Next Generation HVAC System

Yasuo Takagi *, Yoshiki Murakami *, Yuuichi Hanada *, Nobutaka Nishimura *, Kenichi Yamazaki *, and Yasuyuki Itoh *

Abstract: A new HVAC (Heating, Ventilating, and Air-Conditioning) system for buildings is proposed. The key technology for the system is a twin coil air handling unit (AHU) and its advanced control method. One coil is equipped to cool and dehumidify the fresh air intake, and the other coil is for cooling circulated air. The deeply chilled water is necessary only for removing the moisture from the fresh air. The latter coil requires moderately cool water according to the HVAC load. Then 2 kinds of chilled water in terms of temperature should be prepared. The structure helps saving the energy consumption for air-conditioning because the higher chilled water temperature implies the better chiller efficiency (COP: Coefficient of Performance). In addition, an advanced control method that is called an ‘Air-Water cooperation system’ is introduced. The control system mainly focuses on energy savings through changing the temperature of the chilled water and supply air according to the HVAC load and weather conditions. In this paper, we introduce a Next Generation HVAC system with its control system and present evaluation results of the system for the model-building simulator.

Key Words : air-conditioning, HVAC, buildings, control, air-water cooperating operation.

1. Introduction

In order to prevent global warming, Japanese government declares keeping the Kyoto-Protocol and decreasing greenhouse gas (GHG) such as CO2 by 6%, comparing to the GHG emission amount in 1990. Among the GHG, the CO2 emission amount from energy related activities accounts for 87% of the total emission. Then the energy saving is a key factor for reducing the CO2 emission. Among many fields, energy consumption in office buildings and other commerce facilities dramatically increased by 44.6% from 1990 to 2005. Furthermore, about a half of the total energy in a building is consumed by HVAC (Heating, Ventilating and Air Conditioning) systems (Fig. 1) [1]. Then energy savings of HVAC systems are very important.

In this paper, a new HVAC system for buildings is proposed. The key technology for the system is a twin coil air handling unit (AHU) and its advanced control method. One coil is equipped to cool and dehumidify the fresh air, and the other coil is for cooling circulated air. The chilled water is necessary only for removing the moisture from the fresh air. The latter coil only requires moderately cool water. When 2 kinds of chilled water in terms of temperature are prepared, we can save the energy consumption for air-conditioning because the higher chilled water temperature implies the better chiller efficiency (COP).

Next, an advanced control method that is called an ‘air-water cooperation system’ is introduced to control such HVAC systems. The control system mainly focuses on energy savings. The key concept of the control system is cooperation of the chilled water flow and the cooled air supply. The two kinds of flows are controlled so that the total energy consumption is minimized in a HVAC system. The energy is consumed by chilled water pumps, supply air fans, chillers, and cooling towers, depending on the HVAC system structure. Then naturally, the optimization problem for the above-mentioned system is formulated as nonlinear constrained mathematical programming. The difficulties of the optimization control scheme are,

(1) The optimum solution cannot be solved often in real control situations,
(2) The HVAC mathematical models on which optimal solutions are solved, are often inaccurate.

To solve the problem (1), a simple optimal operation function that is derived by off-line calculations is introduced. To solve the problem (2), a remote modeling function is prepared. The constructions and characteristics of the functions are discussed in this paper. Finally, evaluation results of the system are also presented. More than 30% energy saving is achieved for the model-building simulations.

Fig. 1 Energy consumption in an office building.

2. Twin Coil Air Handling Unit

In the conventional air-handling unit (AHU) that supplies air-conditioned air to the rooms in a building, there exists only one coil that is heat exchanger between chilled water and the air, plays two roles. The one is cooling sensible HVAC load that
is generated in the rooms through using lights and electric apparatuses. The other role is to remove sensible and latent heat from fresh intake air. For these purposes, the temperature of the chilled water is around $7^\circ$C. But $7^\circ$C chilled water is required only for the dehumidification of fresh air. $15^\circ$C chilled water is enough for cooling sensible HVAC load that occupies most (70%-80%) of the total HVAC load in Japan. The fact means that in the current HVAC system in Japan, lower temperature chilled water is used not only for dehumidification fresh air that is around 20%-30% of the total load, but also wasted for cooling sensible load. The purpose of the Next Generation AHU is to save the waste.

