DYNAMIC SIMULATION OF NEW CENTRAL HOT WATER SUPPLY SYSTEM FOR RESIDENTIAL BUILDING

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ABSTRACT In order for economically viable distributed generation systems to spread to residential buildings, it is essential to develop an efficient and low-cost hot water supply system. A new hot water supply system had been proposed for this purpose. The key technology for the system is to connect compact heat storage units installed in each household by a single loop of hot water piping. A prototype plastic tank for heat storage was made and tested in heat storage and heat release operation. Since the cross section area of the tank is small, thermal stratification could be kept in heat release process. On the other hand, in heat storage process, water in the tank was perfectly mixed by incoming hot water flow from the bottom of the tank. Dynamic simulation model of the system for 50 households was constructed on a process simulator using a heat storage tank model, and heat supplying performance was evaluated from the calculated results for heat demand patterns obtained by a field research.

Keywords: Household cogeneration system, Heat storage, Single-loop hot water supply, Heat load leveling

1. INTRODUCTION

Household cogeneration systems using a gas engine with a power output of 1 to 25 kW are commercialized in Japan. However, its power generation efficiency is as low as 22.5 to 33 % based on lower heating value. In addition, hourly and seasonal heat demand fluctuation may be extremely large compared with power demand fluctuation for ordinary families due to its high output and brief using. On the other hand, since there is a trend toward nuclear families, heat and power demand for each household will decrease. Therefore, it is necessary for spreading household cogeneration system to develop an energy supply system for residential buildings and apartments. It is essential to develop an efficient and low-cost hot water supply system.

We have been studying a cogeneration system for local communities with generators of several ten to several hundred kW, in which residents can share the power and heat from the generators. This system brings in some advantages. Those are that high efficiency and large capacity engine can be applied, and that intermittent heat demand of each household is expected to become continuous one as the total heat demand. However, the system required simple heat supply system that can reduce heat loss in delivering.

For realizing the system, a new heat supply system, in which distributed compact heat storage units in each household are connected with a single loop of hot water piping, is invented, and some evaluation results on the system performance and some kind of compact heat storage unit had been presented in the previous ICOPE [1, 2, 3].

In this study, a prototype of plastic heat storage tank was made and tested in heat storage and release operation. We also conducted a dynamic simulation of the new heat

supply system for 50 households to evaluate the effectiveness of distributed heat storage in leveling heat transfer rate via the main loop. The effect of the size of heat storage unit was also examined.

2. SINGLE LOOP HEAT SUPPLY SYSTEM

2.1 System Structure

The existing hot water supply system for residential building is shown in Fig. 1(a). The system is called HEATS (housing heating total system). Hot water is constantly circulated at a certain flow rate to fill the customer's heat demand. Since each household receives heat through a plate heat exchanger, hot water temperature will decrease by heat demand and the decrease in temperature may directly lead to decline of heat supply ability using heat exchanger of downstream household. So, HEATS needs high heat capacity flow rate to keep temperature. Usually, three-inch diameter and ladder structured insulated pipelines are used for 50 households.

Figure 1(b) shows a schematic of the proposed heat supply system. In the system, a small heat storage unit is placed in each household for brief using, such as taking a shower and bath water supply, and the heat storage units are connected by a one-inch single-loop pipe. Since brief using can be covered by the heat storage, heat supply rate via the main loop can be reduced. If the pipe diameter and length for heat supply can be reduced to a third and half compared with the HEATS, respectively, the pump power and heat loss from the pipe can be reduced to approximately 1/9 and 1/6, respectively. The proposed system might have a great advantage in operating cost and pipe equipment cost over the HEATS.

2.2 Heat Supply Unit

A schematic diagram of the heat supply unit in each household is shown in Fig. 2. The unit consists of 93 liter hot water heat storage tank, three plate heat exchangers, pumps, valves, and the other control devices. The unit has 5 modes in operation. The first is heat storing from the main loop to the tank, the second is room heating by hot water circulation from the heat storage tank, the third is hot water supply directly from the main loop or indirectly via a heat exchanger, and the last is bath heating by stored heat using a heat exchanger.

