SIMULATION STUDY ON ESTIMATION METHOD FOR FLOW RATE IN AIR-CONDITIONING SYSTEM WITH WATER THERMAL ENERGY STORAGE

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ABSTRACT

It is difficult to investigate the performance of air-conditioning systems with thermal energy storage tanks because flow rate in the system is unmeasured in almost all systems. The aim of this research is to estimate the flow rate of such air-conditioning systems using temperature data in tanks which is easy to measure. In this paper, the effects of heat gain through the tank wall, the time interval of data and the number of temperature measuring points in tank on the accuracy of flow rate estimation are studied using generated temperature data by simulation.

KEYWORDS

thermal energy storage system, flow rate estimation, estimation accuracy

INTRODUCTION

Building equipment systems have became increasingly more complex with the progress of technology development. When the equipment systems have faults, it is difficult for system operators to deal with them. This situation can become the cause of inefficient energy usage and an uncomfortable indoor environment, and can result in the system breaking down. Even if designers aim to realize an appropriate indoor environment without waste of energy, the highest performance of the system will be unachieved without appropriate system operations.

A fault detection and diagnosis system installed in the equipment control system will help system operators to deal with fault conditions immediately and recover the system. One of the simplest systems for a fault detection is an alarm system which alerts system operators when abnormal temperature or flow rate is found. But it is difficult to identify abnormal conditions in the measured data of temperature or flow rate changing continuously. Furthermore, flow rate in the system is unmeasured in many buildings because of expensive flow meters, and it is difficult to measure flow rate accurately because of complex piping in the system. The aim of this study is to investigate the operation condition of the thermal energy storage system with water storage tank of multi-connected complete mixing type by using flow rate estimation, and we have been trying to estimate flow rate with measured data in some actual office buildings (Sagara 1995, Sagara and Nakahara 1996). In this paper, the results of simulation study on estimation accuracy of flow rate in air-conditioning system with water thermal energy storage were presented. Assuming the simple system consisting of a chiller, an air-handling unit and a water storage tank, the data for flow rate estimation were generated by the system simulation using a physical model for water storage tank. The flow rate through the water tank is estimated from the transitional change of generated temperature data in the water tank. And, the effects of measuring resolution in temperature measuring instrument and heat gain through the tank wall on the accuracy of flow rate estimation are reported.

DATA GENERATION METHOD

System and operating condition

The thermal storage system for simulation study is composed of a water thermal storage tank of the multi-connected complete mixing type, a chiller and an air-handling unit (AHU). The storage tank is divided into 26 sub-tanks connected in series and its total volume is 400 m^3. Operating condition of this system is listed in Table 1, the thermal storage system is shown in Figure 1 schematically, and the plan of thermal energy storage tank is shown in Figure 2.

In the thermal storage tank, the ceiling, bottom and outer wall adjacent to soil are insulated, but partition walls between divided tanks are not insulated. Water to the chiller is pumped up from the lower and higher temperature end tanks, and chilled water is put into the lower temperature end tank. Water to the AHU is pumped up from the lower temperature end tank and returns to the higher temperature end tank (see Figure 1).

The following conditions are assumed for simulation.

1. Input/output temperature difference of chiller is always 5 degC regardless of chiller COP.
2. Input temperature to chiller is normally controlled to 11 degC, and output temperature of chiller is 6 degC normally.

3. Input/output temperature difference from AHU is always 7 degC regardless of cooling coil characteristics, and output temperature from AHU is calculated from the input/output temperature difference.
4. Water temperature in each divided tank during no operation period also changes due to heat gain from tank wall.

Physical model of thermal energy storage tank

Type of water thermal storage tank is roughly classified into two types; the multi-connected complete mixing type and the temperature-stratified type. The former type is more popular in Japan because it is easy to construct and have a long history though storage performance is lower than the latter type. Many buildings in Japan have a space under basement floor which is divided by high tie beams for protection against earthquakes. The divided space has been used for water thermal storage tank of the multi-connected complete mixing type. So the physical model for the multi-connected complete type is used in this study. Assumption in modeling is as follows.

