EVALUATION OF DISTRIBUTION SYSTEM PERFORMANCE IN DISTRICT HEATING AND COOLING SYSTEM

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ABSTRACT

In this study, energy simulation program of heat distribution network in a district heating and cooling system was developed. Research on actual condition of heat distribution system of DHC plant was also executed. Using the measurement result, the accuracy of the program is confirmed.

Using this program, the relationship between scale of pipeline network and energy consumption of heat distribution system was examined.

In the final part, importance of chilled water temperature differences at the building side for energy performance of DHC is clarified quantitatively.

INTRODUCTION

In Japan, more than 120 district heating and cooling (DHC) systems have been operated. Furthermore, it is expected to diffuse for energy saving by utilizing urban waste heat. Different from the other heat source systems, one of the important feature of DHC system is the existence of long heat transmission line between the plant and buildings.

Although there are many studies on energy performance, optimum design and optimum operation of heat source equipment in DHC system, there are few works on energy consumption characteristics of heat distribution system such as energy consumption of pumps and heat loss from pipelines.

The aim of this paper is to investigate the energy performance of heat distribution system in DHC system quantitatively. In the first part of this paper, we developed the DHC energy simulation program in which energy consumption of heat distribution system is modeled in detail. The accuracy of the simulation results is confirmed by the measurement results.

Using this program, we examined the following two topics related to the performance of heat distribution system of DHC in the last part of this paper. One is the relationship between scale of pipeline network and energy consumption for heat distribution, which is important factor in planning DHC system. The other is the influence of drop of chilled water temperature difference at buildings' side on energy consumption of a DHC plant, which is a serious problem in DHC operation. For these evaluations, we suggested the energy consumption for heat distribution, which consists of heat loss and energy consumption of pumps, per unit heat demand as an index.

THE OUTLINE OF THE PROGRAM

The simulation program developed in this study consists of two parts: distribution loss calculation part and plant energy simulation part as shown in Figure 1.

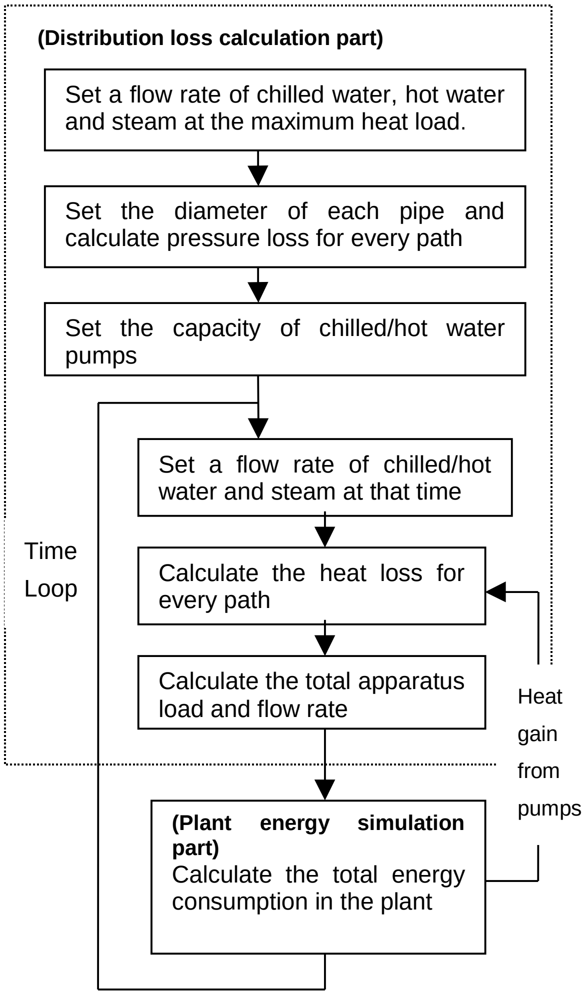

Figure 1 Flowchart of the simulation

The distribution loss calculation part simulates pressure loss and heat loss / gain in pipelines from configurations of pipeline networks such as length, blanches, valves, etc. and heat demand of buildings. In this program, chilled water, hot water and steam can be simulated as heating medium. The pipelines are assumed to be equipped in utility tunnels. In the program, buildings and branches are called "Node" and pipelines between two nodes are called " Path". The temperature and static pressure in each node is computed from the calculated values of pressure and heat loss in neighboring paths. Pressure loss is calculated exactly by the Darcy-Weisbach equation (1) for friction loss, Weisbach equation (3) for bend loss and the Gardel equation for branch and confluent loss without approximation to the equivalent pipe length.