3. PERFORMANCE TEST OF HEAT STORAGE TANK

3.1 Experimental Set-up and Specifications of Heat Storage Tank

A heat storage tank designed for the heat supply unit is shown in Fig.3. Since water in the tank can be used under atmospheric pressure, plastic rectangular tank can be applied. The volume is 93 liter. Water temperature distribution was measured by thermo-couples at the middle in thickness of the indicated point in Fig.3. Sheathed thermo-couple of 0.5 mm O.D. was inserted into a SUS tube of 0.9 mm I.D. and 0.18 mm thickness to set measure point accurately.

Distributor of water inlet was made from copper tube, and was inserted horizontally into the bottom of the tank. Water was injected to the bottom of the tank from in-line holes drilled on the tube wall. Holes position was determined for uniform flow distribution not to disturb thermal stratification. The tank was insulated by grass wool. Void at the top of the tank is for volumetric change due to thermal expansion.

3.2 Test Condition

Temperature distribution in the heat storage tank and change of discharge water temperature were measured in the following operation mode. From the result, the relation between discharge temperature and heat storage amount was evaluated.

(a) Case 1 (Heat storage operation)

At the initial condition, water temperature in the tank was uniform at 18°C. Then, hot water at 75°C was supplied with a constant flow rate. Flow rate was varied in 1, 2, 4, 6, 8, 10 l/min.

(b) Case 2 (Heat release operation)

At the initial condition, water temperature in the tank was uniform at 75°C. Then, cold water at 13°C was supplied with a constant flow rate. Flow rate was varied in 1, 2, 4, 6, 8, 10 l/min.

(c) Case 3 (Heat release operation with moderate return temperature)

At the initial condition, thermal stratification existed. Temperature of the upper layer and lower layer was 70°C and 13°C, respectively. Then, hot water at 49 °C was supplied with a constant flow rate of 1 l/min. This case simulates room heating operation.

3.3 Test Results and Discussion

Test results for Case 1 and Case 2 are shown in Fig. 4(a) and (b), respectively. Water flow rate was 10 l/min. Time variation of vertical temperature distribution of water in the tank is shown in grayscale. Though temperature was

Fig.1 Heat supply system for household building.

Fig.2 Heat supply unit with heat storage in each house.

measured at two points on the same level as shown in Fig. 3, no difference was observed between two temperatures during the measurements. In heat storage operation (see Fig. 4(a)), water temperature distribution kept uniform, and gradually rose. Water in the tank might be well mixed by natural convection caused by temperature difference between tank water and supplied water.

Fig.3 Heat storage tank

In heat release operation (see Fig. 4(b)), high and low temperature area was clearly separated, and temperature was uniform in each area. Thermal stratification was clearly observed. The stepwise moving of boundary is due to the discrete temperature measure points. It was shown from the clear steps that water mixing by upper flow was weak.

Heat storage fraction is plotted against discharge temperature for several water flow rates in Fig.5. In heat storage process, heat storage fraction increased in direct proportion to discharge temperature. It can be said that heat storage amount can be known from discharge temperature in heat storage process. In heat release process, discharge

(a) Heat storage operation (water flow rate 10 l/min)

(b) Heat release operation (water flow rate 10 l/min)

Fig.4 Time variation of vertical water temperature distribution.

Fig.5 Relationship between heat storage fraction and discharge temperature.

temperature was kept around the highest temperature until heat storage fraction decreased to about 20 %. The results show high performance for heat supply. The effect of water flow rate was a little.

Experimental results for Case 3 simulating room heating operation are shown in Fig. 6 (a) and (b). At the initial condition, thermal stratification existed around 59.3 cm in height. High temperature layer was not disturbed by inflow, and discharge temperature was kept high. Low temperature layer was mixed by natural convection, because incoming temperature was higher than water temperature in the lower layer. Relation between discharge temperature and heat storage fraction is shown in Fig. 6 (b). Since the return temperature to heat storage unit was higher than that for Case 2 with 1 l/min of water flow rate, used heat amount with around 70°C of discharge temperature decreased from 80 % to 65 %. Since the lower layer was mixed with return water, discharge temperature characteristic became the same as Case 2 in heat storage process after discharging hot water in the higher layer. In order to increase heat utilization ratio of heat storage, return temperature should be made lower.

