MEASUREMENT OF TOTAL BOILER EFFICIENCY IN AN OPERATING FACTORY IN COMPARISON WITH HEAT PUMP APPLICATION

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Abstract: Reduction of CO2 emissions and energy saving are at present urgent issues in many fields of industries. Steam, occupying a considerable energy consumption rate in the entirety of the industry, is normally generated in boilers. Study on replacement of boilers with heat pump system based on measurement of efficiency is under way. In fact, boiler efficiency is generally thought to be approximately ninety percent. However, the rate of heat loss from steam pipes can not be neglected at times. Accordingly, we executed measurement of total boiler efficiency by considering heat loss from steam pipes in an operating factory. Two methods were employed for the measurement of heat loss from steam pipes. One is how deference is calculated between steam flow rate at the boiler exit and that of machinery using steam. The other is how each drain flow rate from steam traps is measured. Both results are compared and discussed.

Key Words: Steam, Boiler, Steam pipe, Heat loss, Total boiler efficiency

1 INTRODUCTION

Today, realization of a low carbon society is called for, as the importance of energy saving is growing larger day by day. In the industrial field, including manufacturing processes in factories, steam, which occupies a large ratio in total thermal energy consumption, has been supplied mainly by boilers. If the boilers can be replaced with a heat pump system in part, energy consumptions and CO2 emissions will be reduced. In order to compare thermal efficiency of the heat pump with that of the boilers, accurate investigation of energy losses are necessary. However, there has been few examples of heat utilization efficiency being measured at actual industrial facilities in the past. Consequently, we carried out practical measurements of steam flow rates in steam pipes and drain water flow rates from steam traps in an operating factory wherein consumption points (machinery) were located at a considerable distance from the boilers. We applied two methods to obtain measurement, and evaluated heat loss quantity by comparing both results.

2 NOMENCLATURE

d : Diameter of orifice hole [m] F_0: Size of orifice hole [m2]
G : Mass flow rate [kg/s] g: Gravitational acceleration [m/s2]
h: Enthalpy [J/kg] L: Length of tube [m]
P : Drain capture rate ΔP: Differential pressure [Pa]
r: Radius of tube [m] T: Temperature [degree C]
W: Heat quantity [W] X: Degree of dehydration
α: Flow coefficient ε: Expansion factor
γ_1: Specific gravity of fluid at the upper flow of orifice [kg/m3]
η: Efficiency λ: Thermal conductivity [W/m/K]
θ: Thickness [m]

Subscript

boiler: Central boiler element boiler-out: Outlet of the boiler
cap: Captured drain drain: Steam drain
loss: Radiation of heat machinery: Factory machinery
n: Sequential number of steam trap sat-l: Saturated liquid
sat-v: Saturated vapour steam-pipe: Steam pipe
total-boiler: Total boiler system surface: Surface of steam pipe

3 MEASUREMENT METHODS

3.1 Calculation of Total Thermal Efficiency

The total thermal efficiency of a steam supply system, including central boiler elements, steam pipes and machinery, was calculated using Equation (1).

$$\eta_{total-boiler} = \eta_{boiler} \cdot \eta_{steam-pipe} \cdot \eta_{machinery} \tag{1}$$

The boiler efficiency of the central boiler elements was calculated by the heat loss measuring method (ASME 1998). Heat loss caused by combustion was determined by properties of the fuel and temperatures of the exhaust gas. As a result of calculation, the loss was 6 percent. Heat radiation loss from the boiler surfaces was estimated at 2 percent. This proved that the total efficiency was 92 percent.

3.2 Evaluation of Heat Loss From Steam Pipes

Steam pipes cause the largest energy loss in the steam supply system. In this study, the following two methods were applied to evaluations of energy loss.

Evaluation by decrease in steam flow quantity method is based on measurement of steam flow quantity at the boiler outlet and its utilization. The efficiency was evaluated with the decrease in steam which was condensed and discharged as drain water.