1. Water is mixed completely in each divided tank.
2. Water density and specific heat are constant regardless of water temperature.
3. One-dimensional heat conduction in concrete tank wall and ambient soil is applied to calculation of heat gain in each divided tank.
4. Heat capacity of insulation material and air under ceiling is neglected, and thermal resistance between water and surface of tank wall is neglected.
5. All the water in each divided tank is useful to thermal storage and is mixed completely.

Under these assumptions, water temperature in the i th tank is calculated with the following equation (see Figure 3).

$$\rho C_p V_i \frac{d\theta_i}{dt} = \rho C_p q\left(\theta_i - \theta_{i-1}\right) + \sum_{k}^{6} h_{ik} A_{ik} \qquad (1)$$

Heat transfer in concrete tank wall and ambient soil is assumed to be governed by the one-dimensional unsteady heat conduction equation. Temperature in concrete and soil was calculated with a finite difference method for each wall of divided tank under constant soil temperature at 1m distance from concrete wall. Generated data for flow rate estimation are the data in 8th data of simulation started initially with 11 degC uniform temperature in the whole storage tank. The change of chiller output, cooling load, output temperature from chiller and input temperature to AHU are shown in Figure 4, and the transitional change of temperature profiles in storage tank is shown in Figure 5. In this thermal storage system, chiller is

Table 1 Operating condition

Volume of thermal storage tank	400 m^3
Number of divided tanks	26
Capacity of chiller	146 kW
Flow rate in chiller	25 m^3/h
Output temperature of chiller	6 degC
Input/output temperature difference of chiller	5 degC
Input/output temperature difference of AHU	7 degC

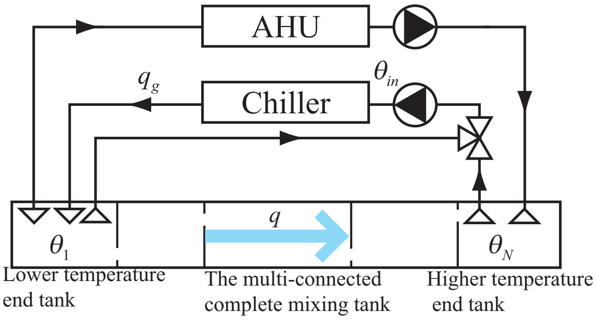


Figure 1 Thermal storage system

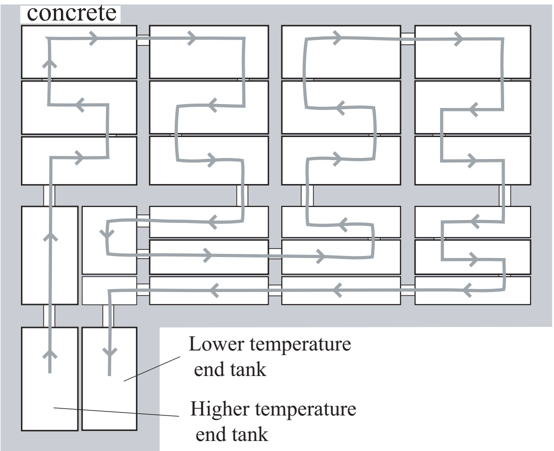


Figure 2 Plan of thermal storage tank

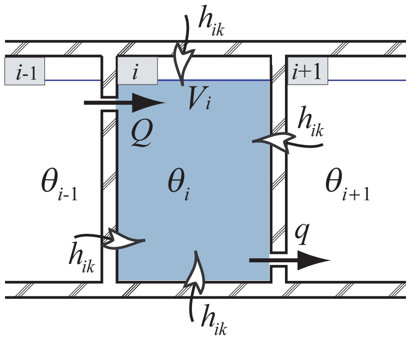


Figure 3 Heat balance in divided tank

operated from 0:00 to 12:00 and from 16:00 to 24:00, and AHU is operated from 8:00 to 18:00 as shown in Figure 4.

FLOW RATE ESTIMATION METHOD

In this study, the flow rate is estimated by heat balance in each divided tank as the following equation in which heat gain through tank wall is neglected.

$$\rho C_p V_i \frac{d\theta_i}{dt} = \rho C_p q\left(\theta_i - \theta_{i-1}\right) \tag{2}$$

The procedure of flow rate estimation is as follows.

