

Modeling of Three-Stage High Pressure Heater with Heat Mass Balance in Business Steam Power Plant

A Haqqo^{1*}, E Tridianto¹, HE Gayuh Prasetya¹

¹ Mechanical and Energy Department Electronic Engineering Polytechnic Institute of Surabaya.

*Corresponding author. Email: arinalhaqqo@outlook.com

ABSTRACT

The steam power plant is one of the business selling electrical products to be sold in state electricity distributors. Steam power plant requires a steam generator support system in order to have high efficiency. One of the components for increase efficiency is the High-Pressure Heater (HPH). Generally, The HPH consists of two main parts the shell side where hot steam flows and the tube side where the feedwater flows. So it is necessary to ensure that the energy used can be absorbed maximally in the HPH. To determine the effectiveness of this can be done by modeling according to the installed plant. In this paper, a three-stage HPH model is simulated to determine the performance, and then the Heat Mass Balance calculation will be carried out from the steam used on the shell side and the heated feedwater on the tube side. From the HPH modeling, the simulation will show how much energy can be absorbed by the feedwater. The heat loss at these 3-Stages HPH is 7613.70 kJ/s until 16331.43 kJ/s. Heat loss value is used for performance evaluation. From this modeling of HPH, Simulation shows good results, but the heat loss indicates that the system can be improved.

Keywords: High Pressure Heater, Heat Mass Balance. Energy, Heat Loss.

1. INTRODUCTION

High-Pressure Heater is a high-pressure feedwater heater. The feedwater heater is one of the additional components in the Rankine cycle, which is designed to increase the feedwater temperature before it enters the boiler. Increasing the feedwater temperature will reduce the amount of coal consumption in the boiler so that the thermal efficiency of the cycle will increase. Feedwater heater is divided into two types, namely Open Feedwater Heater and Close Feedwater Heater. There is mixing between the feedwater and the extracted steam in the Open Feedwater Heater at a higher temperature and pressure. The resulting feedwater has a higher temperature than the feedwater that enters the Open Feedwater Heater. In the Closed Feedwater Heater, the steam flow extracted from the turbine does not mix with the feedwater flow. The extraction process of steam for heating in closed-type feedwater is alluded to as an uncontrolled extraction. The steam flow rate into a high-pressure heater is not constrained by a measure of accessible steam. The operating parameters on shell side in a high-pressure heater are determined by pressure of the steam supplied and not by the amount of surface heat transfer. [1]

Analyzed high-pressure feedwater heater is shell and tube heat exchanger. The Shell side contains the steam inlet and condensate outlet, while the tube side

contains the feedwater inlet and outlet. The steam from the steam generator or the main turbine is supplied to the heat exchanger shell. Heat is transferred from the steam to the feed water by convection and conduction through the tube walls. Due to the heat removal, the steam condenses on the outer tube walls. The condensate is drained from the heat exchanger. [2]

To help determine the 3 Stage HPH strategy process on a complex system of steam power plant, it can be done with modeling the system based on HYSYS. HYSYS is a software used to simulate the existing process on the actual plant. In knowing the plant response through HYSYS.

The pressure heater performance greatly affects the efficiency of the boiler. theoretical calculations were performed as part of the systematic approach to estimating specific heat of flue gas, heat load, effectiveness, and overall heat transfer coefficient. [3]

This modeling and evaluation will make it easier for the industry to estimate operational actions because the performance value can be obtained without going through actual trials in the field. In addition, it will provide financial benefits because industrial power plants only need to calculate and model real plants with simpler equipment without the need to carry out actual operations on HPH.

2. MODELING AND OPERATING CONDITIONS.

This research has an essential function in the industry because the heat mass balance analysis will give heat loss value. This value plays an important role in determining when an industrial power plant undergoes maintenance or overhaul. Of course, losses in power plants are not only in HPH but in this study, HPH is very important in the system. Functionally HPH is used to increase system efficiency so that the heat produced by the boiler can be absorbed by the system optimally. Heat mass balance analysis on HPH can be adapted to actual or field conditions. as a method of evaluating whether the system is working well or not. evaluation results will be related to direct action.