For this purpose, the AHU has two coils (Fig. 2). One is to cool and dehumidify of the fresh air. It uses lower temperature chilled water. The other coil is to cool sensible heat of room air. It uses higher temperature chilled water.

Then most of the chilled water is higher temperature water. The chilled water temperature become warmer, the chiller efficiency COP improves, according to kinematics of the refrigeration cycle principle. Figure 3 explains the refrigeration cycle kinematics that consists 4 stages that are compression step, condensation step, expansion step and evaporation step. Chilled water is obtained by utilizing heat absorption of the evaporation process. In the cycle, electric power is consumed only when compression process is pursued. The amount of energy consumed in the process is approximately proportional to the difference between evaporation pressure and condensation pressure that is also proportional to the temperature difference between the steps.

\[
J = (\text{Cooling Tower Energy Consumption}) + (\text{Chiller Energy Consumption}) + (\text{Water Pump Energy Consumption}) + (\text{AHU Fan Energy Consumption})
\]

Fig. 3 Mollier chart of the refrigeration cycle.

3. Air-Water Cooperating HVAC

3.1 Concept Introduction

In the building, we have chilled and maybe cooling water networks and air duct networks (Fig. 8). The Air-Water Cooperating HVAC operates air-conditioning system so that the consumed energy for HVAC system, that is water network and wind network, should be minimized.

Contrary to the new HVAC system, in the conventional HVAC system of a building, chilled water temperature, cooling water temperature and supply air temperature (VAV: Variable Air Volume) or flow rate (CAV: Constant Air Volume) are constant in all seasons and for all HVAC load. This design principle means that the temperature of the cooling water that is cooled by ambient air is typically $32^\circ$C always, even when outside temperature is moderate, for example $15^\circ$C or hot, i.e. $34^\circ$C. In the cooling tower, energy consumption is inverse proportional to the enthalpy difference between ambient air and saturated air with cooling water temperature. The fact implies there should exist optimal operation temperature of cooling water [2].

In Fig. 4, Q along with the HVAC apparatuses implies consumed energy of the apparatuses. In particular, the temperature difference between cooling water and chilled water is proportional to the consumed electricity of the chiller that occupies major part of the total energy consumption of the HVAC system. Then consumed energy of the chiller in Air-Water Cooperating HVAC is much smaller than the conventional system in spring and autumn. By the same reason, energy saving is obvious in the new HVAC control strategy.

In order to realize optimum operation in the viewpoint of energy saving, in Air-Water Cooperating HVAC, operational set points such as above-mentioned temperatures are calculated so that operational total energy should be minimum. The mathematical programming to be solved is as follows.
3.2 Design Procedure

The concept of the new HVAC operation is straight forward, but it is not very easy to realize the concept. Nonlinear programming with nonlinear constraints is not appropriate to real time control system. Such kind of the calculation often cannot reach the solutions. As for the real time control system, the situation has to be avoided.

In the sequence of the research, we found that the solutions of the optimum operating set points are expressed as a set of the functions. Using the set of functions, we can firstly manage to control in the way of Air-Water Cooperation HVAC. In the section, the procedure of the deriving functions is presented.

Step 1: Using sequential quadratic programming, optimization problem eq. (1) is solved for annual various conditions. Figure 5 shows an example of the electricity dependence on the temperatures. The point of lowest energy consumption is a solution. In the calculations, we shouldn’t care the cases even when the solution is not solved. The solution should be calculated as many as we can. The considered conditions are as follows.

(1) Ambient conditions (temperature and humidity)
(2) Required intake air volume
(3) HVAC load (sensible load and latent heat = steam generation by human breathing)
(4) Air-conditioning zone condition (temperature, humidity and window direction and area)

These variables are finally input variables for optimum operation functions.