The friction loss coefficient λ in Darcy-Weisbach equation is calculated by the Moody's equation(2).

$$\frac{\Delta P}{\rho g} = \lambda \frac{L}{d} \bullet \frac{v^2}{2g} \tag{1}$$

$$\lambda = 0.0055\{1 + \left[20000\frac{\varepsilon}{d} + \frac{10^6}{\mathrm{Re}}\right]^{1/3}\} \tag{2}$$

$$\zeta = 0.131 + 0.163\left(d/r\right)^{3.5} \tag{3}$$

where :

v : velocity [m/s]
L : pipe length [m]
d : pipe diameter [m]
ε : roughness of pipe surface [m]
r : radius of the curvature of bend [m]

Heat loss or gain is calculated from air temperature in tunnels, temperature of heating medium, thermal resistance of heat insulation material and heat gain from pumps. The diameter of pipe is calculated in the program from annual maximum flow rate of heating medium for each path. The air temperature in the utility tunnel is calculated monthly from heat balance between heat conduction in the ground and heat gain from pipes for each path. Heat conduction in the ground is calculated, assuming the ground temperature 1m apart from the wall is 17 deg C. For chilled water, heat gain from pumps are also calculated from the result of the plant energy simulation part.

The plant energy simulation part calculates energy consumption of refrigerators, boilers, pumps and cooling towers every hour.

THE ACTUAL CONDITION IN THE DHC PLANT AND CONFIRMATION OF SIMULATION MODEL

In previous studies on energy simulation of DHC plant, there are few examples of research on the actual condition of energy for heat distribution and heat loss/gain at the pipelines. Accordingly, the authors measured the distribution of temperature and pressure in chilled water and steam pipeline of the DHC plant (A-plant) in Kansai district, Japan. The measurements were carried out for two days, one day in summer and the other day in winter.

The configuration of pipeline network in A-plant and the location of measurement points referred in this paper are shown in Figure 2.

Using the distribution loss calculation part, temperature and pressure distribution of pipeline is calculated from the measured temperature and static pressure at the supply header in the plant. The pipe diameter and the thickness of insulating material are set at actual value of A-plant in this section.

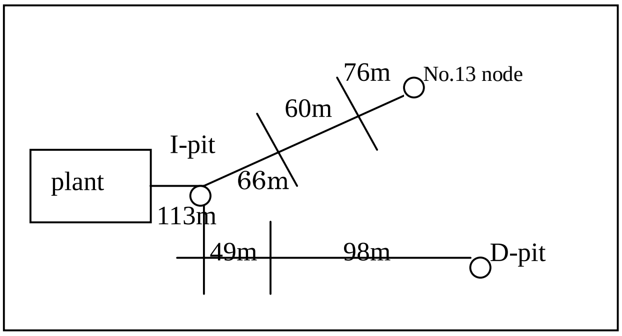

Figure 2. The location of measurement points in the A-plant.

1) Static pressure at chilled water pipeline

Figure 3 shows a calculated and measured value of static pressure of chilled water at the No.13 node and the measured data at the plant for the measurement in summer. Since we measured the pressure by reading the display at the console every 10 minutes, there are more or less time lags between measured and calculated value. The calculated pressure loss is slightly larger than measured value. Figure 2 also shows a static loss calculated without considering bend loss. The measured value lies between both calculated values. Since there are continuous several bends in each pit with branch, the estimation of the bend loss affects the total pressure loss significantly.