Evaluation by heat radiation method is based on measurement of drain water discharged from steam traps equipped on the steam pipes. The efficiency was calculated together with the drain water flow rate by considering that heat radiation from steam pipes caused a certain amount of steam to condense into water.

3.2.1 Evaluation by decrease in steam flow quantity

Steam flow quantity at the boiler outlet was measured using a vortex flowmeter. Length of the steam pipe, which connected the steam header of the boilers to the machinery, was 507.8m. Steam flow near the end of the pipe was measured with an orifice flowmeter as shown as Figure 1. The flow rate was calculated with differential pressure between both sides of the orifice using Equation (2).

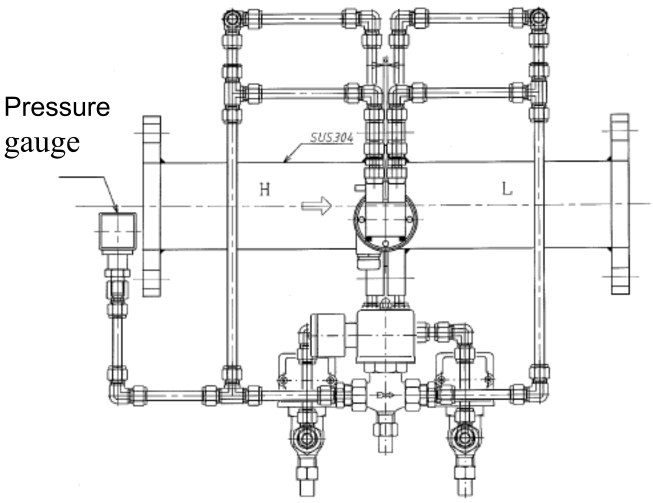

Figure 1: Orifice flowmeter

$$G = \alpha \varepsilon F_0 \sqrt{2 g \gamma_1 \Delta P} = 0.01252\ \alpha \varepsilon d^2 \sqrt{\gamma_1 \Delta P} \qquad (2)$$

The flow coefficient α was determined with regard to the inside diameter ratio of the orifice hole and the pipe. The result was 0.8257 as calculated by a formula of a quadrant edge orifice. The expansion factor was found to be dependent on the differential pressure. In this case, the differential pressure was relatively small in comparison with the steam pressure. The expansion factor was then considered as 1.

The inner diameter of the orifice hole was 0.0811 m. The specific gravity of the steam was determined by the pressure and was found to be 2.5 kg/m3.

Next, the flow quantity was calculated with the differential pressure. Results of the measurements, which were carried out twice on different days, are shown in Table 1. Heat loss ratios were 34 percent, which were almost the same in both cases.

Table 1: Rate of heat loss using calculation of decrease in steam flow rate between boiler exit and machinery

Case	Steam flow at boiler exit	Steam flow at end of pipe	Rate of heat loss
1	380 kg/h	250 kg/h	34 %
2	380 kg/h	250 kg/h	34 %

3.2.2 Evaluation by heat radiation

Heat loss radiated from steam pipe surfaces was calculated with deference to specifications of the thermal insulation material, and showed that thermal conductivity was 0.06 W/m/K and that thickness θ was 25mm. The radius of pipe was 81mm. There were four steam traps on the steam pipe. Distances from the boiler element to each trap are shown in Table 2.

Table 2: Distances from boiler to each steam trap

Trap #	#1	#2	#3	#4	End of pipe
Distance	210.3 m	305.5 m	333.3 m	429.0 m	507.8 m

Heat radiation from the steam pipe, between (n-1)th steam trap and nth steam trap, can be calculated as Equation (3).

$$W_{loss,n} = \frac{2\pi \left(L_n - L_{n-1}\right)\left(T_{sat-v} - T_{surface}\right)}{1/\lambda \cdot \ln\left(\left(r+\theta\right)/r\right)} \tag{3}$$

Drain flow quantity just before nth steam trap can be calculated as Equation (4). That just before the first steam trap can be calculated as Equation (5). Drain discharge quantity from nth steam trap can be calculated as Equation (6).

