Evaluation of Heat Loss from Hot Water Supply System and Insulation Retrofit in a Hotel
— Thermal Analysis of the Piping System and Storage Tank —

†Yoshinori MASUDA (Kyoto University)  SHASE Technical Fellow Shuichi HOKOI (Kyoto University)

Synopsis The heat loss from a hot water supply system was measured in a budget hotel in Kansai area, which has large baths for common use on the top floor and a shower in each guest room. It was found that more than 40% of the heat supply was lost. By retrofitting the system, the heat loss was significantly reduced. Visual inspection and numerical calculation using a simple thermal model clarified that thermal bridging and rain penetration were the main reasons for a large heat loss from hot water supply system.

Introduction
Since 30% or more of the total energy is consumed for hot water supply in a hotel\(^1\), it is important to reduce energy consumption for hot water supply. Although heat loss from a long hot water piping and a storage tank may not be negligible, measurements or survey of the heat loss in real buildings are very limited. This paper reports the measured results of the heat loss from a hot water supply system in a budget hotel, and investigates the possible reasons for the heat loss based on simple thermal models\(^2\).

1. Measured hotel and measured results
1.1 Measured hotel
The hotel under study is a business hotel in the Kansai area of Japan with a floor area of 4708 m\(^2\). It has 11 stories with one underground floor for 168 guest rooms. It is made of reinforced concrete with a partial steel structure. The hotel has a restaurant and store with two large baths for common use that are partly exposed to the outside on the top floor.

1.2 Hot water system
Figure 1 shows the schematics of the hotel’s hot water supply system (HWSS). The hot water is produced by six gas furnaces on the roof (heating capacity: 551.4 kW, gas consumption: 45.0 m\(^3\)/h (13 A)), stored in one storage tank (volume: 4454 L, dimensions: 1400 mm diameter × 2500 mm length), and then sent to the large common-use baths and guest rooms, as well as a cooking room and staff rooms. The unused water returns to the storage tank. Running water is supplied to the tank. When the water temperature drops below 65 °C, the water is sent from the lower part of the tank to the gas furnace and heated before returning to the upper part of the tank.

The guest rooms have no bathtub. Since the common-use baths are supplied with hot water from a separate hot water supply system, it was not measured in the present study.

1.3 Measurement of water temperature and flow rate and inspection of thermal bridge by thermograph
The measured temperatures showed that both the outlet and inlet temperatures of the boiler, T7 and T10, decreased significantly after the operation of the boiler.

Figure 1 Hot water supply system

The difference between the inlet and exit temperatures of the vertical pipeline, T3 (eleventh floor) and T4 (second floor) was 2-3°C. Since such a large temperature drop occurred during the flow from the eleventh floor to the second floor, the heat loss was not negligible. Thus the infrared radiation temperature was measured around the storage tank on the roof and at several points in the pipe shafts. The surface temperatures of the hot water pipe in the pipe shaft on the eleventh floor were more than 10 °C higher than the air temperature despite the insulation. The supporting legs of the storage tank on the roof floor showed an area with high temperature. As the outdoor temperature decreased, the amount of outgoing heat could become significant despite the surface area not being very large.
2. Insulation retrofit for reducing heat loss
2.1 Retrofit of storage tank
Since the heat loss from the storage tank and the connecting parts between the tank and the legs seems significant, the entire leg was covered by 50 mm thick glass wool insulation and finished by Galvalume plates. The heat loss was decreased from 590 MJ/day before the retrofit to 340 MJ/day afterward.

2.2 Insulation retrofit of hot water pipes
(1) Replaced insulation around hot water pipe
The retrofit to the hot water pipes replaced 25 mm glass wool insulation with pipe covers made of 20 mm thick expanded insulation. The retrofit was done for one pipeline from the eleventh floor to the second floor. The heat loss of the retrofitted line decreased from 60 MJ/day before the retrofit to 50 MJ/day afterward. (Fig. 2)

(2) Change of wrapping way of existing insulation
The outline of the retrofit is shown in Figure 3. The way of wrapping for the vertical line 5-6 was changed. The glass-wool layer was loosely tied round the pipe without overlaying. The glass-wool layer was loosely covered and fixed by a metal net (retrofitted on 23 and 24 October, 2013). Furthermore, the aluminum craft cover was not turned up in order not to contact directly with the pipe. The heat loss of the retrofitted line 5-6 decreased by 5 MJ/day after the retrofit (Fig. 4).

3. Analysis of heat loss from storage tank
The temperature distribution around the storage tank and heat loss from the tank were analyzed by a simple thermal model.