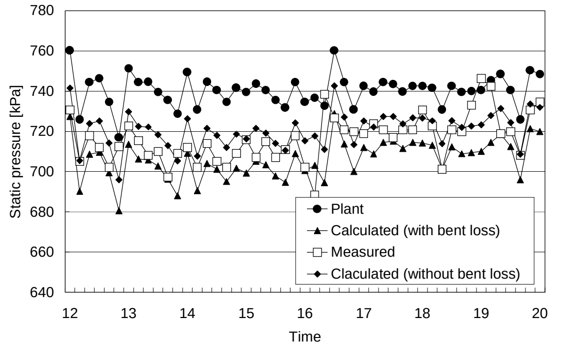

Figure. 3 Calculated and measured static pressure of chilled water at the No.13 Node

2)Chilled water temperature

To measure heat gain of chilled water, chilled water temperature at several branches of the pipeline is measured automatically by data loggers every 30 seconds. Figure 4 shows the measured water temperature in supply pipe at I-pit and D-pit in summer. The measured data at D-pit is staggered by 15 minutes to consider the transit time. This figure suggests us that the temperature change in the distance of 220m is smaller than the accuracy of the measurement (0.1K). On the other hand, the computed temperature changes are smaller than 0.05K. Even if this changes are 0.1K, heat gain ratio is lower than 3% under the condition that chilled water temperature differences at the buildings' side are 7K. Then we can conclude that the magnitude of the error is small in comparison with the level which affects the total energy balance.

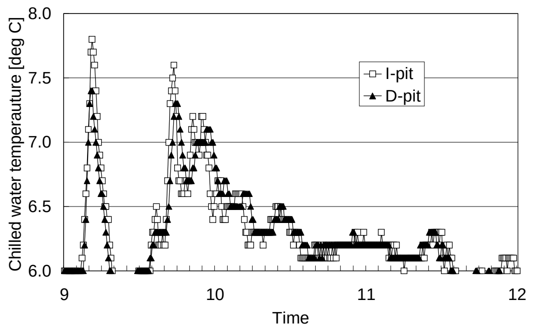

Figure 4. Measured chilled water temperature at I-pit and D-pit

(The data of D-pit is staggered by 15 minutes)

3) Static pressure at steam pipeline

Figure 5 shows a calculated and measured value of static pressure of steam pipeline at the No.13 node and measured value at the plant for the measurement in winter. The pressure is measured by reading the display at the console every 10 minutes. The simulated pressure shows good agreement with measured value.

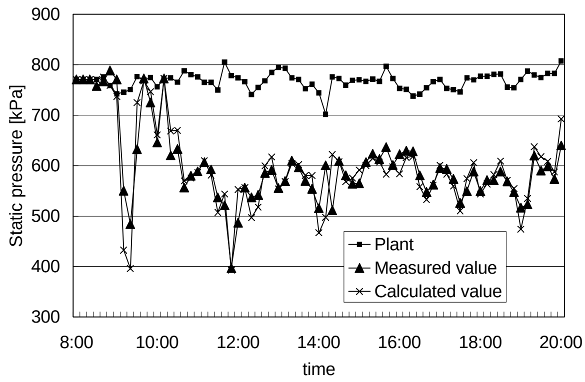

Figure 5. Calculated and measured static pressure of steam at the No.13 Node

CASE STUDY FOR A MODEL DHC PLANT

Using the distribution loss calculation part, which is verified in the preceding section, and the plant energy simulation part, the influence of DHC scale and chilled water temperature difference at the buildings' side on energy consumption for heat distribution system is evaluated.

In the following section, imaginative model DHC plant is set as an object of the study. As the average size of Japanese DHC systems, 16 buildings which have 29,400m^2 floor area in each building are arranged in 400m×400m square as shown in Figure 6. For setting heat demand of the buildings, the unit heat demand estimated by IBEC (Institute for Building Energy Conservation) is used. The unit heat demand is corrected so that at least 10% of cooling demand in a peak season may be existed even in winter.

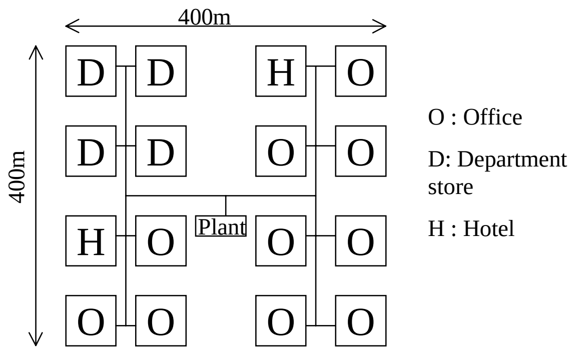

Figure 6.The configuration of the model DHC area.

