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Research Article

Analysis of Exhaust Gas Heat Utilization in Waste Heat Recovery Power Generator at Indarung V Factory PT Semen Padang

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A B S T R A C T

Increasing energy efficiency in the cement production process at PT Semen Padang is carried out by reusing exhaust gas to produce electricity using Waste heat recovery power generation (WHRPG) with a capacity of 8.5 MW. WHRPG is a technology for utilizing exhaust gas heat as a source of heat energy to heat feed water into steam by using a suspension preheater (SP) boiler and air quenching cooler (AQC) boiler. This study aims to calculate the power potential of the steam heat influenced by the steam temperature and the mass flow rate of the steam produced by the boiler, to calculate the efficiency of the boiler using the direct method by comparing the boiler output heat against the boiler input heat, to calculate the turbine efficiency based on the difference between the steam enthalpy enter the turbine against the steam enthalpy out of the turbine and the isotropic enthalpy of the steam out of the turbine and to calculate the power generated by WHRPG at PT Semen Padang. The results obtained in this study are the total potential power of steam heat is 19.778 MW, the boiler AQC efficiency is 70.30%, the boiler SP efficiency is 94.04% and the turbine efficiency is 78.64%. The electricity generated by PT Semen Padang's WHRPG is 3.70 MW.

INTRODUCTION

In the cement industry, about 50% of production costs come from purchasing energy, one of which is electrical energy [1]. The cement production process consists of several stages. The preheating and clinker production stage is the stage that produces the most energy among other stages. This is because the preheater material will be heated, then the material will be converted into clinker in the rotary kiln at a temperature of 1,450 °C.

High temperatures in cement manufacture will produce combustion residual gas and hot air called exhaust gas. The temperature of the exhaust gases derived from the preheating and clinker production stages can reach 300-350°C [2]. Increasing energy efficiency in the cement production process is carried out by reusing exhaust gas to produce electricity using waste heat recovery power generation (WHRPG).

PT Semen Padang is one of the cement factories in Indonesia with a capacity of 8.9 million tons of cement per year [3]. In 2018, PT Semen Padang used a total of 783,950,176 kWh of electrical energy. The use of large amounts of electrical energy encourages PT Semen Padang to improve energy efficiency by building a waste heat recovery power generation with a capacity of 8.5 MW.

Waste heat recovery power generation is a technology for utilizing exhaust gas heat as a source of heat energy to heat feed water into steam using 2 types of boilers, suspension preheater (SP) boilers, which use exhaust gas from preheaters and air quenching cooler (AQC) boilers, which use clinker cooling exhaust gases. Furthermore, steam will be used to rotate the turbine connected to the generator so that it can generate electricity.

The purpose of this study is to determine the magnitude of the power potential of steam heat on the WHRPG, to determine the efficiency of AQC boiler SP boiler and turbine on the WHRPG, and to determine the amount of power generated by the WHRPG at PT Semen Padang.

METHOD

Cement Production Process

The cement production process consists of three main stages. The first stage is the mixing and crushing stage. The second stage is the combustion carried out on the kiln unit. This stage consists of a preheater, calciner, kiln, and cooler. The raw mix goes into the preheater to be heated from 50°C to 950°C [4]. In the calciner, two reactions occur to convert $CaCO_3$ and $MgCO_3$ into CaO and

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MgO. Then the raw mix goes to the kiln. The output material of the kiln is called the clinker. The clinker enters the cooling process until the temperature of 80-100 °C. Then at the third stage, the clinker will be ground and go into the packaging process.

Waste Heat Recovery

Waste heat recovery (WHR) is the process of heat integration, which is the reuse of thermal energy that should be discharged into the atmosphere. The use of WHR in industrial processes can reduce energy costs and CO_2 emissions while improving energy efficiency. Waste heat recovery systems are distinguished for each heat loss range to obtain the most optimal WHR efficiency. Heat loss is classified into several parts, namely high-temperature WHR, with a temperature over 400°C. WHR medium temperature, with a temperature of 100-400°C, and low-temperature WHR, with a temperature of less than 100°C [5].