4. MODELING FOR DYNAMIC SIMULATOR

4.1 Modeling of the Heat Storage Tank

A simulation model for the heat storage tank according to the experimental results shown in the chapter 3 was applied to a process simulator. Since horizontal temperature distribution was uniform, one-dimensional temperature distribution was simulated. The model configuration on the process simulator is shown in Fig.7. Pipe units were used as cross-sectional elements of heat storage tank. Thermal stratification in heat release operation was simulated by increasing the number of sections in pipe unit. The unit was divided into 50 sections. On the other

(a) Water temperature distribution.

(b) Relationship between heat storage fraction and discharge temperature.

Fig.6 Heat storage characteristic in heat release operation with moderate return temperature.

hand, completely mixing in heat storage operation was simulated by increasing water flow rate through the tank. A virtual bypass line (component (d) in Fig. 7) was placed, and high flow rate of 200 l/min was set in the case that the inlet temperature was higher than the discharge temperature. A pipe unit on the simulator takes volumetric change due to temperature change into account, and volume of the pipe unit is constant. Therefore, a junction (component (c) in Fig. 7) was used to make discharge flow rate equal to incoming flow rate. Heat loss was not considered.

Calculated result for Case 2 with 1 l/min of water flow rate was compared with the experimental result in Fig.8. Relation between discharge temperature and heat storage amount are shown. It was shown that both mixing in heat storage operation and discharge temperature in heat release operation were simulated well by the dynamic simulation.

4.2 Heat Load Pattern

Actual measured data of heat demand was used for the dynamic simulation. One-day demand pattern is shown in Fig.9. Heat demand is classified into hot water supply, room heating, and bath water heating. The data is for 50 households on January in Japan monitored by Osaka Gas, Co. Ltd. In that season, tap water is generally as cold as 2°C from 8°C. Therefore, the demand might be the highest heat load of the year. Total demand of 50 households is plotted in Fig. 9 (a) for each using. Time change of the total demand in each household is shown in Fig. 9(b). Each using is high output in short period, and is seen as black dots in the figure. It can be seen that heat demand concentrates in the evening from 20:00 to 23:00, reaches a peak at 21:00, and is mainly used as hot water supply during the duration.

4.3 Model of Heat Supply Unit in Each Household

Dynamic simulation model for the heat supply unit in each household is shown in Fig. 10. Heat exchangers for hot water supply, room heating, and bath water heating were simulated by cooler. Heat transfer amount corresponding to heat demand was removed from the coolers. Heat storage could be performed by a heat exchanger whose heat transfer conductance was set to 1.333 K/kW. The value is based on performance of a plate heat exchanger used in verification test by Osaka Gas. Fifty heat supply units were interconnected by a single loop, and heat supply performance for heat demand pattern in Fig. 9 was evaluated by dynamic simulation. Time step of calculation was 0.1 second. Initial condition of heat storage water was in thermal equilibrium at 5 °C. The detail of the calculation condition will be explained in the next section.

Fig.10 Simulation model of the heat supply unit

4.3 Standard Control Condition

Standard means not to set a limit in heat storage management. *Standard* control conditions are as follows.

Hot water supply to the heat supply system The inlet

Fig.7 Dynamic simulation model of heat storage tank.

Fig.8 Comparison of calculated result with experimental result.

(a) Total heat demand of 50 households.

(b) Distribution map of total amount of heat demand for each household.