Chilled water with the temperature difference between supply and return water of 7K and steam with pressure of 930kPa are used for heating medium. By setting the load factor to 0.85 for distribution line and 1.0 for service line, the pipe diameter at each path is settled under the conditions as follows:

Chilled water :

$$V_{\max} \leq 2.5 m/s$$

Steam :

$$V_{\max} \leq 50 m/s$$

and Pressure loss per unit pipe length is less than 9.8 kPa/m.

The head of chilled water supply pump is set to the sum of pressure loss at maximum flow rate, 147kPa for pressure loss at building and 98kPa for pressure loss at refrigerator.

Insulation of the pipe is settled to be 40mm of rigid expanded urethane for chilled water pipe and 40mm of calcium silicate for steam pipe.

Gas boilers and double effect absorption refrigerating machine are settled as heat source equipment and city gas is selected as the main energy source. Table 1 shows the specifications of heat source equipment.

The number of operating refrigerator is determined in every hour by the required total flow rate of chilled water, which is the sum of required flow rate by buildings and flow rate for by-pass which is at least the half of one refrigerator's rated flow rate. COP of the refrigerator is determined in every hour from the load factor and the cooling water temperature which is calculated from outdoor air temperature and humidity.

In the simulation program, hourly energy consumption of DHC system is calculated for 3 days a month : weekday, weekday with department store is closed, and holiday. After that, these results are transformed into the monthly energy consumption.

Table 1 Specifications of heat source equipment.

Absorption refrigerating machine:
capacity=4220kW/unit, COP=1.23(standard condition),
electric power consumption for accessories=15.6kW/unit
Gas boiler:
efficiency =80.2%
electric power consumption for accessories=11.9kW/unit
Cooling tower:
electric power consumption = 75kW/unit
Cooling water pump:
electric power consumption = 230kW/unit
Chilled water pump:
flow rate = 500m^3/h, pump efficiency = 0.75
motor efficiency = 0.95

ENERGY CONSUMPTION UNDER THE STANDARD CONDITION

The monthly primary energy consumption under the standard condition is shown in Figure 7. "The standard condition" means that the configuration of the DHC area is the same as Figure 6 and chilled water temperature difference is constant at 7K.

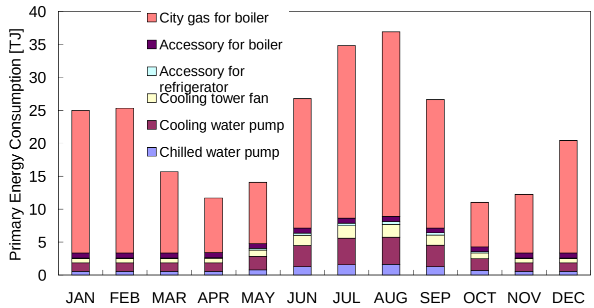

Figure 7 Energy consumption under the standard condition.

The composition of the annual primary energy consumption is shown in Figure 8. 72.5% of the total is used for cooling, 27.5% is used for heating.

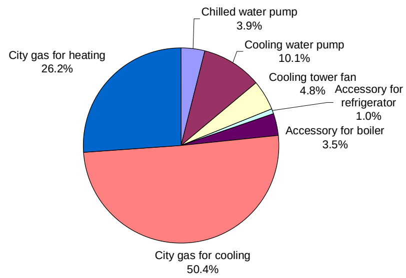

Figure 8 The composition of annual primary energy consumption under the standard condition

The monthly heat loss ratio, which is defined as heat loss per heat demand, is shown in Figure 9 with its composition. Heat gain at pipeline is about 1% of heat demand and less than heat gain from pump. The annual heat loss ratio is about 3%.