Waste Heat Recovery Power Generator

Waste Heat Recovery Power Generation (WHRPG) is a technology to generate electricity by utilizing exhaust gas to rotate a steam turbine specially designed for medium pressure and temperature [6]. The efficiency of WHRPG is significantly influenced by the temperature of the exhaust gas source. There are several sources of exhaust gases in cement production [4]:

a. Exhaust gas from preheater, the average temperature of this exhaust gas is 335°C.
b. Exhaust gas from clinker cooling, the average temperature of this exhaust gas is 305°C.

Waste Heat Boiler

One of the common methods used in waste heat recovery for the cement industry is a waste heat boiler. A waste heat boiler is a boiler that utilizes medium to high-temperature exhaust gases to produce steam, as shown in Figure 1 [7]. A Waste heat boiler uses a heat source from the flow of hot exhaust gases from combustion in the kiln. The heat transfer process that occurs in a waste heat boiler only goes through the process of convection and conduction [6].

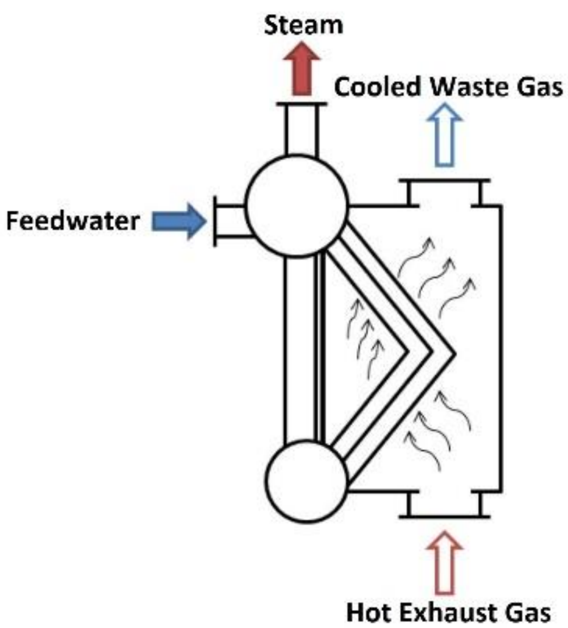

Figure 1. Waste Heat Boiler [7]

Common Components of Waste Heat Recovery Power Generator

Pump

The pump serves to move the fluid from one place to another by raising the pressure of the liquid. The working principle of the pump by converting the mechanical energy of the motor into the energy of the fluid flow [8].

Boiler

The boiler is a closed vessel that is used to heat water to produce steam [9]. The boiler consists of several parts, which are a wall tube, the economizer is a heat transfer device used to heat boiler feed water before it enters the steam drum [10], the steam generator, the superheater, and the steam drum.

Governor

The governor serves to regulate the speed of rotation of the turbine by regulating the amount of steam entering to rotate the turbine generator [11].

Turbine

Energy conversion occurs in turbine blades. Steam will enter the turbine, then be directed by the nozzles and flow to the turbine blade, the blade will work to convert the steam heat energy into mechanical energy, which causes the turbine rotor to rotate, the rotation of this rotor will drive the generator. So that mechanical energy will turn into electrical energy.

Law of Heat

Heat is defined as the energy that flows in the system due to temperature differences. Heat moves from high-temperature systems to low-temperature systems [12]. Specific heat is the heat required to raise the temperature from 1 kg of mass by 1ºC. Specific heat at a fixed pressure condition is called Cp. Specific heat of CO_2 to temperature is shown in Table 1.