2.1. Three-Stages High Pressure Heater Structure

The three heaters are named no. 1, no. 2, and no. 3 high-pressure heaters, according to the high-to-low sequence of their extraction steam pressure.[4] This three-level HPH structure is based on a general large power plan with more than 500 MW capacity. The three-level structure makes this HPH utilizes steam extracted from the high-pressure turbine and the intermediate turbine. This steam input is a source of energy that will be used. [5]

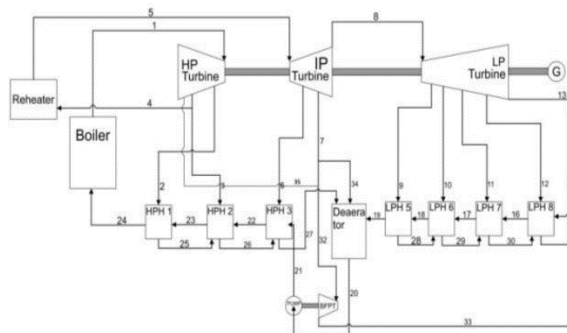


Figure 1 Flow Diagram Steam Power Plant.

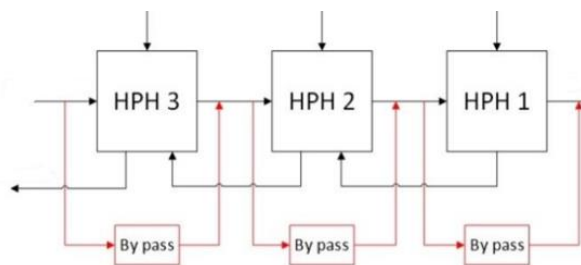


Figure 2 Configuration three stage HPH.

Heat recovery technology with an additional heat exchanger installed with sufficient heat transfer area, based on the research of which, the results indicated that the minimum temperature difference between the

boiler feed water and the waste heat streams in the exchanger will constrain the maximum area of the heat exchanger, and a smaller minimum temperature difference would require larger heat transfer area and higher costs.[6]

Table 1. Specifications

Data HPH 1	Value	Unit
OD / ID / Thick Tube	15.88/11.68/2.1	mm
Total Tube	2664	
Long Tube	16.90	m
Configuration Tube	Triangular Rotated (60 Degrees)	
Diameter Shell	2.1	mm
Heat Transfer area	2250	m ²
Heat Transfer Coeff. Shell	8564.37	W/ m ² .C
Heat Transfer Coeff. Tube	38512.28	W/ m ² .C
Data HPH 2	Value	Unit
OD / ID / Thick Tube	15.88/11.68/2.1	mm
Total Tube	2664	
Long Tube	16.20	m
Configuration Tube	Triangular Rotated (60 Degrees)	
Diameter Shell	2.1	mm
Heat Transfer area	2150	m ²
Heat Transfer Coeff. Shell	8564.37	W/ m ² .C
Heat Transfer Coeff. Tube	38512.28	W/ m ² .C
Data HPH 3	Value	Unit
OD / ID / Thick Tube	15.88/11.68/2.1	mm
Total Tube	2664	
Long Tube	12.80	m
Configuration Tube	Triangular Rotated (60 Degrees)	
Diameter Shell	2.1	mm
Heat Transfer area	1700	m ²
Heat Transfer Coeff. Shell	8564.37	W/ m ² .C
Heat Transfer Coeff. Tube	38512.28	W/ m ² .C

These data will be used in the modeling process in the HYSYS simulation. So that it can get an excellent value that can be evaluated how many errors occur in the system. [5]

2.2. Process Modeling

The process modeling in this paper uses HYSYS software. To get the result modeling process, the operational data schema is needed. The use of the scheme aims to represent the concept of the HPH strategy. The HPH modeling in the software HYSYS.

Heat exchanger modeling and simulation has been extensively addressed in the literature due to its importance in industrial applications. Many kinds of heat exchanger models have been developed targeting different aspects of interest such as, steady state and transient predictions.[7]

To be able to produce simulations, the HYSYS simulation parameters are needed.

Table 2. Operating Conditions.

Variable	Parameters	Unit	Value
Feedwater Input	Temperature	°C	179.2
	Pressure	bar	199.1
	Mass flow	kg/h	2002000
Steam Input HPH 1	Temperature	°C	420
	Pressure	bar	61.2
	Mass flow	kg/h	140800
Steam Input HPH 2	Temperature	°C	332.3
	Pressure	bar	39.5
	Mass flow	kg/h	138700
Steam Input HPH 3	Temperature	°C	447.2
	Pressure	bar	19.5
	Mass flow	kg/h	90960

The data above is operational data as data material to be evaluated. Then theoretical calculations will be carried out based on the results of the modeling output data from HYSYS.

