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Evaluating the Energy Consumption and Heat Loss in the Hot Water Supply and Heating Systems of a Nursing Home

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ABSTRACT

The demand for nursing homes has increased recently due to an increase in the aging population in Japan. Nursing homes are generally equipped with hot water supply and heating systems for bathing, preparing meals, and heating rooms. This equipment utilizes a considerable amount of energy. Few studies have measured heat loss from the hot water supply and heating systems in such facilities. This study evaluated the hot water supply and heating systems of a nursing home located in a cold climate area in Japan.

The temperature and flow rate of the hot water were continuously measured, and the energy consumption and heat loss for each subsystem were calculated. These results clarified that the energy consumption in the hot water supply subsystem was slightly larger than that in heating subsystem. Inefficiencies of the system were also continuously evaluated throughout the study. Heat losses in piping attributed to 38% of the total energy consumed by the hot water supply subsystem. Subsequently, a thermal analysis of the hot water subsystem was performed. The calculated return temperature agreed with the measured return temperatures when the resistance of thermal insulation was decreased by an average of 45%; this result was possibly due to the deterioration of thermal insulation materials or the presence of thermal bridges.

KEYWORDS

Hot water supply, Energy consumption, Heat loss, Nursing home

INTRODUCTION

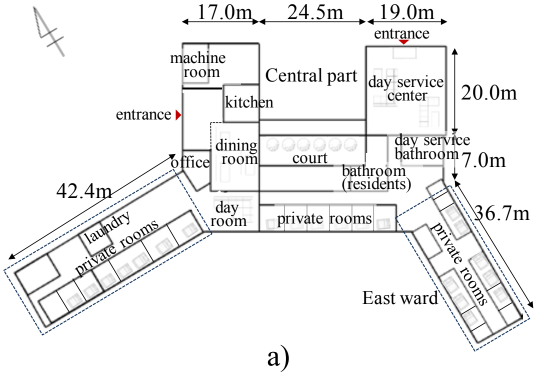
The aging population in Japan reached 26.7% of total population in 2017 and is expected to continue rising, thereby demanding more nursing homes for accommodation (Ministry of Health, Labor and Welfare 2016). These nursing homes consume a significant amount of hot water for bathing and preparing meals, thereby increasing the energy consumption. In addition, heating subsystems that use hot water are popular in cold regions, such as the location of the surveyed facility. While energy conservation in newly constructed buildings is being widely promoted, the importance of commissioning, which is a process to verify that the adopted building system is performing as planned, and energy management for existing buildings has attracted attention. The energy consumed by hot water supply systems accounts for 24%~38% in homes wherein energy consumption is <30 GJ/year (Murakami 2006). However, only a few studies have evaluated the hot water supply systems for nonresidential buildings. Nursing homes, in particular, have not been extensively studied; therefore, energy-saving strategies in such facilities are unavailable. Therefore, a quantitative evaluation of energy usage and heat loss from hot water systems in existing nursing homes will contribute to future energy conservation efforts in nursing homes.

In this study, we measured the temperature and flow rate for each part of the hot water supply and heating systems for a nursing home in Hokkaido, a cold region in Japan, and calculated energy consumption based on the measurements. Furthermore, we identified the cause of heat loss in the hot water subsystems via numerical analysis.

CALCULATION OF ENERGY USED IN SYSTEMS

Methods

The surveyed building is a special nursing home for the elderly with a day service center situated in a cold region wherein the average temperature in the winter falls below 0°C. The building comprises a central part, which includes an office room, a meeting room, a day service room, a machine room and bathrooms, along with western and eastern wards with a total of 29 rooms for residents. Fig. 1 outlines the building.



a)

b)

Scale	One-story/2,903 m^2
Structure	RC
Age of building and system	23 years
Day service center opening hours	Monday–Friday 8: 30 am–5: 15 pm
The number of users	Residents: 60 Day service users: 30
The number of employees	30 people

Fig. 1 Building Outline; a)Plan, b) Specification

Fig. 2 shows the schematic of the hot water supply and heating systems. The hot water is heated by two heavy-oil-fired boilers in the machine room and then used by the three subsystems. The first subsystem named "hot water supply subsystem (HWSS)" supplies hot water to each room. The second subsystem, named "heating subsystem," circulates hot water to all hot water radiators and floor heating equipment throughout the facility. The third subsystem, "bathtub heating subsystem," supplies heat to bathwater via a heat exchanger.

