DEVELOPMENT OF HVAC SYSTEM SIMULATION TOOL FOR LIFE CYCLE ENERGY MANAGEMENT
PART 2: DEVELOPMENT OF COMPONENT MODELS FOR HVAC EQUIPMENT

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ABSTRACT

This paper describes the conversion of equipment characteristics into mathematical formulae, verification of the precision of said mathematical formula, and a concrete simulation tool. The main feature of this simulator is that operation of equipment is solved using temperature and flow, not calories. However, the characteristics of equipment are described using as simple a formula as possible. These formula are verified with actual values, and the simulator was confirmed to provide sufficient accuracy for energy management. When an object is connected to another object, calculation begins immediately without a main program. The detailed structure of objects and perspective of the simulation system are shown.

KEYWORDS

Life Cycle Energy Management, Simulation, HVAC System

INTRODUCTION

The previous paper describes the framework of life cycle energy management (LCEM), the necessity of the energy simulation tool, and the concept of the tool. This paper describes converting equipment characteristics into mathematical formulae, verification of the mathematical formulae precision, and a concrete simulation tool.

Several simulators (DOE-2 2001, DeST 2004, Yanagihara et al. 2004) have been developed in the past, but their use has been mostly limited to researchers. Even when a simulation tool is described plainly and solved clearly for wide diffusion (Sugihara and Oshima 2004), only a limited number of people can use it while understanding the contents if it is written in Fortran or C language. On the other hand, every engineer can operate and understand this tool because it is described plainly, solved clearly, and is solved only on Excel sheets.

When changing equipment characteristics into formulae, attention is paid to ensure that incorporated mathematical formulae can reproduce the energy performance of the actual machine with good precision while having a simple structure that can be handled by Excel. Simple model formulae are created for the refrigerator and cooling tower based on theoretical formulae to avoid complicated calculations and convergent calculations. Iterated calculation is adopted for solving the chilled water coil in the air conditioner to ensure precision. The pump and fan are solved almost theoretically because their principles are clear.

The precision of mathematical formulae is verified by comparing calculated values with measured values. This paper describes an air-conditioning system where objects in Excel sheet form incorporating mathematical formulae are combined.

DEVELOPING EQUIPMENT CHARACTERISTICS FORMULAE INTO MODELS AND OBJECTS

Major equipments are described below.

Cooling tower

Convergent calculation is required generally for the cooling tower. The developed tool, however, obtains the cooling water supply temperature “Td” using a set of coefficients shown in quadratic expressions in the same way as the absorption water cooler/heater model. The cooling tower consists of the parameters 1) to 3) below indicating the cooling performance and the parameter 4) related to operation.

1) Cooling water return temperature “Tdr ” (inlet temperature of cooling tower)
2) Cooling water volume “Vd ”
3) Outside air wet-bulb temperature “WB ”
4) Cooling water temperature set value “Tds ”

In the model, the cooling water supply temperature is obtained from the experimental formula (1).

$$T_d = T_{ds} C_2 C_3 C_4 \qquad (1)$$
$$T_{ds} = a_1 WB^2 + b_1 WB + c_1$$
$$C_2 = a_2 T_{dr}^2 + b_2 T_{dr} + c_2$$
$$C_3 = 1 - (1 - C_4)(T_{dr} - WB)/(27 - a_3)$$
$$C_4 = a_4 V_d^2 + b_4 V_d + c_4$$

Influence coefficients C

C_2 : Cooling water return temperature

C_3 : Cooling water volume

C_4 : Cooling water volume

The cooling tower fan power ratio "C_{tPW}" is obtained from formula (2) where "T_{dset}" is the set temperature when the fan is forcibly stopped, and "T_d" is the cooling water supply temperature in free cooling. Simple linear approximation is adopted here.

$$C_{tPW} = (T_{dr} - T_{dset})/(T_{dr} - T_d) \qquad (2)$$

Figure 1 shows the cooling tower object. The cooling tower object is located inside the dotted line frame in the center, and the outside air object and cooling water pump objects are connected on both sides.
The cooling tower object is divided into the communication part, control part, method (calculation) part and property part from the top.