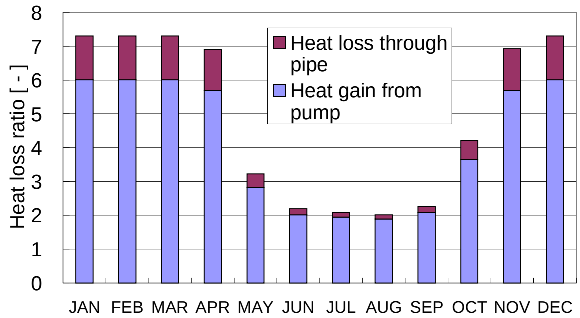

Figure 9 The monthly heat loss ratio under the standard condition.

In this paper, energy consumption for heat distribution is defined as follows:

Total energy consumption for heat distribution per unit heat demand R_t, R_c, R_h

$$R_t=(E_c+E_h)/(Q_c+Q_h)$$

$$R_c=E_c/Q_c$$

$$R_h=E_h/Q_h \quad (4)$$

Energy consumption for cold heat distribution E_c

$$E_c=E_{cp}+E_{closs} \quad (5)$$

Energy consumption for hot heat distribution E_h

$$E_h=E_{hloss} \quad (6)$$

Energy consumption for cold and hot heat loss at pipeline E_{closs}, E_{hloss}

$$E_{closs}=r_cE_{tc}$$

$$E_{hloss}=r_hE_{th} \quad (7)$$

Where:

Q_c,Q_h=annual cold or hot heat demand [MJ/y]

E_{cp}=annual primary energy consumption for chilled water pump[MJ/y]

E_{tc}, E_{th} = Total primary energy consumption for producing cold or hot heat[MJ/y]

r_c, r_h = The ratio of heat gain and heat loss to apparatus load

In case of cold heat, the ratio of E_c to total energy consumption in DHC plant is 5.4% and the ratio of E_c to energy for cooling is 7.4%. In case of heating, the ratio of E_h to total energy consumption in DHC plant is 0.5% and the ratio of E_h to energy for heating is 1.8%.

RELATIONSHIP BETWEEN SCALE OF DHC AND ENERGY CONSUMPTION FOR DISTRIBUTION SYSTEM.

There are more than 120 district heating and cooling systems in Japan and their scale and heat demand density differ from each other remarkably as shown in Figure 10. The geometrical specification such as scale affects energy consumption for distribution system in the way as follows:

1)As scale becomes large, the head of pump is increased.

2)Heat loss from pipe has close relations with diameter and length of pipeline.

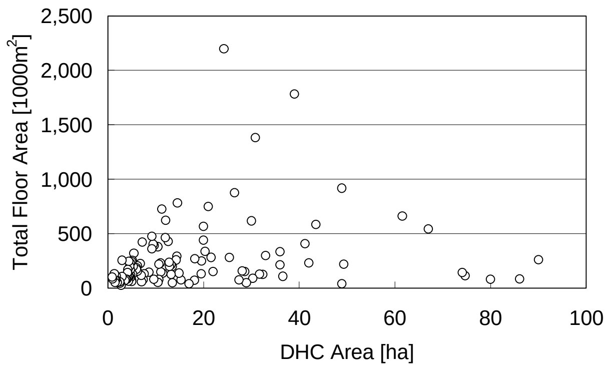

Figure 10. The relationship between the DHC area and the total floor area of buildings in Japan[1].

It is important to get quantitative information about the relationship between scale and energy performance for planning new DHC system. In this section, the change of energy consumption for heat distribution with the scale and heat demand density of DHC system was evaluated by selecting the energy consumption for heat distribution per unit heat demand as an index.

The calculation condition is shown in Table 2. Both case of fixed number of buildings and fixed size of the building are examined. In case of that the heat load density is doubled is also evaluated. To exclude the influence of partial load characteristics, the capacity of refrigerator is set to proportionately with total heat demand.

Table 2. Calculation conditions.

	DHC area [ha]	Number of Buildings	Heat load density
RUN-1	4	16	normal
RUN-2	9	16	normal
RUN-3	16	16	normal
RUN-4	25	16	normal
RUN-5	36	16	normal
RUN-6	4	4	normal
RUN-7	36	36	normal
RUN-8	4	16	doubled
RUN-9	9	16	doubled
RUN-10	16	16	doubled
RUN-11	25	16	doubled
RUN-12	36	16	doubled

Figure 11 shows the change of energy consumption for chilled water pump per cold heat demand E_{cp}/Q_c with scale. The influence of scale is small without the RUN-6 and RUN-7. In case of heat load density is doubled, energy consumption becomes larger since head of the pump is increased.