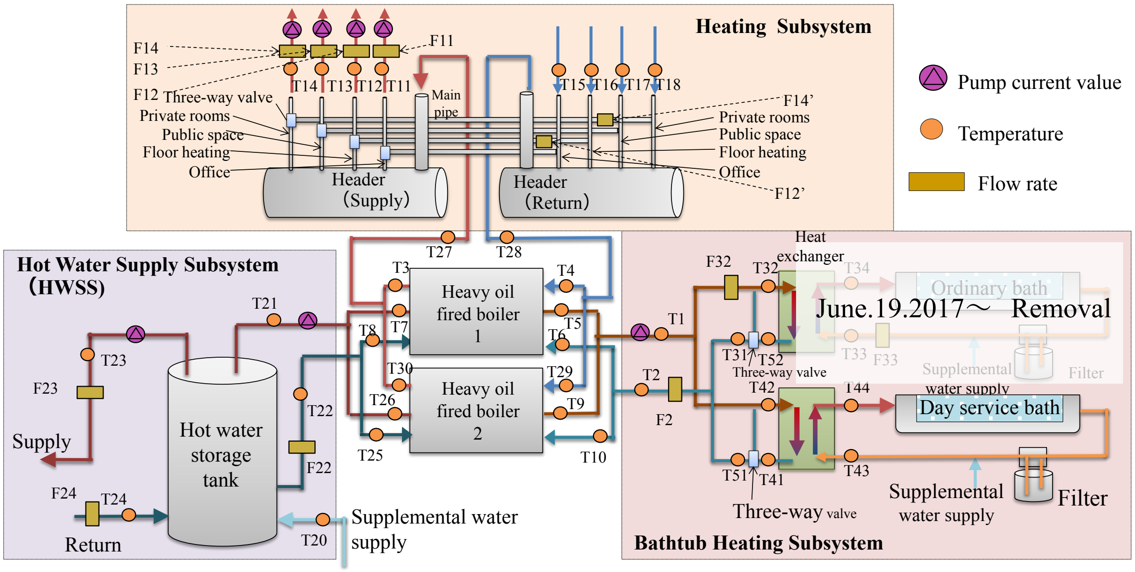


Fig. 2 Schematic of hot water supply and heating systems

Measured items

In this study, the hot water temperature, the flow rate in each subsystem, and the electric current for the pump were measured. The measurement points are shown in Fig. 2. T-type thermocouples were attached to the outer surface of the steel pipe, which was covered by thermal insulation material. The temperatures were mainly measured near the inlet and outlet of each component of the system, such as boilers, the hot water tank, hot water headers, and heat exchangers. The flow rate of the supplied hot water was measured continuously because it was not kept constant. On the other hand, the flow rates in the heating subsystem and bathtub heating subsystem were set to be constant, so measurements taken over a relatively short duration were used to estimate energy consumption. Since the pump was ON/OFF controlled, even in a subsystem with a constant flow rate, we determine the time when the hot water is flowing by the electric current for the pump. The measurements began on September 22, 2016, and the measurement interval was 1 min. The accuracy of T-type thermocouple is ±0.5°C and that of ultrasonic flowmeter is ±1.0% of flow rate. Taking these errors into consideration, the maximum error of heat amount is estimated to be ±13.5%.

Use of heavy oil in each subsystem

Fig. 3 classifies the energy usage in the hot water supply and heating systems. Energy consumption indicated by the thick-lined frame was calculated by equations (1~5) using the measured data. We did not calculate the heat loss caused by the exhaust gas from the boilers or the heat release dissipation from the boiler surface.