Fig. 9 Heat load pattern.

temperature from a heat source to the heat supply system, $T_{\text{supply}} [^{\circ}\text{C}]$, was set to a constant value of 80°C. The flow rate was controlled corresponding to heat supply amount via the main loop. That is to say, the flow rate was controlled to avoid that the return water temperature to the heat source, $T_{\text{m, return}} [^{\circ}\text{C}]$, becomes lower than 50°C to be able to supply heat in bath water heating and room heating. The upper limit of flow rate was set to 120 l/min. Calculation way for supply flow rate is shown in the following expression.

$$F_i = F_{\text{std}} + \delta F_t + \delta F_f \quad (1)$$

$$\begin{cases} \delta F_t = (65 - T_{\text{return}}) & (T_{\text{return}} > 65^{\circ}\text{C}) \\ \delta F_t = 0 & (60^{\circ}\text{C} \leq T_{\text{return}} \leq 65^{\circ}\text{C}) \\ \delta F_t = (65 - T_{\text{return}}) \cdot 2 & (T_{\text{return}} < 60^{\circ}\text{C}) \end{cases}$$

$$\delta F_f = (F_{\text{supply}} - F_{\text{return}}) / 1.5$$

where F_{std} [l/min] is a standard flow rate, and was set to 60 l/min in this calculation. The value of δF_t [l/min] is change in flow rate corresponding to the return temperature, and the value of δF_r [l/min] is change corresponding to flow rate difference between the supply and return.

Heat storage operation

Heat storage operation was limited in a period when each household has no heat demand, and discharge water temperature from heat storage tank (indicated in Fig.10 as T_7) is lower than a certain degree, and main loop water temperature (indicated in Fig.10 as T_1) is higher than a certain degree. The maximum heat transfer rate was set to 10 kW not to take up too much heat in upstream households. The maximum flow rate of heat storage water in each heat supply unit was set to 14 l/min. The thresholds in heat storage operation are as follows.

<1st to 16th household>

Condition to start: $T_1 \geq 65^\circ\text{C}$ and $T_7 \leq 56^\circ\text{C}$

Condition to stop: $Q \leq 2\text{ kW}$ and $T_7 \geq 61^\circ\text{C}$

<17th to 33rd household>

Condition to start: $T_1 \geq 62^\circ\text{C}$ and $T_7 \leq 56^\circ\text{C}$

Condition to stop: $Q \leq 2\text{ kW}$ and $T_7 \geq 61^\circ\text{C}$

<34th to 50th household>

Condition to start: $T_1 \geq 60^\circ\text{C}$ and $T_7 \leq 56^\circ\text{C}$

Condition to stop: $Q \leq 2\text{ kW}$ and $T_7 \geq 62^\circ\text{C}$

where Q [kW] is the heat transfer rate of the heat exchanger for heat storage.

Heat supply Three kinds of heat supply were simulated by using cooler unit instead of heat exchangers. Heat demand was supplied from the flow of heat storage hot water. Flow rate to the cooler was controlled for an appropriate outlet temperature as follows.

For hot-water supply, heat transfer rate of the heat exchanger was estimated from a table based on experimental results. The used heat exchanger has a heat transfer conductance of 0.4 K/kW. Tap water and hot water supply temperature is 5°C and 43°C , respectively. Circulation flow rate of heat storage water is controlled to meet a demand of heat transfer rate. However, if circulation flow rate comes to the upper limit of 14 l/min and heat transfer rate is still in short supply, shortfalls are supplied by direct hot water supply from the main loop. On the other hand, when there is a heat demand for bath water heating, all of hot water demand is covered by direct supply.

For bath water heating, circulation flow rate of heat storage water was maintained at 14 l/min. For room heating, circulation flow rate was controlled to set the return temperature from room heater to 25°C .

Bypass line of heat storage tank The bypass line was used when discharge temperature of the tank (T_7) became below 50°C , because heat load of the main loop became larger due to heat storage.

Fig.11 Calculated results for standard condition of heat storage operation.