1. First of all, initial temperature profile of thermal storage tank is given by measured temperature in divided tanks.
2. The flow rate (q) through thermal storage tank is given by heat balance at the three way valve as the following equation (see Figure 1).

   $$q = \frac{\theta_{in} - \theta_1}{\theta_N - \theta_1} q_g \tag{3}$$

   where flow rate in a chiller is constant during the whole operation period.
3. Assuming that temperature in i-1 th tank is changing linearly from t_j to t_{j+1} as shown in Figure 6-1, input temperature θ_{i-1} to i th divided tank between t_j and t_{j+1} is given as the following equation.

   $$\theta_{i-1} = \theta_{i-1}^{j} + \frac{\theta_{i-1}^{j+1} - \theta_{i-1}^{j}}{t_{j+1} - t_j} t \tag{4}$$

   The equation (2) is a first order linear differential equation. Temperature in i th tank is given theoretically as the following equation by substituting equation (4) to the equation (2).

   $$\theta_i = \left(\theta_i^j - \theta_{i-1}^j + \frac{\theta_{i-1}^{j+1} - \theta_{i-1}^{j}}{t_{j+1} - t_j}\frac{V_i}{q}\right) e^{-\frac{V_i}{q}t} + \theta_{i-1}^j + \frac{\theta_{i-1}^{j+1} - \theta_{i-1}^{j}}{t_{j+1} - t_j}\left(t - \frac{V_i}{q}\right) \tag{5}$$

   The input temperature to i+1 th tank is also given by linear approximation of temperature in i th tank calculated by the equation (4) (see in Figure 6-3). In addition, the temperature in i+1 th tank at the time t_{j+1} is also given by the equation (5) after substituting θ_i (the input temperature to i+1 th tank) to the equation (2).
4. Flow rate in a chiller is estimated by comparing the measured temperature in divided tanks with the calculated one as shown in Figure 7. Using the modified Powell method (Powell 1964, Zangwill 1967), the estimated flow rate is determined as the flow rate which minimizes the error between measured and calculated temperatures, in which the error is summed up in each measured tank for the whole charging period because flow rate in a chiller is constant during the whole operation period.

Initial temperature error

The initial temperature error is defined as a root mean square of error between the original temperature and the given temperature in unmeasured tanks which is calculated by linear interpolation between measured tanks in case that temperature in several tanks is measured as actual systems (see Figure 8).

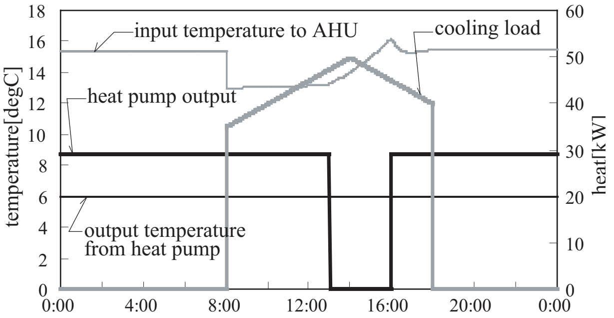
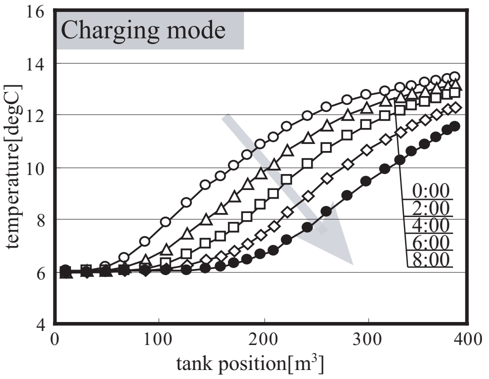
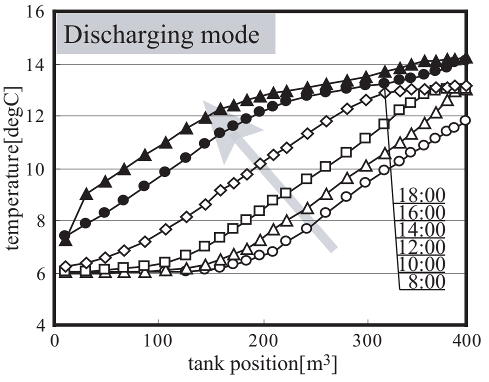