As shown in Figure 12, E_{closs}/Q_c decreases with increase in scale. Figure 13 shows the change of R_c, which is the sum of these two indicators. Since E_{cp} is larger than E_{closs}, the influence of scale is not so clear. In case of heat load density is doubled, R_c increases by approximately 40%.

In case of the RUN-6 and RUN-7, that size of the building is same as RUN-3 and the number of the buildings is changed, the relationship between scale and energy consumption becomes very complicated since configuration of pipeline network is different from the other cases. In case of the RUN-7, E_{cp}/Q_c, E_{closs}/Q_c and R_c becomes larger than RUN-5, since both the length of pipeline and the number of bent loss becomes larger than the case of fixed buildings number. R_c of RUN-7 is larger than RUN-5 by 66%.

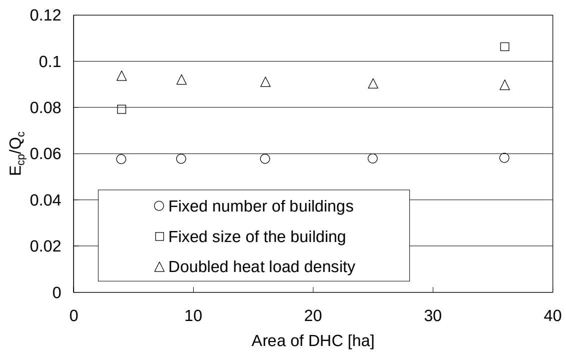

Figure 11 Change of E_{cp}/Q_c with Scale

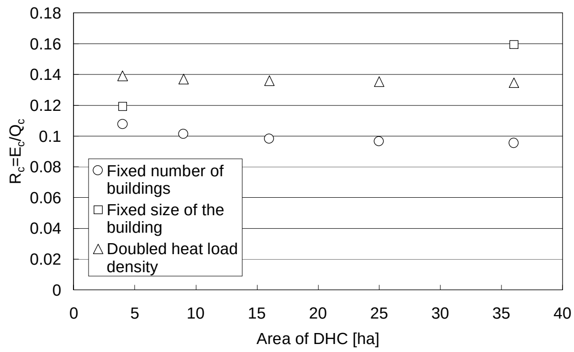

Figure 12 Change of E_{closs}/Q_c with Scale

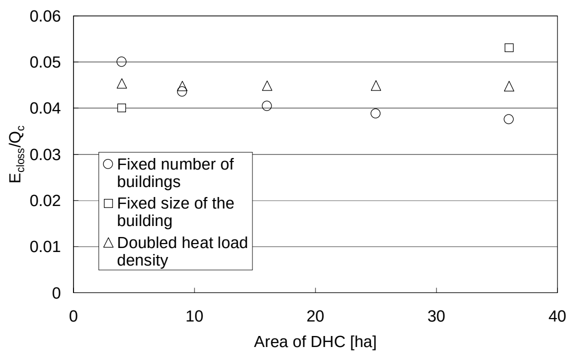

Figure 13 Change of R_c with Scale

Figure 14 shows the change of energy consumption for hot heat distribution R_h. R_h decreases with increase in scale. In case of heat load density is doubled, energy consumption is decreased.

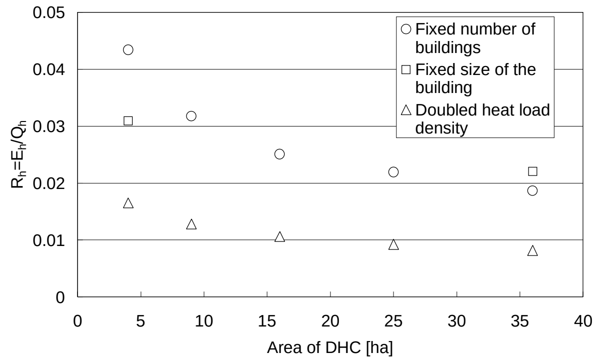

Figure 14 Change of R_h *with scale*

Figure 15 shows the change of total energy consumption per unit heat demand R_t. It increases with increase in scale, however, the range of the difference is small since cold heat demand is larger than hot heat demand. In case of heat load density is doubled, R_t is increased by about 20%.