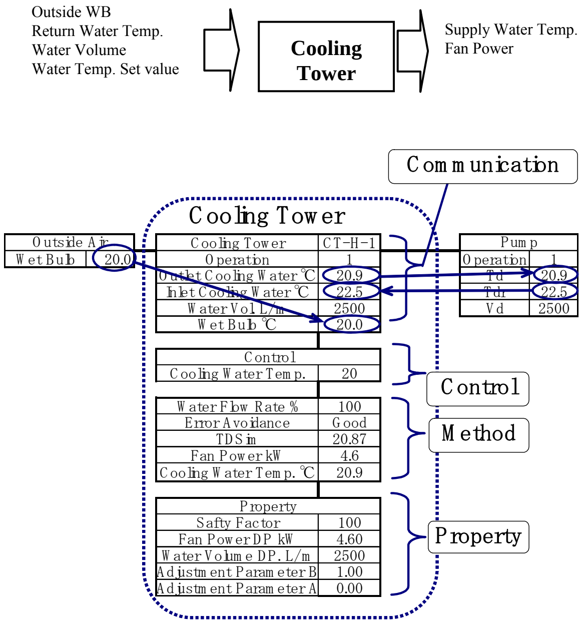


Figure 1 Cooling tower

1) In the communication part, the tool receives data from and sends data to adjacent objects. The user can easily create a large system by only considering connection to adjacent objects because communication is allowed only with adjacent objects.
2) In the control part, the user determines the control conditions. In the cooling tower, the user sets the cooling water supply temperature.
3) In the method (calculation) part, the equipment characteristics formula is written. The tool calculates the cooling water supply temperature and fan electric power using the communication, control and property data, and then displays the calculation result in the communication part.
4) In the property part at the bottom, the user inputs the rated specification of the equipment and correction coefficients for easily correcting the characteristics formula.

Absorption water cooler/heater model (during cooling)

This section describes the model of the absorption water cooler/heater during cooling. The tool includes examination of cooling variable water volume control and chilled variable water volume control that are adopted recently, and offers models handling five influence coefficients - cooling water temperature, chilled water temperature, refrigerator load factor, cooling water volume and chilled water volume.
Products having same characteristics are generalized. The gas consumption "G_{ref}" is calculated by multiplying the gas consumption ratio "g_{ref}" by the rated gas consumption "G_{ref_r}" as shown in the formula (3).

$$G_{ref} = g_{ref} \, G_{ref\text{-}r} \qquad (3)$$

The gas consumption ratio "g_{ref}" consists of five parameters, "C_1: Load factor (q)", "C_2: Cooling water return temperature (T_d)", "C_3: Cooling water volume ratio (v_d)", "C_4: Chilled water supply temperature (T_c)" and "C_5: Chilled water volume ratio (v_c)". Each parameter is "1.0" and "g_{ref}" is "1.0" at rating.

$$g_{ref} = C_1 C_2 C_3 C_4 C_5 \qquad (4)$$
$$C_1 = a_1 q^2 + b_1 q + c_1$$
$$C_2 = a_2 T_d^2 + b_2 T_d + c_2$$
$$C_3 = a_3 v_d^3 + b_3 v_d^2 + c_3 v_d + d_3$$
$$C_4 = a_4 T_c^2 + b_4 T_c + c_4$$
$$C_5 = a_5 v_c^2 + b_5 v_c + c_5$$

Influence coefficient C

C_1 : Load factor

C_2 : Cooling water temperature

C_3 : Cooling water volume ratio

C_4 : Chilled water temperature

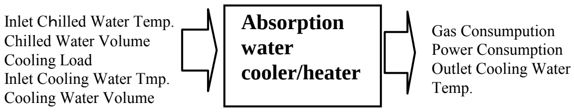
C_5 : Chilled water volume ratio

The cooling water return temperature "T_{dr}" is obtained analytically as shown in formula (6) based on the fact that the exhaust heat increases or decreases in accordance with the ratio of the coefficient of performance at partial load and at rating "C_7 = cop/cop$_{-r}$". Here, "T_d" is the cooling water supply temperature, and "V_d" is the cooling water volume.

$$G_{ref} = C_6 C_7 V_d (T_{dr} - T_d)$$
$$T_{dr} = G_{ref} / (C_6 C_7 V_d) + T_d \qquad (5)$$

C_6: Correlation coefficient of cooling water heat quantity and gas heat quantity
C_7: Ratio of coefficient of performance at partial load and at rating

Figure 2 shows the relationship between inputs and outputs and objects.