Table 1. Specific Heat (Cp) of CO_2 to Temperature [13]

Temperature (ºK)	**Specific heat (Cp) (kJ/kg°K)**	**Temperature (ºK)**	**Specific heat (Cp) (kJ/kg°K)**
275	0.819	450	0.978
300	0.846	500	1.014
325	0.871	550	1.046
350	0.895	600	1.075
375	0.918	650	1.102
400	0.939	700	1.126

Enthalpy and Entropy

Enthalpy is a quantity in thermodynamics that expresses the amount of thermal energy, which is the energy contained in a system plus the energy used to perform work when the pressure is constant. Whereas entropy is a quantity in thermodynamics that expresses the thermal energy of a system per unit of temperature [14].

Power Potential of Steam Heat

The power potential of steam heat is the amount of power contained in the steam produced by the boiler. It can be expressed by equation (1) [15]:

$$Q_{steam} = \dot{m}_{steam} \times h_{steam} \quad (1)$$

where:

Q_{steam} = steam heat potential (kJ/s)
$\dot{m}_{steam}$ = steam mass flow rate (kg/s)
h_{steam} = enthalpy of steam (kJ/kg)

Input Power to The Boiler

The input power to the boiler consists of power from the heat exhaust gas of the kiln unit and power from preheated feed water in the economizer. It can be expressed by equation (2) [15]:

$$Q_{in} = \dot{m}_{gas} \times Cp_{gas\,in} \times T_{gas\,in} + \dot{m}_{water} \times h_{water} \quad (2)$$

Output Power from The Boiler

The output power from the boiler consists of power derived from hot exhaust gases that have decreased in temperature due to heat transfer and power from steam produced by the boiler. It boiler can be expressed by equation (3) [15]:

$$Q_{out} = \dot{m}_{gas} \times Cp_{gas\,out} \times T_{gas\,out} + \dot{m}_{steam} \times h_{steam} \quad (3)$$

where:

$\dot{m}_{gas}$ = exhaust gas mass flow rate (kg/s)
$\dot{m}_{water}$ = feedwater mass flow rate (kg/s)
$Cp_{gas\,in}$ = specific heat of gas enter boiler (kJ/kg °C)
$Cp_{gas\,out}$ = specific heat of gas leave boiler (kJ/kg °C)
$T_{gas\,in}$ = boiler inlet gas temperature (°C)
h_{water} = enthalpy of boiler feed water (kJ/kg)
$T_{gas\,out}$ = boiler outlet gas temperature (°C)

Boiler Efficiency

This study uses a direct method for the calculation of boiler efficiency. Direct method or input-output method by directly comparing the power from the heat absorbed by the feed water until it changes phase into steam (output power) with the power the heat of the exhaust gas from the kiln (input power). It can be expressed by equation (4) [16]:

$$\eta_{boiler} = \frac{Q_{out}}{Q_{in}} \times 100\% \quad (4)$$

where:

Q_{out} = output power from the boiler (kJ/s)
Q_{in} = input power to the boiler (kJ/s)

Turbine Efficiency

The turbine efficiency calculated in this study is isentropic. Isentropic efficiency is the comparison between the actual work of the turbine and the performance that the turbine can achieve under ideal conditions.

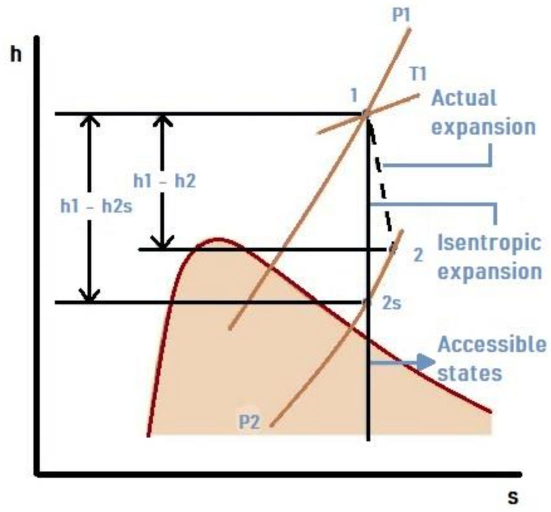

Figure 2. Diagram Mollier [17]