Since the ratio of energy for heat distribution is 6% as shown in the preceding section, the range of the changes of R_t in this section seems to have a small influence on the total energy consumption of DHC system.

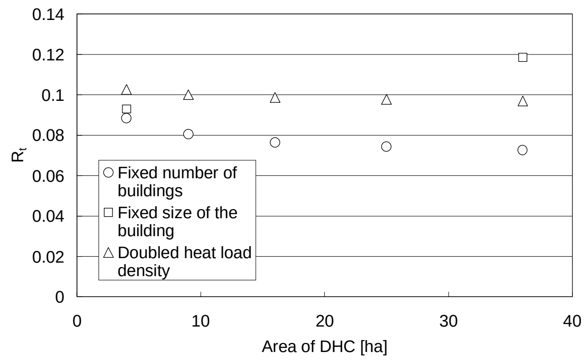

Figure 15 Change of R_t with scale

RELATIONSHIP BETWEEN THE CHILLED WATER TEMPERATURE DIFFERENCES AT THE BUILDINGS' SIDE AND ENERGY PERFORMANCE.

For all the buildings in the A-plant, the actual condition of the chilled water temperature difference between supply and return water at the buildings' side was surveyed for a year. With regard to the relationship between the cold heat demand and the temperature difference, the buildings are classified into three patterns as shown in Figure 16.

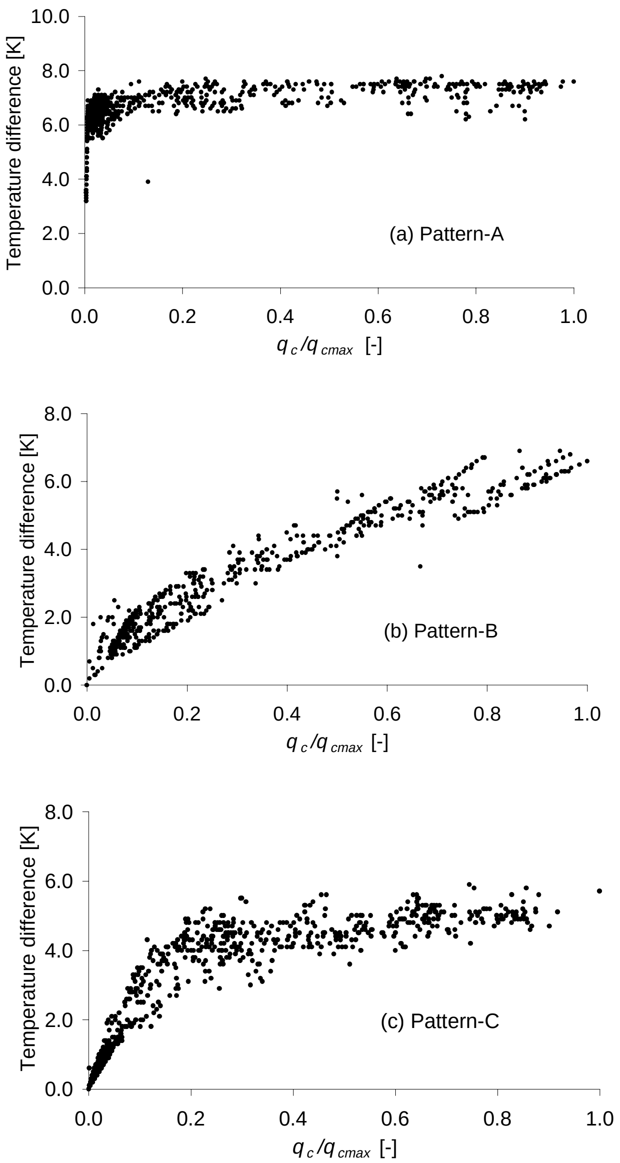

Figure 16. Actual condition of chilled water temperature difference at the buildings' side

In pattern-A, the temperature difference is constant at the designed value over a year.