Absorption Water cooler/heater	RA-H-1-01
ERROR	0.00
ON/OFF (ON=1,OFF=0)	1.00
Mode 0:Stop 1:Cooling 2:Heating	1.00
Operating Procedure	2.00
Cooling/Heating Capacity (kW)	527
Chilled/Hot Water Volume (l/min)	1,370
Outlet Chilled/Hot Water (℃)	7.00
Inlet Chilled/Hot Water (℃)	11.0
Cooling Water Volume (l/min)	2,500
Inlet Cooling Water (℃)	24.5
Outlet Cooling Water (℃)	27.9
Cooling/Heating Load (%)	72

Control	
Outlet Chilled Water SP (℃)	7.0
Outlet Hot Water SP (℃)	60.0
Operating Procedure (Heating)	2
Operating Procedure (Cooling)	2

Operating Procedure (Cooling)	2
Outlet Cooling Water (℃)	27.9
Capacity Cooling/Heating (kW)	379.7
Chilled/Hot Water Flowrate (%)	91
Cooling Water Flowrate (%)	100
Cooling/Heating Load (%)	72
Gas Consumption (%)	62
Gas Consumption (Nm3/h)	24.2
Power Consumption (kW)	3.2
COP	1.23

Property	
Max. Heating Load (kW)	527
Max. Coolig Load (kW)	425
Chilled/Hot Water Volume DP (1/m	1512
Cooling Water Volume DP (1/min)	2500
Power Consumption DP (kW)	3.20
Gas Consumption DP (Nm3/h)	38.80
Adjustment Parameter a	1.00
Adjustment Parameter b	0.00

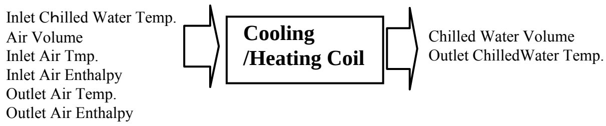
Figure 2 Absorption water cooler/heater

Coil model (cooling)

Because the heat exchange model of the cooling coil is highly nonlinear, it is difficult to obtain the solution in an algebraic equation. The tool obtains the coil exit condition using a technique called wet surface coefficient method that inversely executes the coil row number calculation procedure. With this technique, the tool obtains the chilled water volume and chilled water return temperature from the air condition on the coil entrance side and coil exit side while regarding the coil row number as a known value as shown in Fig. 3.
The water volume at which the exchange heat quantity "Qt" in the wet surface coefficient method shown in the formula (6) becomes equivalent to the exchange heat quantity "Qa" on the air side shown in the formula (7) is obtained by convergent calculation using the Newton-Raphson method by iteration in the spreadsheet software. When the chilled water volume is obtained, the chilled water return temperature is also obtained dependently.

$$Qt = WSF\ Kf\ Af\ Row\ MTD \quad (7)$$
$$Qa = \rho c\ Va\ (Ii - Io) \quad (8)$$

WSF: Wet surface coefficient
Kf: Heat transfer coefficient
Af: Coil front area   Row: Row number
MTD: Logarithmic mean temperature difference
ρ: Density   c: Specific heat   Va: Air volume
I: Air enthalpy (i: Entrance, o: Exit)



Cooling/Heating Coil	CC-S-1-00
ERROR	0
Chilled/Hot Water 0:stop 1:Supply	1
Room 0:Stop 1:Cooling 2:Heating 3:Mi	1
Fan 0:Stop 1:Cooling 2:Heating	1
Air Volume m³/h	6,590
Chilled/Hot Water Volume lit/min	174
Inlet Chilled Water Temp. ℃	7.00
Outlet Chilled/Hot Water Temp. ℃	10.97
Inlet Air Temp. ℃	27.98
Inlet Air Enthalpy. ℃	59.94
Inlet Air Humidity kg/kg'	0.0125
Outlet Air Temp. ℃	14.00
Outlet Air Enthalpy. ℃	37.98
Outlet Air Humidity kg/kg'	0.0095
Judgment	0