5. CALCULATION RESULTS FOR 50 HOUSEHOLDS

5.1 Result of the standard condition

Calculation result for two days operation based on the *standard* control is shown in Fig.11. Time change of total heat demand, total heat supply from the main loop, total amount of heat release/storage rate from/to distributed heat storage, and heat supply rate by direct hot water supply from the main loop are shown. Heat release/storage rate was calculated as the difference between heat demand and heat supply from the main loop for each household. The initial condition of heat storage units is in thermal equilibrium at tap water temperature of 5°C . Since these daily fluctuations were almost the same after the second day, result for the second day is considered. In evening, stored heat is used for increasing heat demand. However, heat storage amount of some households might become empty before the time with the peak of total heat demand (8pm to 9pm), then heat storage operation starts in the time with high heat demand. The maximum heat supply amount was 213 kW and was about 18% lower than the maximum heat demand. It cannot be said that heat storage is effective to decrease the maximum heat supply amount via the main flow. Since it was shown that heat storage operation affected on an increase in heat consumption during the peak period, restrictive period on heat storage operation was set.

5.2 Advanced Heat Storage Management

Three kinds of restrictive period as shown in follows were set.

I-Heat storing period

When there is no heat demand, each household can start heat storage operation with 1 kW heat transfer rate in this period. If they have hot-water demand, hot water should be supplied by direct supply from the main loop to keep heat storage. If they have room-heating demand, heat transfer rate is increased to 5 kW including room-heating demand. If they have bath water heating demand, bypass line is used, and heat storage operation is paused. This period was applied to 11:00~17:00 for odd number households and 11:30~17:30 for even number ones to avoid intensive use in the beginning of the period.

II-Heat storage keeping period

To keep heat storage for heat supply during the peak period, heat storage keeping period was applied to 17:00~19:00 for odd number households and 17:30~19:30 for even number ones. In this case, the bypass line is used in supplying heat for room heating or bath water heating. Direct hot water supply is utilized for hot-water demand.

III-No heat storing period

Since heat storage operation increase total heat

supply via the main loop, no heat storing period was applied to around the peak period in the evening, 19:00~23:30 for odd number households, 19:30~24:00 for even number ones.

5.3 Results for the Advanced Heat Storage Management

Calculation result of the second day is shown in Fig.12. Heat demand, heat supply amount, usage of heat storage, and direct supply amount are shown in Fig. (a). Mean temperature of heat storage in each house is shown in Fig. (b). Temperature is shown in grayscale. Heat flow for heat storage increased in the afternoon, and heat storage for most households became full at 17:30, the end of the heat storing period. The heat storage was kept in the keeping period. Therefore, utilization amount of heat storage became larger during the peak period. It can be said the heat storage management is effective to decrease the maximum rate of total heat supply via the main loop. In this case, the maximum value was 147 kW. It can be reduced by 43%.

It can be seen in Fig. 12(b) that around half the households still keep large heat storage amount in the midnight. Therefore, the calculation was done for smaller heat storage tank with 46 litter. The result is shown in Fig.13 (a), (b). By reducing heat storage capacity, the temperature difference between before and after heat utilization became higher. In this case, the maximum rate of total heat supply via the main loop was almost the same in the case with 93 litter heat storage tank.

6. CONCLUSIONS

A dynamic simulation model of new hot water supply system for a residential building of 50 households had been constructed, and heat supply performance was evaluated. In the system, a compact plastic hot water heat storage tank is placed in each household and hot water is supplied via a single loop of interconnecting pipe. At first, a model of heat storage tank in considering with thermal stratification was constructed. Then, heat supplying performance was evaluated from the calculation results for heat demand patterns obtained by a field research. It was shown in the results that a time restriction on heat storage operation was effective to decrease the heat supply rate via the main loop. The effect is expected to lead to a decrease of pipe diameter and heat loss from the circulating hot water flow.

A verification test on the proposed system had been carried out for 7 households in Osaka Gas's experimental housing *NEXT21*. The tested results will be presented by Mr. Morita, et al. in the other paper of ICOPE-09.

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(a) Total heat balance in heat supply system.

(b) Mean temperature of heat storage in each house.

Fig. 12 Case with limitation in heat storage operation.
(heat storage capacity 93 litter)

(a) Total heat balance in heat supply system.

(b) Mean temperature of heat storage in each house.

Fig. 13 Effect of heat storage capacity reduction
(heat storage capacity 46 litter)