The state marked with 2s in Figure 2 can only be achieved if there is no internal irreversibility, this state is called turbine isentropic expansion. On the expansion inside the turbine $h_2 > h_2s$, so the work of the turbine is smaller than the work of the maximum turbine (isentropic expansion). The isentropic efficiency of the turbine can be expressed by equation (5) [18]:

$$\eta_{turbin} = \frac{h_1 - h_2}{h_1 - h_{2s}} \times 100\% \quad (5)$$

Turbine enthalpy can be calculated using the following steps:

1. Calculate the fraction of steam out of the turbine, the fraction of steam is the percentage of water vapor (moisture) contained in the steam. The fraction of steam out of the turbine can be expressed by equation (6) [19]
$$x_2 = \frac{S_1 - S_f}{S_g - S_f} \quad (6)$$
2. Calculate the isentropic enthalpy of the steam out of the turbine.
$$h_{2s} = h_f + \left(x_2\left(h_g - h_f\right)\right) \quad (7)$$
3. Calculate the enthalpy of the steam out of the turbine.
$$h_2 = h_1 - \left(\frac{W_t}{\dot{m}_{in}}\right) \quad (8)$$
4. Calculate the ideal work of the turbine.
$$\dot{W}_{t\,s} = \dot{m}_{in} \times (h_1 - h_{2s}) \quad (9)$$

where:

x_2 = fraction of steam out of the turbine
S_1 = entropy of steam entering the turbine
S_f = entropy of *saturated liquid*
S_g = entropy of *saturated vapor*
h_f = enthalpy of *saturated liquid*
h_g = enthalpy of *saturated vapor*
h_{2s} = isentropic enthalpy of the steam out of the turbine
h_2 = enthalpy of the steam out of the turbine
h_1 = enthalpy of the steam entering the turbine
$\dot{W}_t$ = work of the turbine
$\dot{W}_{t\,s}$ = ideal work of the turbine
$\dot{m}_{in}$ = mass flow rate of steam entering the turbine

Data and Testing Techniques

The research flow starts from collecting the data at the WHRPG unit, Bureau of Power and Utilities at PT Semen Padang. The data is obtained in a form of a daily report from the AQC boiler, SP boiler, water line, and steam line on September 24-28, 2022. The data collected consists of, feed water mass flow rate, steam mass flow rate, gas mass flow rate, inlet gas temperature, outlet gas temperature, steam temperature, steam pressure, feed water temperature, and feed water pressure for each boiler. Steam temperature enters the turbine, steam pressure enters the turbine, steam temperature out the turbine, and the steam pressure out the turbine and power generated by the generator.

The formula used to calculate the magnitude of the power potential of steam heat on the WHRPG and analyze the factors that influence it. Another formula is used to calculate the efficiency of the AQC boiler and SP boiler on the WHRPG. Then determine the losses that occur in each boiler and the factors that affect these losses. Another formula is used to calculate the efficiency of the turbine and the work of the turbine. Then determine the losses that occur in the turbine and the factors that affect these losses. The data is collected to determine the amount of power generated by the WHRPG at PT Semen Padang. Research flowchart is shown in Figure 3.