Figure 4 Input temperature, chiller output and cooling load



(1) Charging mode



(2) Discharging mode

Figure 5 Temperature profile in storage tank under normal condition

$$e_i = \sqrt{\frac{\sum_{i=1}^{n}\left(\theta_i^{*0} - {}^{*}\theta_i^{0}\right)^2}{n}} \tag{6}$$

Average temperature error

The average temperature error is the minimum error which gives the estimated flow rate, and is defined as a root mean square of error between calculated and measured temperatures in divided tanks during the whole charging period as the following equation.

$$e_o = \sqrt{\frac{\sum_{i=1}^{n}\sum_{j=1}^{m}\left(\theta_i^{j} - \theta_i^{*j}\right)^2}{nm}} \tag{7}$$

Normalized flow rate error

The normalized flow rate error is the accuracy index of estimated flow rate in a chiller, and is defined as an error between the estimated flow rate and the right flow rate used in data generation simulation, and it is normalized by flow rate in data generation simulation as the following equation.

$$e_f = \frac{q_g - q_g^{*}}{q_g^{*}} \tag{8}$$

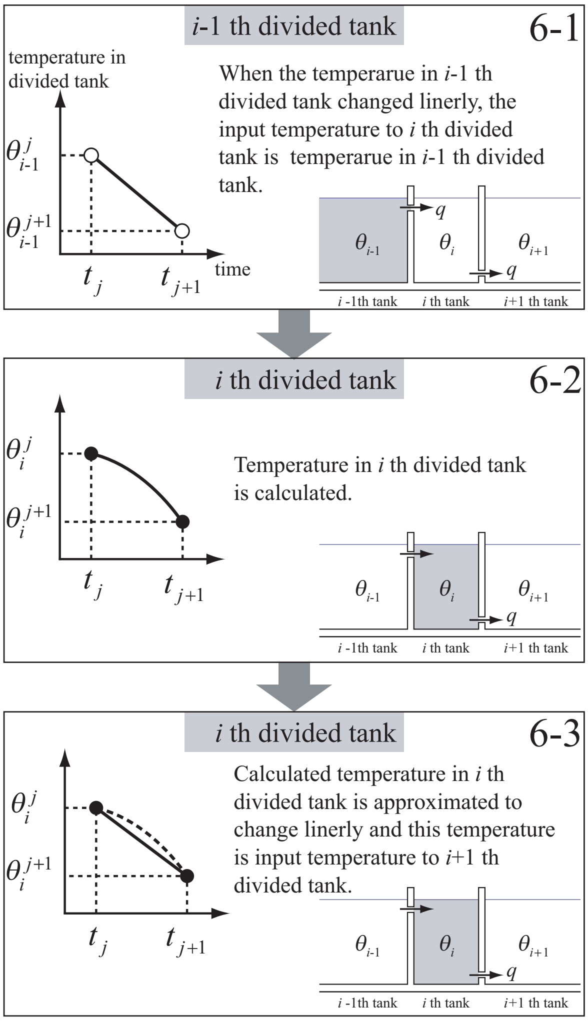


Figure 6 Calculation method of temperature in i+1 th divided tank

RESULTS AND DISCUSSIONS

Results of flow rate estimation under various conditions using temperature data generated by simulation were presented, and the effect of these conditions on accuracy of flow rate estimation was discussed.

Effect of heat gain through tank wall

In this section, flow rate was estimated by using temperature data in all divided tanks at measuring time interval of 1 minute in order to find attention to the effect of heat gain on accuracy of flow rate es-