$$G_{drain,n} = \frac{W_{loss,n}}{h_{sat-v} - h_{sat-l}} + G_{drain,n-1} \cdot \left(1 - P\right) \tag{4}$$

$$G_{drain,1} = \frac{W_{loss,1}}{h_{sat-v} - h_{sat-l}} + G_{boiler-out} \cdot \left(1 - X_{boiler-out}\right) \tag{5}$$

$$G_{cap,n} = G_{drain,n} \cdot P \tag{6}$$

In this measurement, pressure of steam was 0.50 MPa Gauge, and the saturation temperature was 152.7 degrees Celsius. The heat of evaporation, which was defined as the difference in enthalpy between saturated vapour and water, was 2105.26 kJ/kg.

Wetness at the boiler discharge was 0.2 percent, the drain capture rate was estimated at 60 percent (Chitose and Umezawa 2009), and surface temperature of the steam pipe was 30 degrees Celsius. Note that this data was obtained in summer.

Drain flow rates at each steam traps were obtained by substituting actual values into equations. Results are shown in Table 3.

Table 3: Calculated drain flow rate

Trap #	#1	#2	#3	#4
Drain flow	35.0 kg/h	15.7 kg/h	4.6 kg/h	16.4 kg/h

On the other hand, the discharged steam drain was measured at two of the four steam traps. The drain was led to a container holding cold water. We measured speeds in which the quantity of water increased at steam traps #1 and #4.

As a result, calculated values of drain discharge were nearly equal to the actually measured values. Results are shown in Table 4. In this experiment, the measurement of steam drain was based on ASME PTC (ASME 2005).

Table 4: Comparison of drain flow rate between calculation value and measurement value

	Distance from upper trap	Calculation value of drain flow rate	Measurement value of drain flow rate	Deviation
Trap #1	210.3 m	35.0 kg/h	32.9 kg/h	6.4%
Trap #4	95.7 m	16.4 kg/h	17.3 kg/h	5.2%

This result showed that the calculated values and the actually measured values were similar and within a deviation under 7 percent. Thus, the estimation of thermal conductivity of the insulation material shows high validity.

3.2.3 Calculation of heat radiation

Due to the above mentioned results, heat loss from the boiler to the end of the steam pipe was calculated by substituting the total length of the pipe into Equation (3). The result obtained was 80.7kW. When the quantity of steam flow was 380 kg/h, the heat quantity supplied into the steam pipe was 290 kW. As a result, the heat radiation ratio was 28 percent.

4 DISCUSSIONS

Table 5 shows comparison of the results of heat loss ratio between the two methods. Results showed that heat loss ratios had dissimilar values, that is, 34 percent and 28 percent, respectively. However, note that steam leak loss was not considered in the heat radiation calculation. During measurement using the flowmeter, we confirmed the presence of one steam leak point on the pipe by observation. If the heat leak ratio was supposed to be 6 percent, both heat loss ratios had almost identical values. We considered that the heat loss from steam pipes was 28 percent without leak loss. Generally, steam pipes in factories have several leak points which lead to heat loss. Thus, we believe that the results of evaluation by decrease in steam flow quantity, that is, 34 percent of heat loss from steam pipes, is a reasonable value.

Table5: Comparison of results between two methods

	Heat loss ratio	Note
Evaluation by decrease in steam flow quantity	34%	
Evaluation by heat radiation and drain flow	28%	Leak loss is not included.

Heat loss ratio of steam consumption in manufacturing processes can be estimated by quantity and temperature of products and from discharged drain from machinery. When we conducted measurement of some manufacturing processes, the average value of heat loss was 7 percent, and the heat utilization efficiency was 93 percent.

Each element of heat loss of a steam supplying system is shown in Table 6. Remaining heat from the boiler to the drain is shown in Figure 2.

As a result, the total heat utilization ratio was 56 percent.