In pattern-B, the flow rate is constant and the temperature difference is proportional to heat demand over a year.

In pattern-C, the temperature difference becomes proportional to heat demand when heat demand is small. It is supposed that this pattern occurs by the failure of valve control when flow rate is small.

To clarify the influence of the temperature difference to energy performance, energy simulation for the model DHC plant is executed.

In this simulation, patterns of temperature difference is defined as the same for all the buildings. Temperature difference (dt) under the three conditions is set as follows:

Pattern-A : dt=7 [K]

Pattern-B : $dt=7(q_c/q_{cmax})$

Pattern-C : $dt=35(q_c/q_{cmax})$ for $q_c/q_{cmax}<0.2$

dt=7 [K] for $q_c/q_{cmax}>0.2$

where:

q_c = hourly cold heat demand [MJ/h]

q_{cmax} = Maximum cold heat demand [MJ/h]

Figure 17 shows the calculated value of R_c for three patterns. When the dt is smaller than the designed value, the number of operating pumps is increased and heat gain from pumps is also increased. Then, compared to the pattern-A, R_c is increased by 306% in case of pattern-B and by 35% in case of pattern-C.

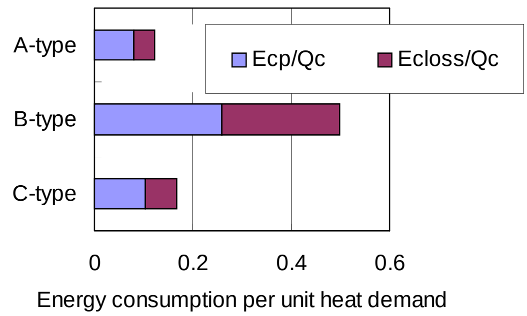

Figure 17. Energy consumption for Chilled water distribution for three patterns.

In regard to total energy consumption in DHC plant, energy consumption of refrigerator is also increased since load factor of refrigerator is decreased. Then, total energy consumption is increased by 70% in the pattern-B and by 10% in the pattern-C compared to the pattern-A as shown in Figure 18.

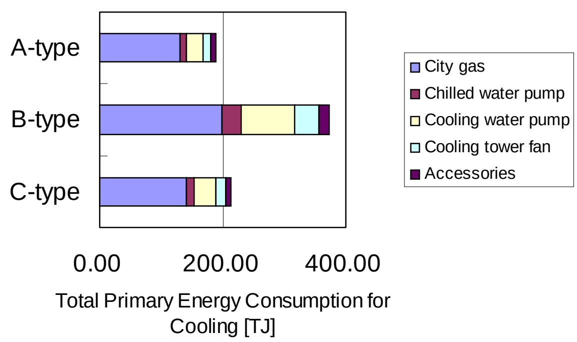

Figure 18. Total energy consumption for three patterns.

CONCLUSION

In this paper, we focused on the heat distribution system performance in the district heating and cooling system, and the simulation program which evaluates the energy consumption of heat distribution system was developed. After the verification by the measurement results of temperature and static pressure distribution in a DHC system, the basic characteristics of the energy consumption of heat distribution system in the model DHC plant was examined. The results are summarized as follows:

1) In the annual energy consumption of the model DHC plant, the energy consumption for heat distribution, which consists of energy for pump and energy consumption for heat loss, occupies 6% of the total.

2) Energy consumption for distribution systems decreases with increase in scale in the majority of cases. On the other hand, it increases with increase in heat load density. However, these changes are small in comparison with the whole energy consumption of DHC plant.

3) If the chilled water temperature difference between supply and return water at the buildings' side becomes smaller than the designed value, not only energy for heat distribution system but also total energy consumption in DHC plant increases in considerable degrees.

ACKNOWLEDGEMENTS

The authors would like to express their thanks to the staffs of the A-plant, Mr. Satoshi Nakamura, Mr. Toshinari Momose and Ms. Ritsuko Egusa for their kind assistance in this study.

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[1] The Japan Heat Service Utilities Association, "Handbook of the Heat Service Utilities", 1998. (in Japanese)