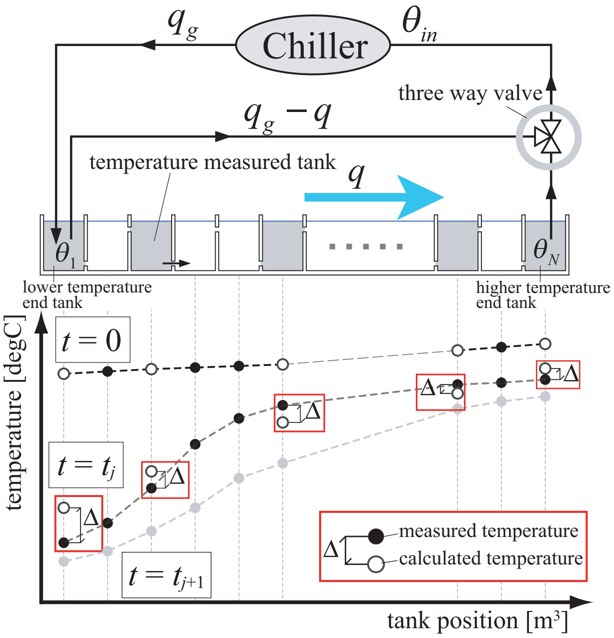


Figure 7 Rlow rate estimation method

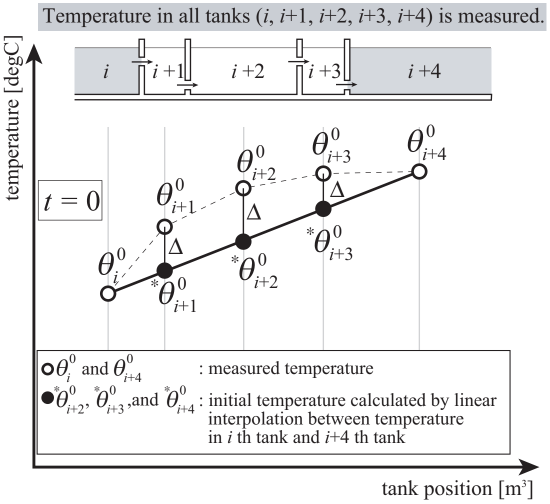


Figure 8 Calculation method of initial temperature error

timation. The generated data are rounded off to one decimal place, two decimal places and three decimal places in order to find the effect of measuring accuracy on the estimation accuracy, because temperature in divided tanks is measured only to one decimal place actually with temperature measuring instruments. Relationship between the normalized flow rate error and the average temperature error is shown in Figure 9. The flow rate is estimated accurately when the data without heat gain are used for flow rate estimation. In contrast, when the data with heat gain is used for, the flow rate in a chiller is estimated as 5% lower. In addition, the number of digits after decimal point of temperature data for estimation have small effect on accuracy of flow rate estimation as shown in Figure 9.

Effect of measuring time interval

Flow rate was estimated by using data generated at the time interval of 1, 5, 10, 30 and 60 minutes with instrument accuracy to 1, 2 and 3 decimal places. Relationship between the normalized flow rate error and the average temperature error is shown in Figure 10, which shows that measuring time interval have pretty small effect on accuracy of estimation. In the below discussion, the data at the time interval of 60 minutes were used for estimation.

Effect of the number of divided tanks

Table 2 shows the number of divided tanks and tank number, in which temperature is assumed to be measured for flow rate estimation (Tank No.1 and Tank No.26 are skipped because these are used in all conditions). For example, Figure 11 shows the transitional change of temperature profiles calculated from temperature data in tanks of No.1, 3, 5, 7, 9 and 26. Actually, temperature in divided tanks is measured only to one decimal place. Corresponding to this actual condition, temperature data used for flow rate estimation are given to one decimal place from simulation results with heat gain. Relationship between the normalized flow rate error and the average temperature error is shown in Figure 12(1), relationship between the normalized flow rate error and the initial temperature error is shown in Figure 12(2), and relationship between the average temperature error and the initial temperature error is shown in Figure 12(3). As shown in Figure 12(1) and (2), accuracy of estimation becomes better as the number of divided tanks used for estimation increases and the average temperature error reduces. And, in case of large error in the initial temperature, the error in estimated flow rate becomes large in spite of small error in the average error. As shown in Figure 12(2), accuracy of estimation becomes better as the initial temperature error