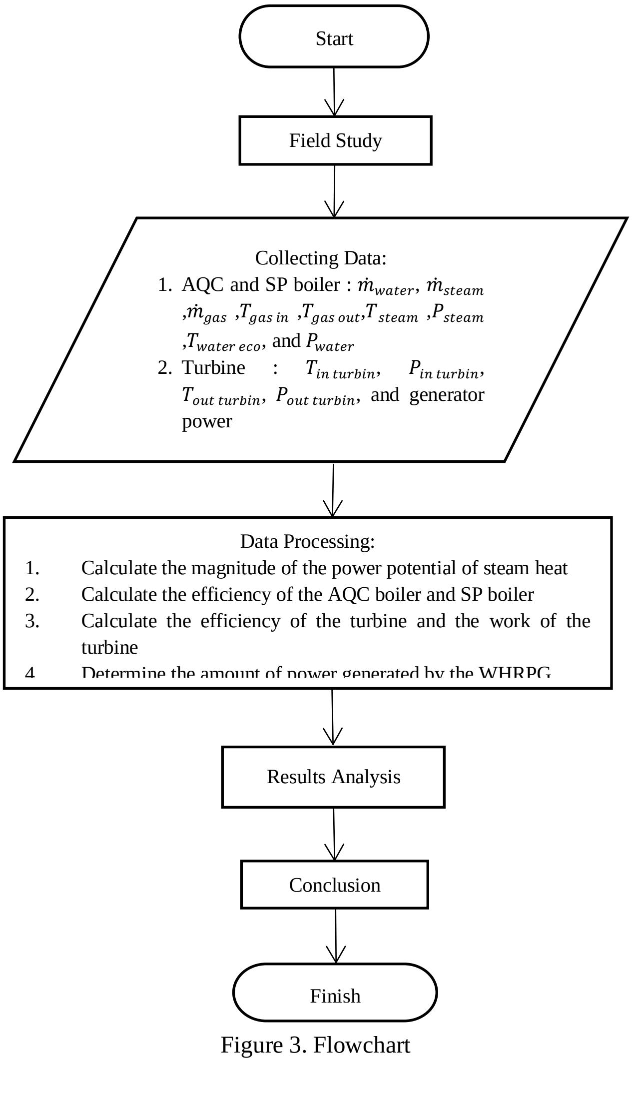

Figure 3. Flowchart

RESULTS AND DISCUSSION

The power potential of Steam Heat in Air Quenching Cooler Boiler

The steam enthalpy value based on the average steam pressure and temperature is 2,874.536 kJ/kg. While the steam enthalpy value based on the average steam enthalpy data is 2,874.020 kJ/kg. The difference in steam enthalpy is due to some of the steam enthalpy being pressurized at 1.12 MPa, at higher pressure the value of the steam enthalpy decreases. Power potential calculation from steam heat in AQC boiler is shown in Table 2, while daily average steam heat potential in AQC boiler is shown in Table 3.

Table 2. Power Potential Calculation Data from Steam Heat in Air Quenching Cooler Boiler

Parameter	Unit	Value
Steam heat potential ($\dot{m}_{steam}$)	kg/s	2.073
Steam pressure (P_{steam})	MPa	1.110
Steam temperature (T_{steam})	°C	223.940
Steam enthalpy (h_{steam})	kJ/kg	2,874.536

Table 3. Daily Average Steam Heat Potential in Air Quenching Cooler Boiler

Date	$\dot{m}_{steam}$ (kg/s)	T_{steam} (°C)	h_{steam} (kJ/kg)	Q_{steam} (MW)
24-09-22	1.808	226.10	2,878.250	5.238
25-09-22	2.185	221.96	2,868.567	6.295
26-09-22	2.382	230.88	2,897.451	6.931
27-09-22	1.756	217.89	2,859.153	5.035
28-09-22	2.253	221.18	2,870.682	6.490
Average	**2.703**	**223.94**	**2,874.020**	**5.983**

The power potential of the steam heat in the boiler AQC can be calculated based on equation (1).

$$Q_{steam} = \dot{m}_{steam} \times h_{steam}$$
$$= 2.073 \times 2{,}874.020$$
$$= 5{,}957.8\frac{kJ}{s} = 5.96\ MW$$

The power potential of Steam Heat in a Suspension Preheater Boiler

The steam enthalpy value based on the average steam pressure and temperature is 3,152.795 kJ/kg. While the steam enthalpy value based on the average steam enthalpy data is 3,152.903 kJ/kg. The difference in steam enthalpy is due to some of the steam enthalpy being pressurized at 1.13 MPa, at a lower pressure the value of the steam enthalpy increases. Power potential calculation from steam heat in SP boiler is shown in Table 4, while daily average steam heat potential in SP boiler can be seen in Table 5.