Table 6: Heat utilization efficiency analyzed by elements

Elements	Elemental efficiency	Accumulated efficiency
Central boiler element	0.92	0.92
Steam pipes	0.66	0.61
Manufacturing processes	0.93	0.56

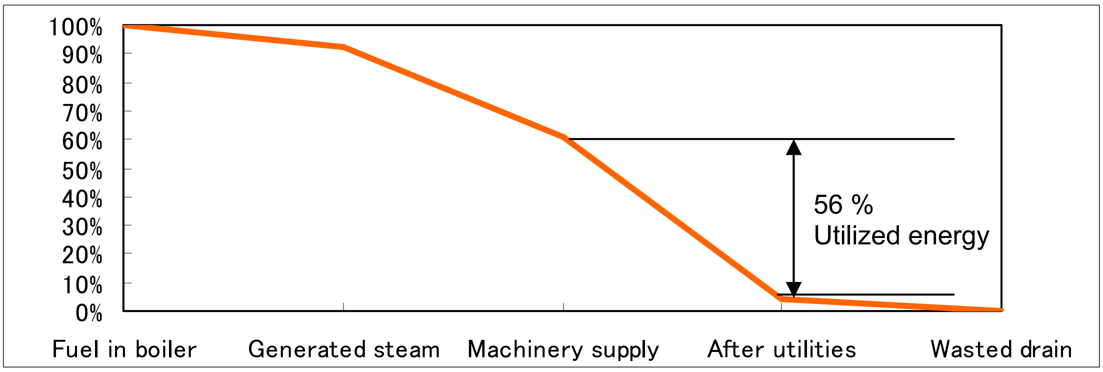

Figure 2: Remaining heat of steam

5 COMPARISON WITH HEAT PUMP APPLICATION

Energy consumptions and CO2 emissions were compared between a case that a heat pump is applied to the factory and the current condition of the boilers. Heat pumps can be equipped dispersedly in a factory because they are generally smaller than boilers. When the heat pump was located contiguously to the machinery, heat losses from steam pipes are negligibly small. Total COP of the heat pump was then regarded as 3.0 with consideration to the latest heat pump products.

Comparison of primary energy consumptions is shown in Table 7. Gross calorific value of electricity is officially announced by the Agency for Natural Resources and Energy. As a result, primary energy consumption of a heat pump is about 46 percent of that of a boiler.

Table 7: Comparison of primary energy consumptions

	Total Efficiency (COP)	Gross Calorific Value of Primary Energy	Primary Energy Consumptions per 1.0kJ Output
Electric Heat Pump	**3.0**	**8.81 kJ/kWh**	**0.82 kJ**
Gas Boiler	**0.56**	**1.0 kJ/kJ**	**1.79 kJ**

Comparison of CO_2 emissions is shown in Table 8. Basic unit of CO_2 emissions for electric power consumption is calculated by Tokyo Electric Power Company according to the Act on Promotion of Global Warming Countermeasures. That for fuel gas is defined by the same law. As a result, CO_2 emission of a heat pump is about 40 percent of that of a boiler.

Table 8: Comparison of CO2 emissions

	Primary Energy Consumptions per 1.0kJ Output	Basic Unit of CO2 Emissions per Primary Energy Consumption	CO2 Emissions per 1.0kJ Output
Electric Heat Pump	0.82 kJ	0.0436 kg-CO2/kJ	0.036 kg-CO2
Gas Boiler	1.79 kJ	0.0499 kg-CO2/kJ	0.089 kg-CO2

6 CONCLUSION

We carried out measurements of boiler efficiency in an actual factory utilizing two methods. Both results were almost the same regarding steam leak points in steam pipes. These methods can also be utilized for investigation and analysis of energy use in other factories.

As a result of estimation using the total efficiency of boilers, it is proved that primary energy consumptions and CO_2 emissions can be reduced by heat pump application.

We will continue to examine and utilize the results to achieve further energy saving and reduction of CO_2 emissions in the future.

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