Control	
Initialization	0

Chilled/Hot Water 0:stop 1:Supply	1
Chilled Water Volume ?/min	174
Water Volume+ ?/min	174
Outlet Chilled/Hot Water Temp.⁻ ℃	10.97
Outlet Chilled/Hot Water Temp.⁺ ℃	10.97
Coolin/Heating Load kW	48.2
Sensible Heat kW	30.7
Air Velosity m/s	3.051
Water Velosity⁻ m/s	1.160
Water Velosity⁺ m/s	1.160
Heat Transfer Rate⁻ W/m²KRow	889
Heat Transfer Rate⁺ W/m²KRow	889
SHF —	0.64
WSF [—]	1.34
dt1⁻ ℃	17.00
dt1⁺ ℃	17.00
dt2 ℃	7.00
Log-mean temperature difference⁻	11.27
Log-mean temperature difference⁺	11.27
Cooling/Heating Load⁻ kW	48
Cooling/Heating Load⁺ kW	48
Δqt— kW	0.00
Δqt+ kW	0.00
Residual kW min/lit	0.27
Chilled water Volume lit/min	174
Determination Volume of Water lit/min	174
Initial Water Volume lit/min	1350
Min. Water Volume lit/min	2700
Max. Water Volume lit/min	0
Judgment [good or error]	good

Property	
Face Area of Coil m²	0.6
Pipe Coefficient	10
Tube Number par 1Column	30
Flow	0.5
Row Number	6
Min. Water Volume lit/min	2700
Max. Water Volume lit/min	0
Differential Interval lit/min	0.00000001

Figure 3 Cooling coil

Pump model and fan model

The pump and the fan are handled in the same way. The piping or duct is included respectively in the pump model or the fan model. Figure 4 shows the pump object.

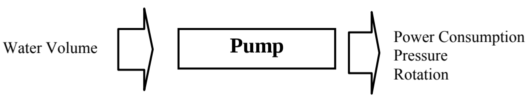
When the flow rate "Q" is given, the required pressure "P" in the transfer system remains constant or exponential on the control method. With regard to the equipment operation points meeting this condition, the discharge pressure "P" and number of revolutions "n" are obtained while the PQ characteristics are changed based on formula (8) where the PQ characteristics and flow rate at approximate rating are in proportion to the number of revolutions "N" at rating in quadratic expression. The power "Pw" is calculated in the formula (9).

$$P = a\,Q^2 + b\,Q\,(n/N) + c\,(n/N)^2 \qquad (8)$$

$$Pw = \rho\, g\, Q\, P/60000/\eta \qquad (9)$$

ρ: Fluid density
g: Gravitational acceleration
P: Pressure
η: efficiency

The tool can simulate operations under various controls as shown in Fig. 5 by combining simple algebraic equations as described above.



Primary Pump	PC-E-1-00
ERROR	0
ON/OFF (ON=1,OFF=0)	1
Mode 0:Stop 1:Cooling 2:Heating	1
Operating Procedure	2
Chilled/Hot Water Volume (l/min)	1370
Outlet Cilled/Hot Water (℃)	7.00
Inlet Chilled/Hot Water (℃)	10.97
Max. Water Volume lit/min	1450
Min. Water Volume lit/min	725
Cooling/Heating Capacity (kW)	527

Control	
CWV:0 VWV(P=Const):1 VWV(P∝Q^2)	2

Initial Water Volume ?/s Vwin	33.2
Initial Pressure kPa Pin	220
Required Water Head Pd	104
Required Rotaion Nd	34
Rotaion N	34
Water Head P	104
Power Consumption (kW)	3.6

Property	
Water Flow Rate DP (lit/min)	1450
Water Head DP (kPa)	176
Actual Pump Head kPa	0
Pressure Drop P=A*Q^n+B :A	0.2
(kPa) :B	0
Efficiency of Pump	0.67
Min. Water Volume ?/min	725
Rotation DP (Hz)	50
Max. Rotation (Hz)	60
Min. Rotation (Hz)	20
PQ Characteristic of Pump :a	-1.41E-01
P=a*Q^2+b*Q+c :b	3.99E+00
(kPa) :c	243.35
Adjustment Parameter a	1
Adjustment Parameter b	0