Table 4. Power Potential Calculation Data from Steam Heat in Suspension Preheater Boiler

Parameter	Unit	Value
Steam heat potential ($\dot{m}_{steam}$)	kg/s	4.376
Steam pressure (P_{steam})	MPa	1.140
Steam temperature (T_{steam})	°C	349.780
Steam enthalpy (h_{steam})	kJ/kg	3,152.795

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Table 5. Daily Average Steam Heat Potential in Suspension Preheater Boiler

Date	$\dot{m}_{steam}$ (kg/s)	T_{steam} (°C)	h_{steam} (kJ/kg)	Q_{steam} (MW)
24-09-22	4.145	349.25	3,151.333	13.061
25-09-22	4.491	345.91	3,144.673	14.118
26-09-22	4.458	353.95	3,161.963	14.098
27-09-22	4.336	354.80	3,163.800	13.719
28-09-22	4.436	346.59	3,146.214	13.956
Average	**4.373**	**350.10**	**3,153.597**	**13.790**

The power potential of the steam heat in the boiler SP can be calculated based on equation (1).

$$Q_{steam} = \dot{m}_{steam} \times h_{steam}$$
$$= 4.376 \times 3{,}152.903$$
$$= 13.797{,}1 \frac{kJ}{s} = 13.80\ MW$$

Power Potential Analysis of Steam Heat

Table 6. Comparison of the Effect of Temperature and Steam Mass Flow Rate on the Power Potential of Steam Heat

$\dot{m}_{steam}$ (kg/s)	T_{steam} (°C)	h_{steam} (kJ/kg)	Q_{steam} (MW)
4.083	347.0	3,146.447	12.848
4.083	348.8	3,147.064	12.864
4.083	350.2	3,153.327	12.876
4.083	362.9	3,150.317	12.990
3.750	348.8	3,150.521	11.815
3.833	348.9	3,151.144	12.079
3.889	348.8	3,150.929	12.254
4.083	348.8	3,150.317	12.864

Based on Table 6, by varying the steam temperature, it is known at the same steam mass flow rate, there is a small difference in the power potential of the steam heat. This is due to the change in the enthalpy value of steam to relatively small changes in vapor temperature. So it was found that the effect of steam temperature is relatively small to the power potential of the steam heat as described in Figure 4.

Furthermore, by varying the steam mass flow rate, it is known at the same steam temperature, there is much difference in the power potential of the steam heat. So it was found that the influence of the steam mass flow rate is quite large on the power potential of the steam heat as shown in Figure 5.

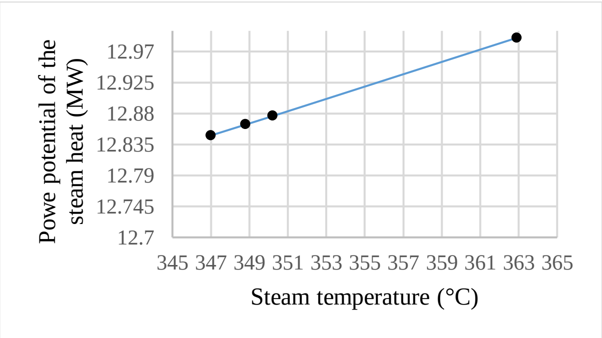

Figure 4. Effect of Steam Temperature on the Power Potential of Steam Heat

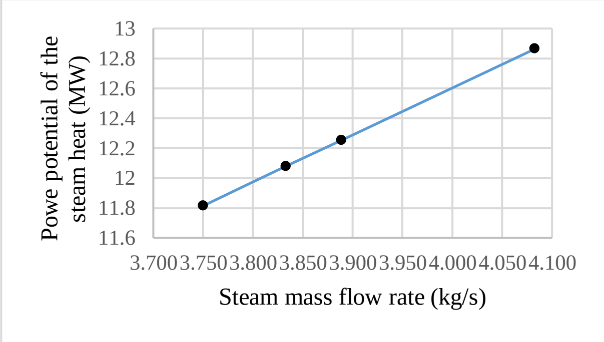

Figure 5. Effect of the Steam Mass on the Power Potential of the Steam Heat

Air Quenching Cooler Boiler Efficiency

The input power to the AQC boiler is calculated using equation (2).