Based on the design data, the temperature and pressure of the HPH will be as shown in this table. The design data will be used as to how well the performance value achieves the design value. However, fundamentally the design value is an ideal condition so that the performance value is undoubtedly below the design value.

Table 3. Design Operations.

Variable	Parameters	Unit	Value
Feedwater Output	Temperature	°C	310
	Pressure	bar	280
Steam Output	Temperature	°C	290
	Pressure	bar	23

3. PROCESS MODELING AND HEAT MASS BALANCE

3.1. Heat Transfer (h_i and h_o)

To produce a suitable simulation, the parameters obtained from the calculation are needed. Heat transfer in the tube section will be affected by feedwater.

Previously, the Reynolds number must be known to determine the next heat transfer calculation. [8]

$$Re = \frac{4\dot{m}\left(\frac{np}{nt}\right)}{\pi Di \mu} \quad (1)$$

Descriptions :

- Re = Reynolds number.
- \dot{m} = Mass flow rate (kg/s or lbm/h).
- np = Number of observed tube passes.
- nt = total tube.
- Di = Diameter in tube (m or ft).
- μ = Fluid Viscosity (kg/m.s or lbm/ft.h).

After knowing the Reynolds number value, the next calculation is carried out, namely calculating the heat transfer coefficient on the tube side, whose formula is influenced by the results of the Reynolds number. The equation is as follows: [8]

For laminar flow ($Re \leq 2100$),

$$h_i = (k/Di) 1.86[Re Pr Di/Pr]^{1/3} \quad (2)$$

For transtion flow ($2100 < Re < 10^4$),

$$h_i = (k/Di) 0.116[Re^{2/3} - 125]Pr^{1/3}[1 + (Di/L)^{2/3}] \quad (3)$$

For turbulent flow ($Re \geq 10^4$),

$$h_i = (k/Di) 0.023Re^{0.8}Pr^{1/3}(\mu/\mu_w)^{0.14} \quad (4)$$

Descriptions :

- h_i = Heat Transfer Coefficient in tube ($W/m^2.K$)
- k = Fluid Thermal Conductivity ($W/m.K$)
- Pr = Prandtl number

After obtaining the value of the heat transfer coefficient on the tube side, it will then calculate the heat transfer coefficient on the shell side, which begins with calculating the condensate loading can be calculated through the following equation.: [9]

$$\Gamma^* = \frac{W}{Lnt^{2/3}} \quad (5)$$

Descriptions :

- Γ^* = Condensate loading (kg/s.m or lbm/h.ft)
- W = Fluid mass flow (kg/s or lbm/h)
- L = tube long (m or ft)

So that the heat transfer coefficient can be calculated through the following equation:

$$h_o = 1.52 \left(\frac{K_L^3 \rho_L (\rho_L - \rho_V)}{4 \mu_L \Gamma^*} \right)^{1/3} \quad (6)$$

Descriptions :

- Ho = Heat Transfer Coefficient in shell (W/m².K)
- k_L = Condensate Fluid Thermal Conductivity (W/m.K)
- ρ_L = Condensate Density (kg/m³)
- ρ_V = Steam Density (kg/m³)
- μ_L = Viskositas condensate (kg/m.s)

3.2. Overall Heat Transfer Coefficient (UA)

Overall heat transfer coefficient of condenser supported by the value of convective heat transfer from the tube wall and shell and conductive heat transfer from the tube wall. The overall heat transfer coefficient can be found in the equation section below. [8]

$$U_c = \left[\frac{D_o}{h_i D_i} + \frac{D_o \ln(D_o/D_i)}{2k} + \frac{1}{h_o} \right]^{-1} \quad (7)$$

3.3. Heat Mass Balance

The heat transferred is the amount of heat that moves from the shell and tube sides through the tube walls in the heat exchanger per unit time. For that, we use the energy balance equation: [8]

$$\dot{m}_{Shell} (h_{Shell\ in} - h_{Shell\ out}) = \dot{m}_{Tube} (h_{Tube\ out} - h_{Tube\ in}) \quad (8)$$

and the heat transferred can be shown by the following equation:

$$q_{Shell} = \dot{m}_{Shell} (h_{Shell\ in} - h_{Shell\ out}) \quad (9)$$

$$q_{Tube} = \dot{m}_{Tube} (h_{Tube\ out} - h_{Tube\ in}) \quad (10)$$

Description:

q_{Shell} = The heat transfer rate of the hot fluid flow, kJ/s

q_{Tube} = The heat transfer rate of the cold fluid flow, kJ/s

\dot{m}_{Shell} = Mass flow rate in shell, kg/s

\dot{m}_{Tube} = Mass flow rate in tube, kg/s

Another formula for calculate for get value heat transfer.