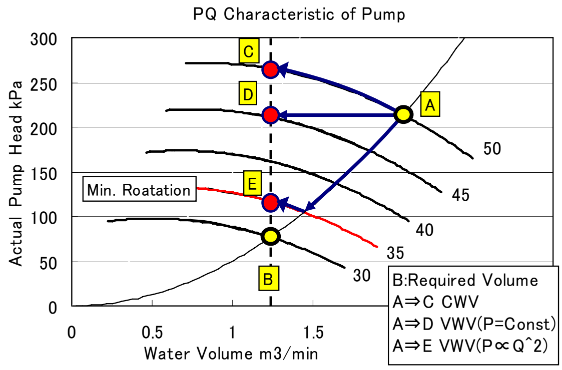


Figure 5 Pump (fan) control

Heat source controller

The tool determines the number of operating heat source equipment while adjusting the secondary side system in the air conditioner and the primary side system in the heat source equipment.

Figure 6 shows a heat source controller object. There is a header connected to the heat source equipment, and a header connected to the air conditioner. The upper part summarizes each system. Major functions are itemized as follows:

·Giving operation signals sent from the secondary side to the heat source side.

·Calculating the total flow rate (heat quantity) on the secondary side, and determining the number of

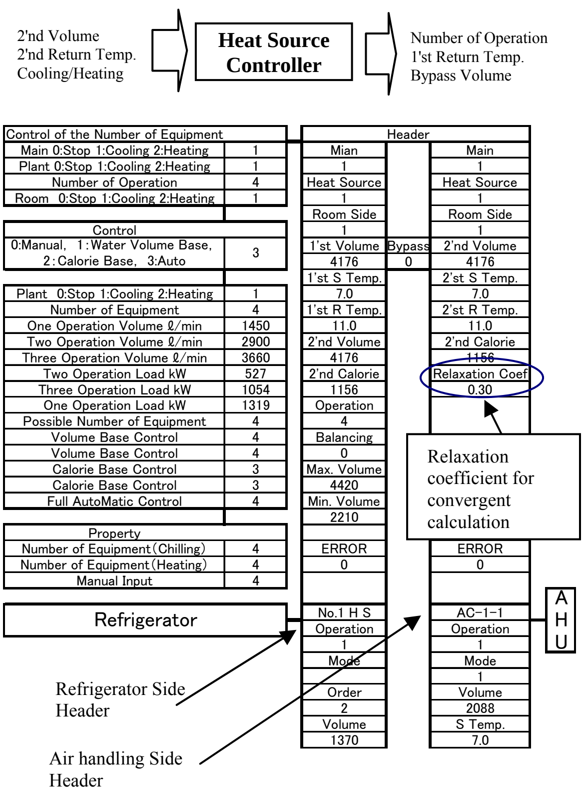


Figure 6 Heat source controller

heat source equipment (while assuring the minimum flow rate)

·Calculating the water volume in each heat source equipment and bypass water volume

·Calculating the temperature on the primary side and secondary side

·Error signals are gathered from the primary side and secondary side

The number of operating heat source equipment and the water volume in each heat source equipment are calculated by convergent calculation using relaxation coefficients.

CALCULATION FORMULA PRECISION VERIFICATION AND CONVERGENT CALCULATION

The validity of the precision of calculation models is verified using the air-conditioning operation data in an office building. It is confirmed that the calculation model has sufficient precision in any object in energy performance evaluation.

Cooling tower

Figure 7 shows the calculated cooling water supply temperature in the X axis, and the measured cooling water supply temperature in the Y axis for comparison. Calculated values basically agree with measured values even if the input condition changes.

Refrigerator

Figure 8 shows the gas consumption in the refrigerator in the same way as the cooling tower, and Figure 9 shows the cooling water exit temperature (cooling water return temperature) from the refrigerator. Calculated values agree well with measured values, and the precision is sufficient in practical use.