$$Q_{in} = \dot{m}_{gas} \times Cp_{gas\,in} \times T_{gas\,in} + \dot{m}_{water} \times h_{water}$$
$$= \left(\frac{400{,}000 \times 1.033}{3{,}600}\right) \times 1.025 \times 244.26 + (2.238 \times 771.95)$$
$$= 30{,}464.69 \frac{kJ}{s} = 30.46\ MW$$

The output power from the AQC boiler is calculated using equation (3).

$$Q_{out} = \dot{m}_{gas} \times Cp_{gas\,out} \times T_{gas\,out} + \dot{m}_{steam} \times h_{steam}$$
$$= \left(\frac{400{,}000 \times 1.401}{3{,}600}\right) \times 0.925 \times 107.16 + (2.073 \times 2{,}874.020)$$
$$= 21{,}389.06 \frac{kJ}{s} = 21.39\ MW$$

Table 7. Daily average efficiency Air Quenching Cooler Boiler

Date	Q_{in} (MW)	Q_{out} (MW)	AQC boiler efficiency (%)
24-09-22	30.501	19.752	64.72
25-09-22	30.236	22.567	74.65
26-09-22	31.210	22.376	71.65
27-09-22	29.713	20.144	67.76
28-09-22	30.644	22.019	71.79
Average	**30.429**	**21.402**	**70.30**

In general, the boiler efficiency ranges from 70-90% [20]. The efficiency in this range indicates that the process of absorbing thermal energy from exhaust gases and steam formation in the AQC boiler is quite good.

Suspension Preheater Boiler Efficiency

The input power to the SP boiler is calculated using equation (2).

$$Q_{in} = (\dot{m}_{gas} \times Cp_{gas\,in} \times T_{gas\,in}) \times 2 + \dot{m}_{water} \times h_{water}$$
$$= \left(\left(\frac{265{,}000 \times 0.82}{3{,}600}\right) \times 1.101 \times 375.46\right) \times 2 + (4.416 \times 771.95)$$
$$= 53{,}313.26 \frac{kJ}{s} = 53.313\ MW$$

The output power from the SP boiler is calculated using equation (3).

$$Q_{out} = \dot{m}_{1gas} \times Cp_{1gas\,out} \times T_{1gas\,out} + \dot{m}_{2gas} \times Cp_{2gas\,out} \times T_{2gas\,out} \dot{m}_{steam} \times h_{steam}$$

$$= \left(\frac{265{,}000 \times 1.048}{3{,}600}\right) \times 1.020 \times 236.45 + \left(\frac{265{,}000 \times 1.079}{3{,}600}\right) \times 1.010 \times 220.73 + (4.376 \times 3{,}152.795)$$

$$= 50{,}109.36 \frac{kJ}{s} = 50.109\ MW$$

Table 8. Daily average efficiency Suspension Preheater Boiler

Date	Q_{in} (MW)	Q_{out} (MW)	SP *boiler efficiency* (%)
24-09-22	52.795	49.181	93.14
25-09-22	53.444	50.695	94.82
26-09-22	53.727	50.484	93.96
27-09-22	53.588	49.921	93.37
28-09-22	52.990	50.273	94.32
Average	**53.306**	**50.128**	**94.04**

Efficiency in the range of more than 90% indicates that the process of absorbing thermal energy from exhaust gases and steam formation in the boiler SP is very good.