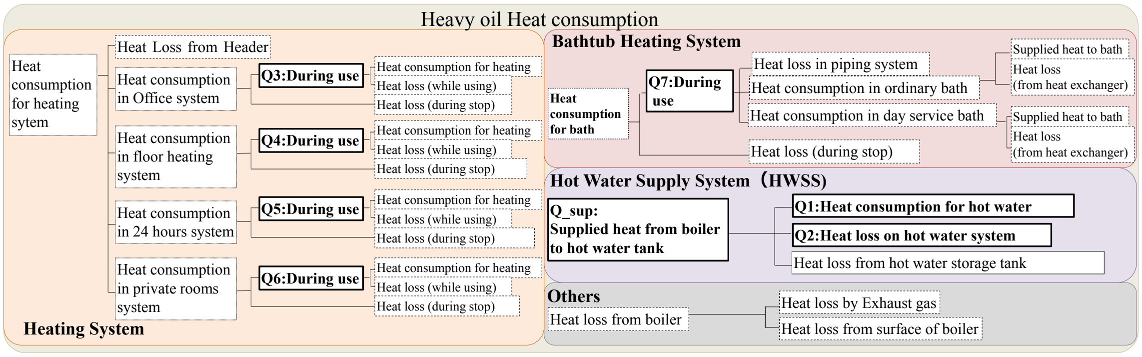


Fig. 3 Classification of energy use in hot water supply and heating systems

$$Q_{sup} = \sum_{1}^{1440}\left(T21(t) - T22(\mathrm{t})\right) \cdot \mathrm{F22\rho c\Delta t}, \tag{1}$$

$$\mathrm{Q1} = \sum_{1}^{1440}\left(T23(t) - T20(\mathrm{t})\right) \cdot \left(\mathrm{F23(t)} - \mathrm{F24(t)}\right)\mathrm{\rho c\Delta t} \tag{2}$$

$$\mathrm{Q2} = \sum_{1}^{1440}(T23(t) - T24(\mathrm{t})) \cdot \mathrm{F24\rho c\Delta t}, \tag{3}$$

$$\mathrm{Q3} = \sum_{1}^{1440}(T11(t) - T16(\mathrm{t})) \cdot \mathrm{F11\rho c\Delta t}, \text{and} \tag{4}$$

$$\mathrm{Q7} = \sum_{1}^{1440}(T1(t) - T2(\mathrm{t})) \cdot \mathrm{F2\rho c\Delta t}. \tag{5}$$

In the HWSS, hot water is temporarily stored in the hot water storage tank (Qsup). Qsup is mainly transferred to the water as heat (Q 1), but some of the supplied heat is lost in the hot water pipes over the whole circulation pathway (Q 2) or from the hot water tank. The heating subsystem is comprised of four branches for office space, public space, private space and floor heating. Heat loss from the pipes occurs during both *on* and *off* operation. From the measured data, the total amount of heat consumed (including losses) during operation for the office space (Q 3) can be calculated. The heat consumption for the other spaces (Q4, Q5, and Q6) are calculated in the same manner as Equation (4). In the bathtub heating subsystem, as with the heating subsystem, the total amount of heat during use (Q 7) can be calculated.

However, since the pumps are frequently *off* in this subsystem, it is necessary to take the heat loss during *off* operation into consideration. "T" and "F" in the equations correspond to those in Fig. 2, Q is the daily heat consumption [MJ/day], ρ is the water density [kg/m^3], c is the specific heat of water [MJ/(kg･K)], and F is the flow rate [m^3/min].Δt is time interval [min].

Results and discussion

Fig. 4 shows the annual heavy oil use every week from Dec 1, 2016 to Dec 31, 2017. The bar graph shows each energy usage. While the energy consumption for the heating subsystem accounts for 17%, the HWSS accounts for 21%. Moreover, Heat losses in piping account for 38% of the energy consumption for the HWSS. The line graph shows the total energy consumption calculated based on heavy oil consumption. The difference between the sum of each energy usage and the total energy consumption can be 61% and is likely related to heat loss from the boilers. In this facility, the ON/OFF of the boiler was found to be very frequent. Every time the boiler is turned ON/OFF, it caused air purging to remove impurities, placing a large load on the boilers. In addition, a high air-fuel ratio of 1.3 or more is set. Heat loss from the boilers must be examined in detail in the future.