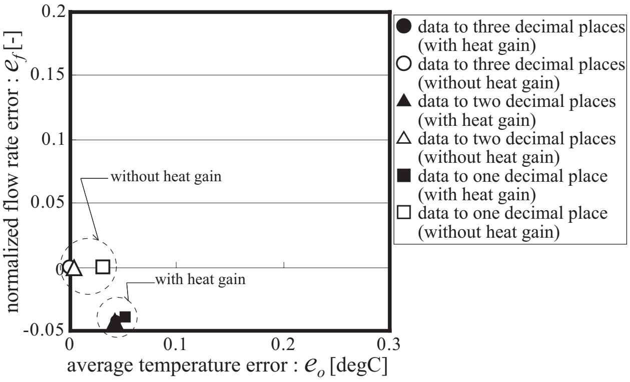


Figure 9 Relationship between average temperature error and normalized flow rate error with/without heat gain

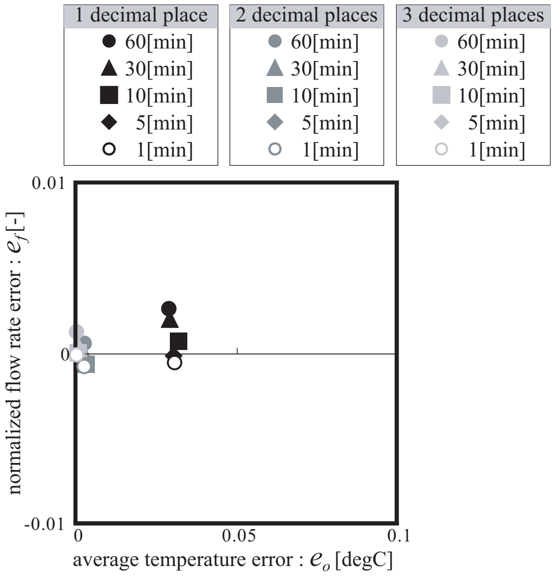


Figure 10 Relationship between average temperature error and normalized flow rate error without heat gain

Table 2 The number of divided tanks and tank number for flow rate estimation

Number of tanks	3	4	6	8	13	18	20	22	26
Number of estimation cases	5 cases	5 cases	4 cases	3 cases	4 cases	3 cases	1 case	1 case	1 case
Tank No. used for estimation	3	5,8	3,5,7,9	3,7,9,15,17,19	3,5,7,9,11,13,15 17,19,21,23,25	2,3,4,5,6,7,8,9,10 11,12,13,14,15,16,17	without 5,9,13,17,21,25	without 3,9,15,2	all tanks
	7	8,18	15,17,19,21	3,6,9,11,13,15	2,3,4,5,6,7 8,9,10,11,12	10,11,12,13,14,15,16,17 18,19,20,21,22,23,24,25	-	-	-
	13	3,5	4,7,15,20	13,15,17,19,20,24	15,16,17,18,19,20 21,22,23,24,25	2,3,5,7,9,10,11,13,14 15,18,19,21,22,23,25	-	-	-
	18	16,20	3,5,19,21	-	-	-	-	-	-
	22	8,15	-	-	-	-	-	-	-

reduces. Judging from above, the initial temperature profile is important to estimate flow rate accurately.

As shown in Figure 12(3), flow rate in a chiller is estimated accurately in most cases as the initial temperature error and the average temperature error are small. In Figure 12(3), some results have small error in the average temperature in spite of large error in the initial temperature. This is because the change of temperature in divided tanks used for estimation is small, and the difference between measured and calculated temperatures in these tanks is small relatively. As a typical example, Figure 13 shows the change of temperature estimated by using three tanks in which temperature has been unchanging so largely in tank No.1 and 3.

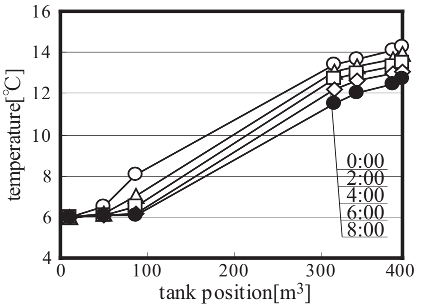
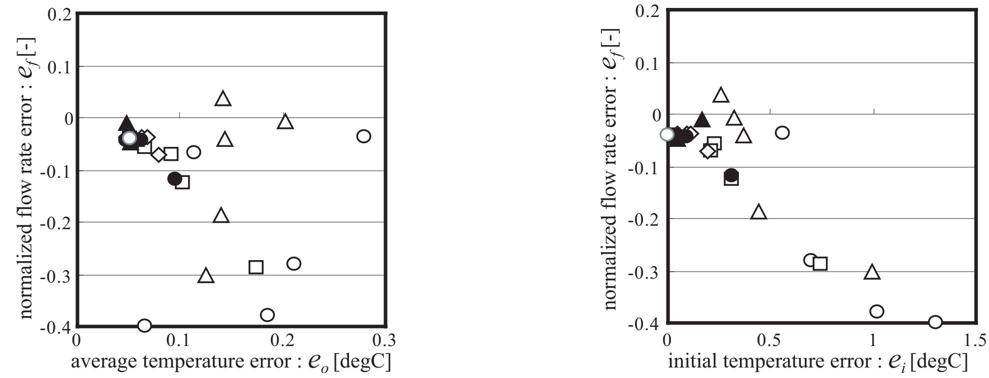