Boiler Efficiency Analysis

Table 9. Daily Average Boiler Losses

Date	AQC *boiler losses* (MW)	SP *boiler losses* (MW)
24-09-22	10.750	3.614
25-09-22	7.669	2.748
26-09-22	8.835	3.243
27-09-22	9.569	3.667
28-09-22	8.625	2.716
Average	**9.027**	**3.178**

Losses in boilers can occur due to the long service life of the boiler. This can cause a buildup of particles in the boiler pipes that are carried away by the feed water. That will inhibit the transfer of heat from the exhaust gases to the feed water.

The large losses in the boiler AQC are caused by the operating conditions of the boiler that are different from the design. Where the gas temperature that enters the AQC boiler in the design is 310 °C, while the operating conditions are 244.26 °C. Operating temperatures that are much lower than design temperatures result in a reduced feedwater mass flow rate entering the AQC boiler.

The reduction of the feedwater mass flow rate aims to increase the steam temperature to be higher than the saturation temperature. If the steam temperature produced by the boiler is lower than the saturation temperature, the steam produced is saturated steam (contains water) so that it cannot be used to rotate the turbine.

Steam Turbine

Steam expands inside the turbine. The expansion causes a decrease in pressure and this process occurs continuously. A decrease in the pressure of steam through the blades of the turbine will lead to an increase in the speed of the steam. In turbines, there was a decrease in steam temperature by 250,98 °C and a decrease in steam pressure by 1,203 MPa. The average power generated by the generator in this study was 3.70 MW.

Losses in the turbine can occur due to the influence of the level of steam wetness. In the final stage of turbine rotation, the temperature of the steam inside the turbine begins to drop and resulting in the steam turning into wet steam. At a certain level of wetness, it causes the rotation of the turbine blades to be hampered and erosion of the turbine blades. Losses in the steam turbine can also occur due to the influence of friction between the steam and the nozzles and the blades of the turbine. Friction between steam and nozzles can cause a decrease in steam speed, thereby reducing the kinetic energy of steam to rotate turbine blades.

Table 10. Daily Average Turbine Efficiency

Date	$\dot{m}_{in}$ (kg/s)	h_2 (Kj/kg)	h_2s (Kj/kg)	P_g (MW)	$\dot{W}_{t\,s}$ (MW)	Turbine efficiency (%)
24-09-22	5.953	2,396.032	2,226.679	3.48	4.783	79.32
25-09-22	6.674	2,386.017	2,234.078	3.92	5.337	81.15
26-09-22	6.604	2,443.213	2,241.892	3.68	5.289	75.07
27-09-22	6.093	2,406.835	2,237.175	3.53	4.759	79.12
28-09-22	6.690	2,409.682	2,227.448	3.67	5.049	77.18
Average	**6.401**	**2,406.043**	**2,233.306**	**3.70**	**5.043**	**78.64**

Table 11. Daily Average Turbine Losses

Date	$\dot{W}_t$ (MW)	$\dot{W}_{t\,s}$ (MW)	Turbine losses (kW)
24-09-22	3,865	4,865	999,878
25-09-22	4,356	5,356	999,919
26-09-22	4,085	5,527	1.442,435
27-09-22	3,920	4,952	1.032,613
28-09-22	4,078	5,344	1.266,171
Average	**4,111**	**5,207**	**1.096,708**

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CONCLUSIONS

Based on the results of research that has been done, the power potential from the steam heat in the AQC boiler is 5.983 MW, the power potential from the steam in the SP boiler is 13.795 MW, and the total power potential from the steam heat at the WHRPG is 19.778 MW. The efficiency of the AQC boiler is 70.30% with losses of 9.027 MW, while the efficiency of the SP boiler is 94.04% with losses of 3.178 MW. Losses in boilers can be caused by factors of long enough boiler service life and factors of boiler operating conditions that are different from the design. Turbine efficiency is 78.64% with losses of 1,097 MW. Losses in the turbine can be caused by the factor of the level of wetness of the steam and the friction factor between the steam and the nozzles and the blades of the turbine. The electrical power generated by the waste heat recovery power generator at PT Semen Padang is 3.70 MW.

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