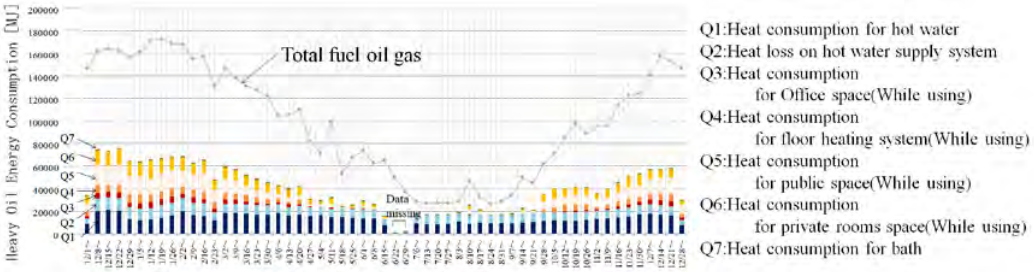


Fig. 4 Use of annual energy consumption of heavy oil in facilities

From Fig. 4, it can be seen that the energy consumption for the HWSS is quite large throughout the year, thus it would be efficient to lower the hot water set temperature. However, since the heat loss is also large, the hot water temperature may drop below a certain level (45~50°C) during the hot water circulation, which may no longer inhibit Legionella bacteria (JAHMEC Guideline 2017).

NUMERICAL ANALYSIS ON PIPING HEAT LOSS

In order to investigate measures to reduce the heat loss from the HWSS, a thermal analysis of the subsystem was conducted, focusing on the performance of the thermal insulation material, the construction situation in situ, and the heat bridge of equipment.

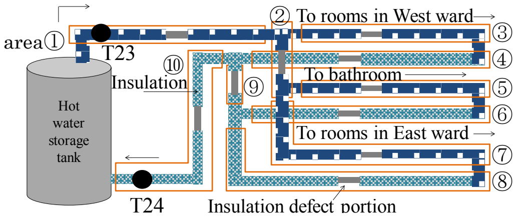
With reference to the equipment drawing of the facility, the HWSS was modeled as shown in Fig. 5. The specifications of the carbon steel piping and the thermal insulating material (fiberglass insulation) are listed in Table 1 and Table 2, referring to JIS G 3452 and JIS A 9504, respectively. The measured temperatures and flow rates used for calculation are listed in Table 3. The temperature just after the hot water tank exit (T23) was used as an input in this calculation. Then the calculated and the measured return temperatures just before entering the hot water storage tank (T24) were compared. The deterioration of the insulation materials and the portion without thermal insulation were considered to be the primary causes of piping heat loss. In this facility, there was no insulation at the holes of the building base and the floor slab through which the pipes run. These uninsulated segments, about 10 cm long each, were found every 5 to 8 m, and the total length was estimated to be 5 m of the 350 m total piping network. These uninsulated segments were taken into consideration in the simulation model. The calculation cases are given in Table 4. The calculation was carried out for 6 hours starting at midnight on December 1st, during which the hot water is circulating at the constant flow rate (98 L / min). The heat balance equation of the hot water in the pipe and the boundary condition between the hot water and the underfloor air are given as follows:

$$C_w \rho_w \frac{\partial T_w}{\partial t} = \frac{\partial}{\partial x}\left(\lambda_w \frac{\partial T_w}{\partial x}\right) - C_w J \frac{\partial T_w}{\partial x}, \tag{6}$$

$$-\lambda_w \frac{\partial T_w}{\partial n} = K_w (T_a - T_w), \tag{7a}$$

$$K_w = \frac{\frac{1}{r_p}}{\left(\frac{\ln\frac{r_i}{r_p}}{\lambda_i} + \frac{1}{r_i h_a}\right)} \ , \tag{7b}$$

where x is the direction of water flow [m], J is the flow rate [kg/(m^2・s)], C is the specific heat [J/(kg・K)], ρ is the density of water [kg/m^3], T is temperature [K], λ is the thermal conductivity [W/(m・K)], h is the heat transfer coefficient [W/(m^2・K)], K$_w$ is the overall heat transfer coefficient [W/(m^2・K)], r=D/2 (D is outer diameter [m]) $\frac{\partial}{\partial n}$ is the normal direction differential on the boundary between the pipe and insulation material, and the subscript w, a, i and p are water, air, insulation and piping, respectively. Equation (7b) refers to Transport Phenomena 2002.