Figure 11 Temperature profiles (tank No.1,3,5,7,9,26)

In this system, flow rate in a chiller is estimated within about 10% error in case that the number of measured tanks used for estimation are more than 8 tanks.

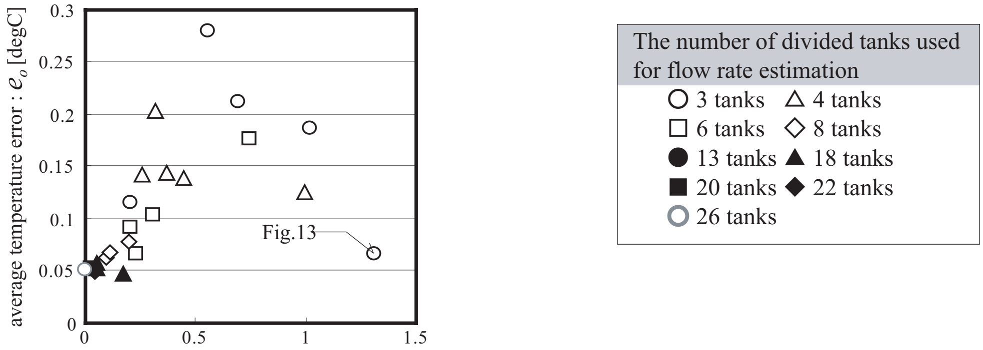
CONCLUSION

In this paper, flow rate in a chiller is estimated by using the data generated by simulation of the multi-connected complete mixing tank, and the effect of various conditions on the accuracy of flow rate estimation is discussed. The number of digits after decimal point of temperature data for estimation and measuring time interval have small effect on accuracy of flow rate estimation. The estimated flow rate used by the temperature data with heat gain is estimated as 5% lower than that without heat gain. Flow rate in a chiller is estimated within about 10% error in case that the number of measured tanks used for estimation are more than 8 tanks.



(1) Relationship between average temperature error and normalized flow rate error

(2) Relationship between initial temperature error and normalized flow rate error



(3) Relationship between initial temperature error and average temperature error

Figure 12 Results of flow rate estimation

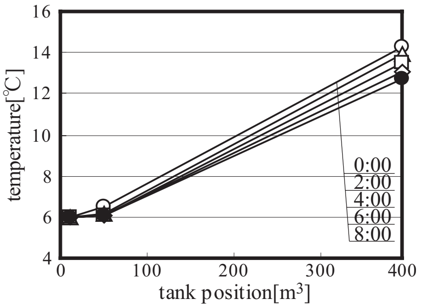


Figure 13 Temperature profiles (tank No.1,3,26)

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SYMBOL LIST

h : heat gain through tank wall [J/m^2]
A : area of tank wall [m^2]
q_g : flow rate in chiller (constant) [m^3/h]
q_g^*: flow rate in chiller for simulation (constant) [m^3/h]
q_a : flow rate in air-conditioning system [m^3/h]
q : flow rate in thermal energy storage tank [m^3/h]
θ^* : measured temperature in divided tank [degC]
$^*\theta$: calculated initial temperature in divided tank [degC]
V : volume of divided tank [m^3]
C_p: specific heat of water [J/kg K]
ρ : water density [kg/m^3]
n : the number of divided tanks [-]
m : the number of calculation steps [-]
i : tank number [-]
j : time step number [-]
k : wall number in divided tank [-]

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