P_{\text{cw}}n = LC_{\text{t}} \times CTn \]  \hspace{1cm} (26)

Where, \( LC_{\text{ch}} \): chilled water flow rate of a chiller, \( C_n \): number of chiller, \( LP_{\text{ch}} \): chilled water pump flow rate, \( P_{\text{ch}}n \): number of chilled water pump, \( LC_{\text{cw}} \): condensed water flow rate of a chiller, \( LP_{\text{cw}} \): condensed water pump flow rate, \( P_{\text{cw}}n \): number of condensed water pump, \( LC_{\text{t}} \): condensed water flow rate of a cooling tower, \( CTn \): number of cooling tower.

Finally, the energy of whole chilled water system is described as equation 27. The optimization is to find parameters which minimize \( P_{\text{wt}} \) simultaneously satisfying equations of all equipment above.

\[ P_{\text{wt}} = \sum_{n=1}^{C_n} P_{\text{wc}}(n) + \sum_{n=1}^{P_{\text{ch}}n} P_{\text{wchp}}(n) + \sum_{n=1}^{P_{\text{cw}}n} P_{\text{wcpwp}}(n) + \sum_{n=1}^{CTn} P_{\text{wt}}(n) \]  \hspace{1cm} (27)

Where, \( P_{\text{wt}} \): electric power of whole chilled water system, \( P_{\text{wc}}(n) \): electric power of a chiller, \( P_{\text{wchp}}(n) \): electric power of a chilled water pump,\( P_{\text{wcpwp}}(n) \): electric power of a condensed water pump, \( P_{\text{wt}}(n) \): electric power of a cooling tower.

In addition, we surveyed some actual sites and researched which parameters are important and often adjusted by operators. We considered them as target parameters to be optimized (variables) such as the number of chillers & pumps, VSD speed of pumps, temperature of the chilled water, condensed water and the flow rate of the condensed water.

CONVENTIONAL OPTIMIZATION

Conventionally, a single equipment has been analysed for the system optimization. Some limited interrelationships have been analysed try-and-error based.

We studied one trial which targeted cooling towers & chillers and changed, only one parameter, the temperature of condensed water from 20 to 32 degC. 32 degC is its design point. 20 degC is on the cooling tower “operation curve” at the outdoor air wet-bulb of 10 degC. It cannot go down below 20 degC. We calculated electric power of each equipment one by one. Figure 16 shows the calculation result.

As the temperature of condensed water decreases, chiller electric power goes down and cooling tower electric power rises. The curve of total power shows its bottom around 24 degC of condensed water temperature. More trial effort would be required to figure out its exact value. Other equipment for example pumps are ignored because their electric power is considered as constant. If the electrical power includes all equipment, the electrical power of the design point is 8175 kW and the optimum point is 7654 kW. The energy saving rate is 6%.

Next step, we need to change other parameters simultaneously. Such one by one calculation method is no longer available because of its complexity.

Figure 15: Chiller pressure drop based on chilled water flow

Figure 16: Calculation result of chillers, cooling towers and total electric power

MATHEMATICAL OPTIMIZATION

If we change all parameters at the same time, we need to use a method of mathematical optimization. It has been widely used and developed in the fields of commercial logistic, financial and mechanical design analysis. There are not many studies to apply this method to the chilled water system operation. This time, we conducted this trial.
If calculation models are simple equations for example linear relations, linear analysis method (simplex LP) is commonly used. But, actual calculation models are higher-order equations, logarithm and discrete values (number of operating equipment). Due to the complexity of the calculation model, we studied and used GRG non-linear method (Generalized Reduced Gradient). The generalized reduced gradient (GRG) method is one of the most popular methods for solving nonlinear optimization problems. Variables are divided into a set of basic (dependent) variables and a set of non-basic (independent) variables. A reduced gradient is then computed to find the minimum in the search direction. This process is repeated until convergence.

The image of this method is to search on a complex curved surface composed of multiple mathematical formulas and find the most recessed bottom.

Table 1 shows the calculation result by using GRG method about the same system in the previous chapter (CONVENTIONAL OPTIMIZATION). A parameter indicated by red colour was optimized by conventional method in the previous chapter. Parameters indicated by blue colour are additionally optimized by GRG method.

Even the condensed water temperature, GRG method provided more precise value of 23.6 degC than the conventional method. In addition, many parameters such as operation number of chillers & pumps, part load factor of chillers, head of pumps, condensed water temperature and flow rate are additionally optimized. They are closely affecting each other. In the result, the energy saving rate reaches 18%. It is greater than conventional method of 6%.

### Table 1: Calculation result by using GRG method

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Parameter</th>
<th>Baseline</th>
<th>Optimization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chiller</td>
<td>Number</td>
<td>6</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Part Load Factor</td>
<td>0.5</td>
<td>0.6</td>
</tr>
<tr>
<td></td>
<td>Condensed water flow m³/h</td>
<td>1724</td>
<td>1327</td>
</tr>
<tr>
<td></td>
<td>COP</td>
<td>7.0</td>
<td>8.8</td>
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<tr>
<td></td>
<td>Total electric power kW</td>
<td>3794</td>
<td>3002</td>
</tr>
<tr>
<td>Cooling Tower</td>
<td>Number</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Temperature degC</td>
<td>32.0</td>
<td>23.6</td>
</tr>
<tr>
<td></td>
<td>Total flow rate m³/h</td>
<td>10342</td>
<td>6637</td>
</tr>
<tr>
<td></td>
<td>Total electric power kW</td>
<td>77</td>
<td>330</td>
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<tr>
<td>Chilled Pump</td>
<td>Number</td>
<td>6</td>
<td>5</td>
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<td></td>
<td>Flow rate / pump m³/h</td>
<td>1448</td>
<td>1738</td>
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<td></td>
<td>Head kPa</td>
<td>588</td>
<td>517</td>
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<td></td>
<td>Total electric power kW</td>
<td>1964</td>
<td>1694</td>
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<tr>
<td>Condensed Pump</td>
<td>Number</td>
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<td>3</td>
</tr>
<tr>
<td></td>
<td>Flow rate / pump m³/h</td>
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<td>2212</td>
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<td></td>
<td>Head kPa</td>
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<td></td>
<td>Total electric power kW</td>
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<td>Pipe System</td>
<td>Pipe &amp; Fitting loss kPa</td>
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<td>157</td>
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<td></td>
<td>Chiller loss kPa</td>
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<td>127</td>
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<td></td>
<td>Total pressure drop kPa</td>
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<tr>
<td></td>
<td>All Total Power kW</td>
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<td>6722</td>
</tr>
</tbody>
</table>

![Figure 17: Image of GRG non-linear method](image)

Especially, the electric power of the chilled water pumps and condensed water pumps was reduced by 14% and 27%. In the result, GRG method reduces all total electric power not only by 18% more than the baseline but also by 12% more than the conventional method.

### Conclusion

This time, we studied calculation models of all equipment in the chilled water system and applied the method of mathematical optimization (Generalized reduced gradient (GRG)). It can solve multiple complicated mathematical formulas (interrelationships) and provide optimum parameters which minimize energy of whole chilled water system. We confirmed that this method is superior to the conventional method and is expected that the energy consumption of the chiller system can be reduced by 10 to 20%.

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