Area	①	②	③	④	⑤	⑥	⑦	⑧	⑨	⑩
Pipe size (NPS)	80A (3)	65A ($2^1/2$)	40A ($1^1/2$)	20A ($^3/4$)	40A ($1^1/2$)	40A ($1^1/2$)	32A ($1^1/4$)	20A ($^3/4$)	40A ($1^1/2$)	40A ($1^1/2$)
Length in area	30m	44m	53m	53m	30m	30m	38m	38m	33m	30m

Fig. 5 Thermal model of the HWSS

Table 1 Specification of piping used for analysis

	80A(3)	65A($2^1/2$)	40A($1^1/2$)	32A($1^1/4$)	20A($^1/4$)
Pipe inner diameter [mm]	80.7	67.9	41.6	35.7	21.6
Lining thickness [mm]	4	3.5	3	3	2.5
Piping thickness [mm]	4.2	4.2	3.5	3.5	2.8
Insulation thickness [mm]	20	20	20	20	20

Table 2 Material properties used for analysis

	Hot water	Piping	Fiberglass	Air
Specific heat [J/(kg・K)]	4186	—	—	—
Density [kg/m^3]	1000	—	—	—
Thermal conductivity [W/(m・K)]	0.59	(pipe)53 (lining)0.17	0.043	—
Heat transfer coefficient [W/(m・K)]	—	—	—	9.3

Table 3 Measured temperature and flow rate used in calculation

Hot water supply temperature	T23 (near the hot water tank)
Underfloor temperature	20°C (constant)
Hot water supply flow rate	98L/min(constant)

Table 4 Computational condition

Case 1	no deterioration of thermal insulation and no insulation defect
Case 2	no deterioration of thermal insulation and 5 m insulation defect
Case 3	45% deterioration of thermal insulation and 5 m insulation defect

Calculation result

Fig. 6 shows the calculated results for the three cases compared with the measured results. In

Case 1, the return temperature of the hot water is 1.0°C lower than the supply temperature, while the measured return temperature decreased by 1.5 to 2.0°C. There is almost no difference in the return temperature between Case 1 and Case 2, although the heat loss at the uninsulated segment is about 2.2 times larger than the normal (insulated) pipe. This is probably because the total length of the uninsulated segments is very short compared to the total length of the hot water pipe. Since the actual length of the uninsulated segments has not been confirmed over the whole crawl space, a detailed check is necessary in the future. In Case 3, the calculated temperature agrees very well with the measured temperature.

One possible reason that the thermal resistance of the insulation may have decreased by 45% on average is that the insulation material was wound up on the pipe too tightly (Masuda 2014). Another possible reason is that heat loss at thermal bridges such as piping flanges and hanging metal hooks may have a significant influence.

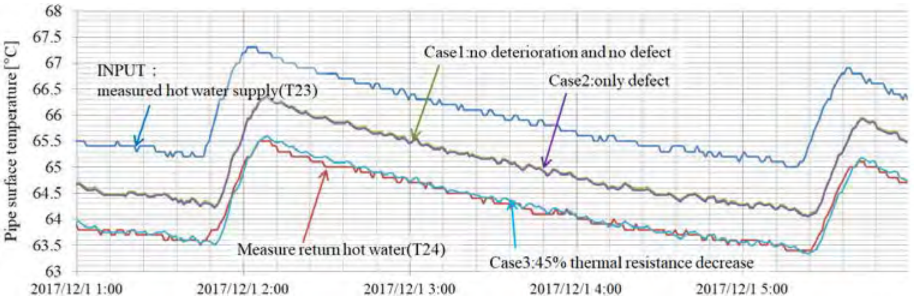


Fig. 6 Comparison of calculated and measured return temperatures of the hot water

CONCLUSION

We surveyed the annual heavy oil consumption in one nursing home, which served as reference data for energy conservation measures and performance verification of other facilities for elderly people. In the case of this considered building, we observed that piping heat loss in the HWSS was significant throughout the year. We investigated reasons for the large heat loss by conducting a thermal analysis and concluded that the heat insulation performance might have decreased by 45% on average. To identify the causes and locations of the heat loss, future work should consider temperature distribution in the underground space through which the hot water pipes run.

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