![Figure-2 Heat loss from hot water piping [2012.9.24–10.10]](image)

![Figure-3 Change of wrapping way of existing insulation](image)

![Figure-4 Heat loss from hot water piping [2013.10.13–11.2]](image)

3.1 Heat balance of storage tank (3-dimensional cylindrical model)
Since the storage tank was almost cylindrical lying horizontally, it was modelled as a cylinder (Fig. 5).

\[
\rho u \frac{\partial T}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left( r \lambda \frac{\partial T}{\partial r} \right) + \frac{1}{\partial \theta} \left( \lambda_\theta \frac{\partial T}{\partial \theta} \right) + \frac{1}{\partial z} \left( \lambda_z \frac{\partial T}{\partial z} \right)
\]

where, \( r, \theta, \) and \( z \) are radial, circumferential, and axial directions, respectively.

In numerical calculations, circumferential (\( \theta \)) direction was uniformly divided into 12 increments, and axial (\( z \)) direction was divided into 10 increments with 0.3 [m] width. In the radial (\( r \)) direction, 24 non-uniform increments were used depending on the material. The measured values of \( T_{24} \) and \( T_{12} \) (average values) were used as the center temperature of the tank, and the outdoor and boundary temperatures of the legs, respectively.

Figure 6 shows the calculated temperature distribution at the steady state after the retrofit of the leg portions. At the upper part of the tank (8th node of \( j8 \) section: 63.3°C), the calculated temperature agrees well with the measured value of \( T_{26} \) (62.8°C), but the calculated result at the lower part (8th node of \( j2 \) section: 62.2°C) is higher than the measured. The temperature at the leg portion (25th node of \( j1 \) section: 55.1°C) is slightly higher than the measured value of \( T_{32} \) (50.2°C). The calculated heat loss from the whole storage tank 100.4 [MJ/day] does not agree with the measured result 284 [MJ/day] (October, 2013).

![Figure-5 3-dimensional cylindrical thermal model of storage tank](image)
3.2 A larger thermal conductivity value of insulation

When a thermal conductivity 5 times larger than the design value in section 3.1 is used, the calculated heat loss becomes 250.6 [MJ/day], and thus the agreement with the measured result is very improved.

The insulation of the storage tank was specified as follows; 80K-50mm rock-wool insulation board fixed by steel net, over which Galvalume plate, and then finished by sealing.

In November, 2013, the real situation was checked by visual inspection. Figure 7 shows the insulation of the manhole when the cover was removed. The color of the insulation has been changed from the original yellow, and the water ran down when the cover was removed for inspection. The rainwater on the day before the inspection seems to have penetrated.

The analysis where the thermal conductivity value 5 times larger than the design value, 0.18 [W/mK], is used seems not unreasonable, considering the degradation of insulation performance caused by rain water penetration.

Similar absorbed water was observed in the insulation of the connecting pipe with the gas boiler. In addition to the rainwater, thermography confirmed that the supporting metals, metal suspension fittings, and a name plate worked as thermal bridges. These also seem to give an influence on the heat loss.

4. Analysis of heat loss from piping system

4.1 Two-dimensional cylindrical heat balance model

Based on a simplified thermal model of a vertical hot water pipe (in a pipe shaft) for one floor, the heat loss from the piping system is calculated. A proposed model is shown in Figure 8. The temperatures of the pipe, insulation, floor slab are calculated by Equation (2), while the hot water temperature in the pipe is given by Equation (3).

\[
\frac{\partial T}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial T}{\partial r} \right) + \frac{\partial^2 T}{\partial z^2}
\]

(2)

\[
\frac{\partial T_{\text{w}}}{\partial t} = \frac{D}{2} \frac{\partial^2 T_{\text{w}}}{\partial z^2} + \frac{D}{2} v \frac{\partial T_{\text{w}}}{\partial z}
\]

(3)

where, \( r \) and \( z \) are radial and axial directions, respectively. A symmetric distribution is assumed in the circumferential direction (no heat flow).

The left figure of Figure 8 schematically shows the several fittings attached to the hot water pipe. On both the uppermost (11th floor) and the lowest floors, there are a bulb, a set of flange connection (two plates), two supporting metal fittings. The floor slab is also in contact with the pipe. On a standard floor, only a supporting fitting and the slab contact the pipe. The model consists of hot water, steel pipe, glass-wool, aluminum craft paper, and air, in order from the center to the outside of the hot water pipe.

These were modelled by a cylinder, while bulb, flange fittings, and supporting metal were replaced by a thermal bridge similar to the flange. The radius was assumed as uniform within one floor, and either nominal diameter 40A or 25A was selected on each floor.