Chilled water coil model

Figure 10 shows comparison of the cooling water return temperature. Calculated values agree well with measured values from 13°C (high-load operation) to 23°C (low-load operation) by using graphs and mathematical formulae of the comprehensive heat transfer coefficient released by manufacturers.

It is confirmed that the calculation model has sufficient precision in any object in energy performance evaluation as described above.

Convergent calculation using "iteration" function

Because the refrigerator and cooling tower are coupled, the cooling water supply temperature and cooling water return temperature are determined by convergent calculation using iteration.

A flowchart of solving this relationship using Fortran is shown in Figure 11. Based on this flowchart, a subroutine for the refrigerator and cooling tower was written and a program for inputting the respective calculation results was created and run to obtain a convergent solution.

Solving the relationship in Excel can be performed by just connecting the object as shown in the upper part of Figure 12.

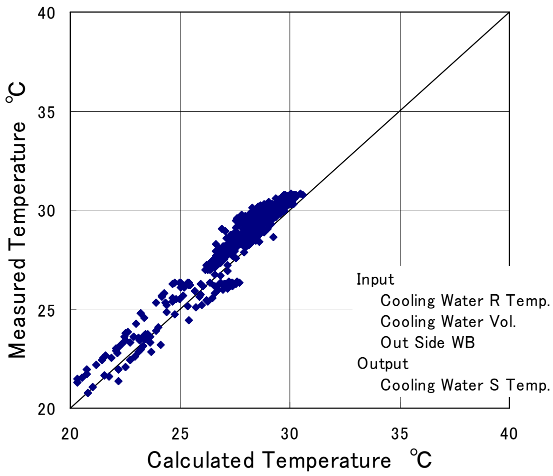


Figure 7 Cooling water supply temperature verification results

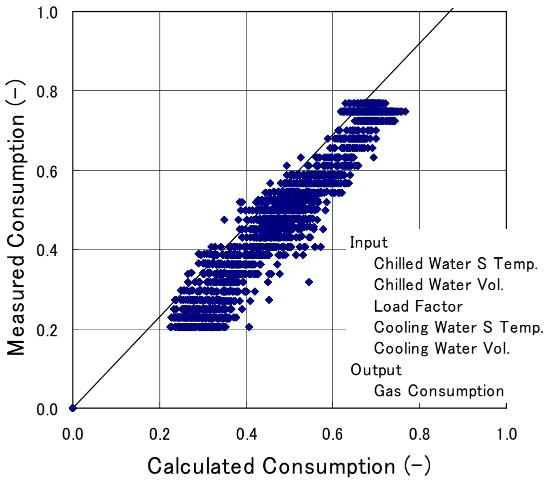


Figure 8 Gas specific-consumption verification result

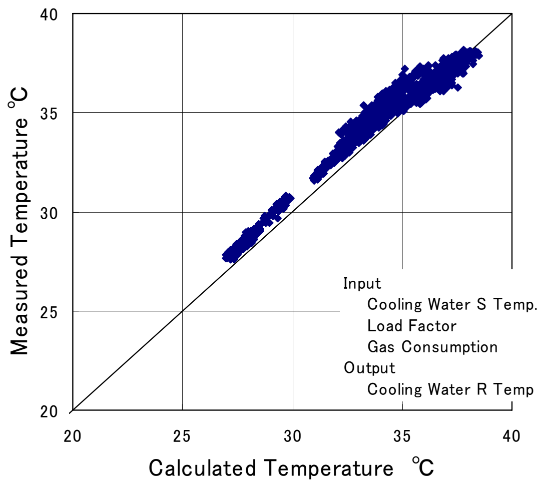


Figure 9 Cooling water return temperature

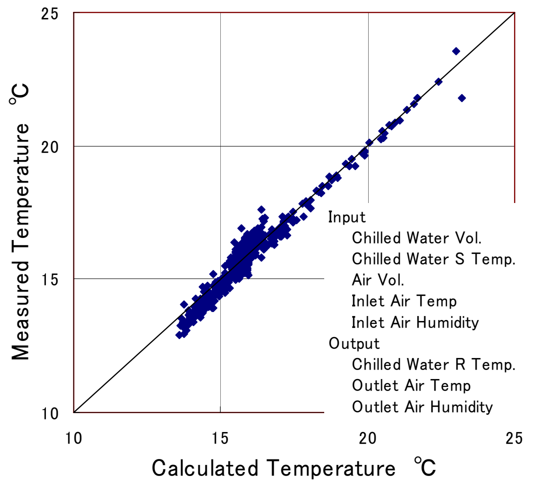


Figure 10 Chilled water return temperature from coil verification

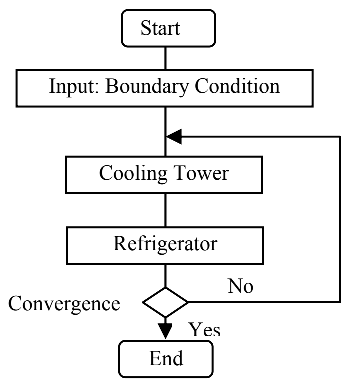


Figure 11 Flow chart of refrigerator and cooling tower

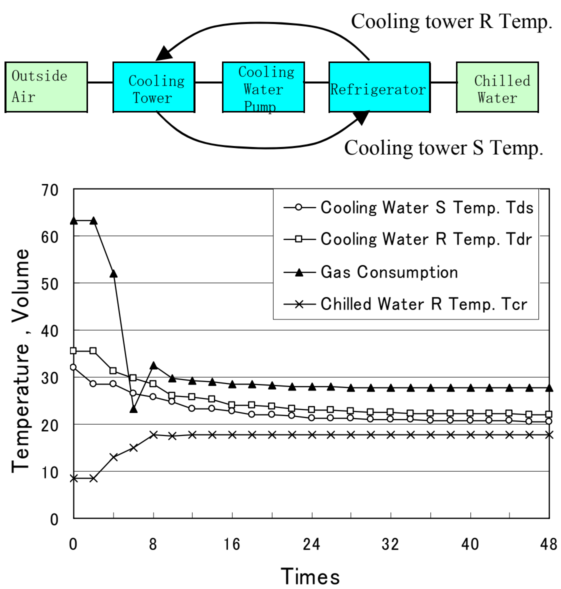


Figure 12 Calculation times and convergence

Calculations are performed as in Figure 11 using the Iteration function of Excel to obtain a solution.

The lower part of Figure 12 shows the convergence process of the cooling water supply temperature, cooling water return temperature, refrigerator gas consumption and chilled water return temperature. The tool executes calculations 48 times until the fluctuation becomes “0.01ºC, 0.01 Nm^3/h” or less.