Step 2: Based on the optimum solutions, multivariable 2nd order polynomials are derived by least mean square method.
\[ Y_k = c_{0k} + \sum_{i=1}^{m} c_{i0k} X_i + \sum_{i=1}^{m} \sum_{j=i+1}^{m} c_{ijk} X_i X_j, \quad (2) \]

Where \( Y_k \) is the \( k \)-th set value for HVAC system, and \( c_{ijk} \) is the coefficient of the equation corresponding to the suffixes. \( m \) is the number of the input variables. \( X \) depicts the following input variables.

\[ X = \text{air conditioned zone specified temperature/ambient temperature and humidity/HVAC load (sensible and latent heat)} \]

\[ Y = \text{set points of chilled water temperature and flow rate/cooling water temperature and flow rate/fresh air flow rate/supply air flow rate/ambient temperature and humidity} \]

The predicted values by derived functions and original optimum solution coincide very well. The example is shown in Fig. 6.

Figure 7 shows HVAC control system structure using the operation functions. The optimizer in the figure contains operation functions and outputs set values of chillers, cooling towers and AHU. In the remote PC, the parameters of the HVAC model are adjusted according to the measured data. These adjustments improve optimization accuracy. And local controllers are conventional PID’s. The PID controls inverter drivers as current HVAC systems do. By these optimized set values, inverter introduced modern HVAC system capability is fully utilized.

4. Energy Saving Evaluation

4.1 Building Model

Energy saving capability is evaluated by using building model. The building model consists of typical room model with sensible and latent heat load and air-conditioning system model. The air-conditioning system of the building model used here is shown in Fig. 8. The system consists of cooling towers, chillers, pumps and fans. Here in order to dehumidify the outside air, lower temperature chilled coolant is supplied by local small chiller. Then AHU have two coils, one coil is cooled by chilled water and the other coil is chilled by the refrigerant.

The model has the same 150 rooms whose specifications are as shown in Table 1.

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Heat load conditions.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Human(kW)</td>
<td>2.17</td>
</tr>
<tr>
<td>Apparatus(kW)</td>
<td>5.61</td>
</tr>
<tr>
<td>Light(kW)</td>
<td>3.74</td>
</tr>
<tr>
<td>Room Volume(m3)</td>
<td>486</td>
</tr>
<tr>
<td>Steam generation(g)</td>
<td>1</td>
</tr>
</tbody>
</table>

Fig. 7 Air-Water flow cooperating air-conditioner.

Fig. 8 Air-conditioning system in office buildings.
Chiller model consists of heat transfer model and refrigerant characteristic model that is described reference [3],[4]. COP characteristics are shown in Fig. 9.

\[
\frac{1}{K} = \frac{1}{5117.9 \cdot v_w^{0.8758}} + \frac{1}{728.95 \cdot v_a^{0.6045}} + 0.00022
\]

Where \(v_w = \text{water velocity}\) and \(v_a = \text{air velocity (m/ sec)}\). Combined these physical models, building model is prepared for the evaluation.

4.2 Results

Air-Water cooperating HVAC capability for energy saving is tested by the building simulator mentioned above. Figure 10 (a) shows how much the energy will be saved by the control. In this case, more than 30% of total energy is saved. Furthermore we notice that energy saving in spring and fall season is larger than that of summer season. The result is anticipated because of the principle of the control. The most of the energy is saved in the chiller operation, because chiller consumes the best part of energy consumption. Figure 10 (b) shows coordinated set point of various values. These values change according to the HVAC load and weather conditions.

(a) Energy saving of Air-Water cooperation.

(b) Set points cooperation for HVAC system.
5. Conclusions

HVAC loads of office buildings are relatively lower than the maximum load that is considered when HVAC equipments are designed. Furthermore, the sensible load occupies 70-80% of the total HVAC load. The latent heat load that requires lower temperature chilled water occupies only 20-30% of the total load. Viewing the fact, adopting the two-coil air handling unit, we can save the lower temperature chilled water by 70%. This leads to COP improvement of the chillers and energy saving in HVAC systems.

In order to capitalize the energy saving capability, we developed the Air-Water Cooperation HVAC system. The system changes temperature set points so that the heat load of the HVAC should be carried to outside with the minimum energy consumption. Furthermore, in order to secure the control, the optimum operation function was introduced, based on the fact that optimal solution lies on the 2nd order multivariable polynomials.

Finally, energy saving capability was made assured by simulations using the building model. The technology will greatly help the energy saving in office buildings, shopping building and so on.

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References


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