In numerical calculations, the radial (r) direction was divided into 15 non-uniform increments, depending on the material. In the axial (z) direction, a floor height (3010 [mm]) was uniformly divided into 60 increments. The measured hot water temperature T3 was used as the upper end temperature of the pipe, the measured value of F4 as a water flow rate, and the measured value of T14 as the air temperature.

4.2 Calculated results

The calculated temperatures are shown in Figure 9. These agree well with the temperatures measured by thermography.

Table 1 compares the calculated and measured results of the heat loss and the temperature drop during the flow process from the upper to the lower ends of the pipe. The heat loss calculated using a design value of the insulation thickness, 25 mm, is 47.5 [MJ/day], which is less than the measured result 58.2 [MJ/day]. The insulation thickness of 12 mm gives a larger heat loss of 64.5 [MJ/day], a better agreement with the measured value. This means that the expected (design) insulation performance was not realized.

Looking into the breakdown of the calculated heat loss, each heat loss is ordered as follows; thermal bridge<floor slab<glass-wool insulation.
A very large heat loss occurs through the pipe surface insulated by glass-wool, since it has the largest surface area.

![Figure-8 Two-dimensional cylindrical thermal model of hot water piping system](image)

**Table-2 Measured PL (perimeter length) of hot water pipes**

<table>
<thead>
<tr>
<th>FL</th>
<th>Dia.</th>
<th>PL when 25mm thick [mm]</th>
<th>PL before Retro. [mm]</th>
<th>PL after Retro. [mm]</th>
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<tbody>
<tr>
<td>11</td>
<td>40A</td>
<td>309.6</td>
<td>225.5</td>
<td>278.3</td>
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<tr>
<td>10</td>
<td></td>
<td></td>
<td>224.3</td>
<td>277.7</td>
</tr>
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<td>9</td>
<td></td>
<td></td>
<td>224.3</td>
<td>268.8</td>
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<tr>
<td>8</td>
<td></td>
<td></td>
<td>222.7</td>
<td>253.0</td>
</tr>
<tr>
<td>7</td>
<td></td>
<td></td>
<td>227.5</td>
<td>258.0</td>
</tr>
<tr>
<td>6</td>
<td>32A</td>
<td>291.0</td>
<td>224.0</td>
<td>253.3</td>
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<tr>
<td>5</td>
<td></td>
<td></td>
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<td>280.0</td>
</tr>
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<td></td>
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</tr>
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<td>15A</td>
<td>242.4</td>
<td>197.3</td>
<td>206.5</td>
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<td>175.0</td>
<td>195.5</td>
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**Table-1 Calculated and measured heat loss, and temperature drop (3-4 pipeline)**

<table>
<thead>
<tr>
<th></th>
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<th></th>
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</thead>
<tbody>
<tr>
<td>25mm thick</td>
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<td>3.7 : 18.0 : 25.8</td>
<td>2.0</td>
</tr>
<tr>
<td>12mm thick</td>
<td>64.5</td>
<td>4.3 : 18.5 : 41.7</td>
<td>2.3</td>
</tr>
<tr>
<td>Measured</td>
<td>58.2</td>
<td>---</td>
<td>2.5</td>
</tr>
</tbody>
</table>

4.3 Measurement of diameter of hot water pipe

The thermal insulation of the pipes in the shaft space was carried out by covering the pipe with the glass-wool insulation with aluminum craft paper, which was then tightly covered by steel net. Since insulation performance of the glass-wool degrades due to compression, and thermal bridge can be formed by a direct contact of aluminum craft paper to the pipe, the heat loss through the insulated part of the pipe may be significant. Therefore, we measured the perimeter length of the pipes before and after the insulation retrofit. Table 2 lists the measured results of the perimeter length of the pipes along the vertical line 5-6. The insulation thickness before the retrofit (based on a standard specification) were, 12 mm in 40A pipe, 11 mm in 32A pipe, 14 mm in 25A pipe, and 15 mm in 15A pipe. (Although the design thickness of glass-wool insulation for hot water pipe less than 80A is 20 mm according to the construction standard for thermal insulation, 24K 25 mm glass-wool was adopted in this hotel.) Therefore, the analysis in section 4.2 assuming an insulation thickness of 12 mm is not necessarily unreasonable.

**Table-2 Measured PL (perimeter length) of hot water pipes**

1. Conclusion

1) Visual inspection and numerical calculation clarified that rain penetration and thermal bridging were the main reasons for a large heat loss from hot water supply system.
2) By carefully covering (not too tight) the pipes with the insulation material, a decrease in the heat loss of 5 [MJ/day] per one vertical piping line was obtained.
3) The heat loss through the insulated pipe surface amounts to a large fraction due to its large surface area, and it increases more when the insulation is tightly fastened.

**References**