The time required for this calculation is less than 1s.

ENTIRE CONFIGURATION EXAMPLE

A prototype is available for free after registration from http:// www.mlit.go.jp/gobuild/sesaku/lcem/ lcem.htm.

More than 1,400 people have already received the prototype. Seminars are also held, so that in Japan not only researchers but also general engineers are starting to use this tool.

Figure 13 shows a structural example of the upgraded tool to be distributed next time. The heat source consists of two systems of absorption water cooler/heater and two systems of air-cooled heat pump chiller. The air conditioner is divided into the chilled/heated water coil, humidifier and outside air intake fan, and connected to the indoors by way of VAV. The boundary condition consists of the outside air on the heat source side (leftmost) and the indoor sensible heat load and latent heat load (rightmost). When the boundary condition is given, the tool determines the temperature and flow rate in each object and the required number of refrigerators, and then calculates the gas consumption and electric power consumption at the same time.

The user can input numeric values manually for the boundary condition. When the user prepares time-series data, the tool executes annual calculation using macros.

CONCLUSION

An air-conditioning simulation tool is developed. The developed tool adopts the object cells method, is easily handled, and is available in every phase from planning to operation for application to life cycle energy management.

This paper indicates incorporated mathematical formulae for equipment characteristics, and verifies that the tool offers sufficient precision in energy management.

· This paper indicates structures of objects created in Excel.

· This paper indicates convergent process using the iteration function of Excel.

· The homepage URL of the Land, Infrastructure and Transportation Ministry offering the prototype tool is listed. This paper explains the outline of the upgraded tool to be distributed next time.

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Chairman: S. Murakami
Outline and Operation Method Study Group: T. Nobe Chief examiner of WG1: M. Ito, Chief examiner of WG2: H. Niwa, Chief examiner of WG3: M. Okumiya, Chief examiner of WG4: Y. Sakamoto

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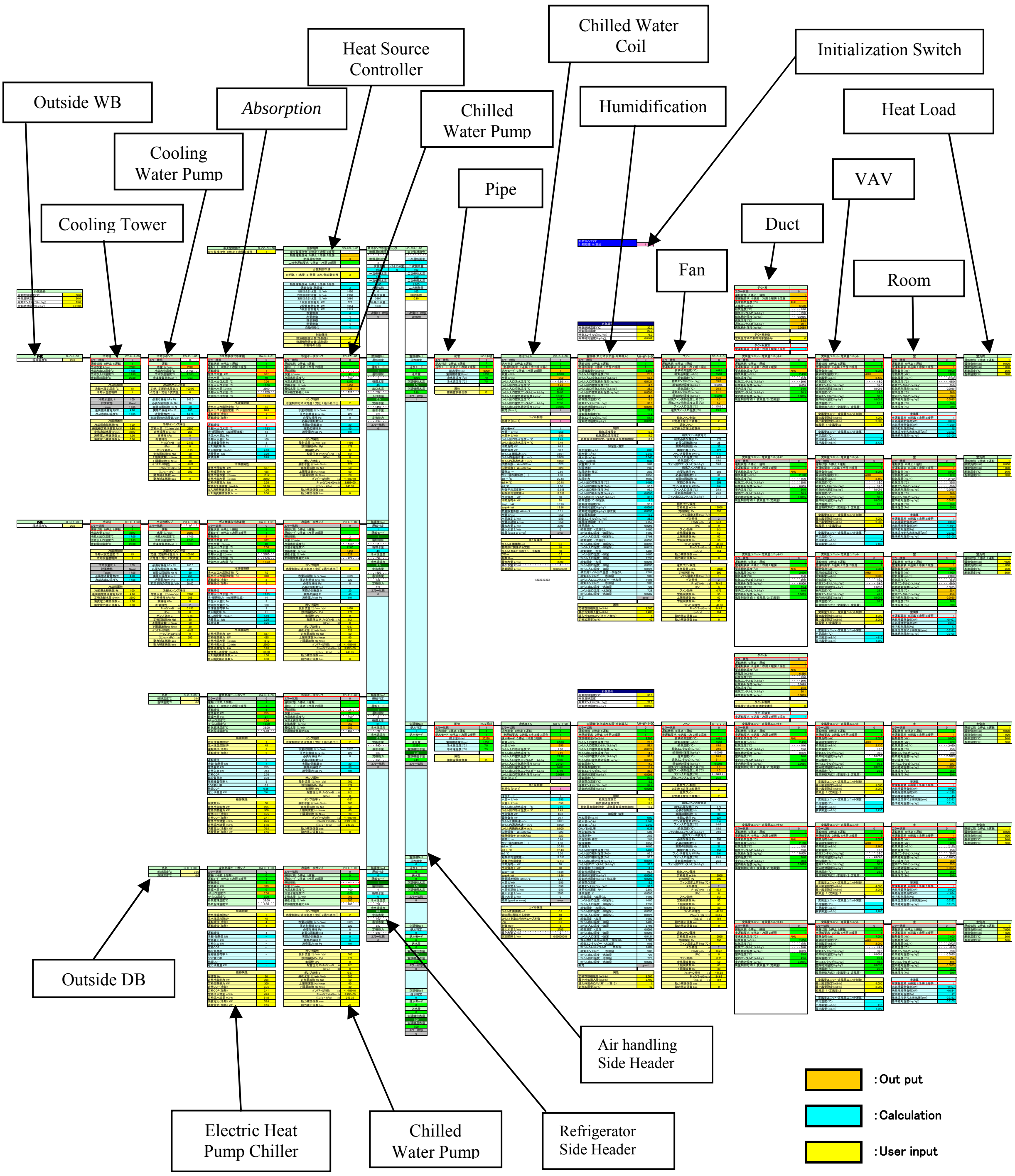

Figure 13 Entire system