$$q_{Shell} = \dot{m}_{Shell} \times C_p \text{ tube} \times (\Delta T_{shell}) \quad (11)$$

$$q_{Tube} = \dot{m}_{tube} \times C_p \text{ shell} \times (\Delta T_{tube}) \quad (12)$$

Description:

q_{Shell} = The heat transfer rate of the hot fluid flow, kJ/s

q_{Tube} = The heat transfer rate of the cold fluid flow, kJ/s

\dot{m}_{Shell} = Mass flow rate in shell, kg/s

\dot{m}_{Tube} = Mass flow rate in tube, kg/s

Cp. tube/shell = Coefficient heat transfer, kJ/Kg.K

$\Delta T_{tube}/shell$ = temperature difference, K

Energy efficiency is based on the first law of thermodynamics . It may take different forms and different names depending on the type of the system. Usually, energy efficiency can be written as: [2]

$$\eta = \frac{\text{Energy tube}}{\text{Energy shell}} \quad (13)$$

4. RESULT AND DISCUSSION

4.1. Result Simulation and Calculation

Before the simulation is carried out, it is necessary to calculate the shell and tube heat exchanger parameters according to the theoretical basis that has been explained. The following is the result of the parameter calculation.

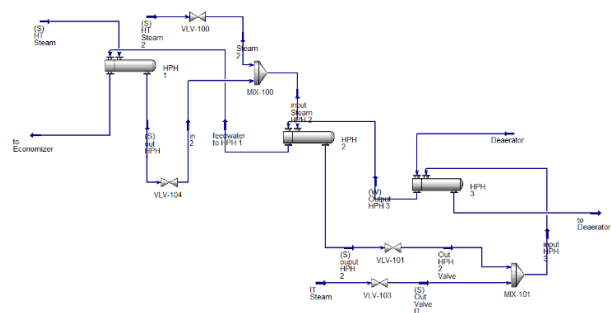


Figure 3 Modelling Three-stages HPH

HPH 1 is the highest hot working HPH system using high pressure turbine extraction. From the output value above, it can be explained that the feed/feedwater condition is expected to be used in the boiler. Meanwhile, the drain from HPH 1 will be used for heating in HPH 2. Furthermore, the drain from HPH 2 will be used in HPH 3.

Initially, the data is calculated by assuming the outline enthalpy (ho) under ideal conditions but in the actual case. There is a boundary, namely the condition of the transition film between the hot and cold sides. This causes the initial calculation to produce a heat transfer coefficient (UA), then after getting this value, it can be used in modeling software and get the simulation results.

Table 4. Result Calculation HPH 1

Temp. Wall	555.4890072	K	282.489	C
calculation hi				
Properties				
u (viscosity)	0.00010398	kg/ms	Pr	0.81392
cp	4.8381	kJ/kg ^o K	uw	0.000093663
conductivity	0.61807	W/m ^o K	u/uw	1.110150219
density	793.64	kg/m ³		
Re	451504.0096			
hi	38512.28602	W/m ² ·K		

Calculation ho from Temp. wall				
Tfilm	300.6167554	C	573.6168	K
Tsteam	355	C	628	K
Properties				
u,s	7.59825E-05	kg/ms	Pr	1.2275
cp,s	6.959	kJ/kg ^o K	k,f	0.55203
k,s	0.057638	W/m ^o K	Rho,f	693.73
Rho,s	23.912	kg/m ³	u,f	0.00008924
			cp,f	5.708168
r*	0.012009601			
ho	8564.374748	W/m ² ·K		

Perhitungan U dan UA yang pakai Tave	
Overall U	4612.789907 W/m ² ·K
Overall UA	10378777.29 W/ ^o C

Table 5. Result Calculation HPH 2

Tw	522.5685784	K	249.5686	C
Perhitungan hi				
Properties				
u (viscosity)	0.00012034	kg/ms	pr	0.83875
cp	4.5616	kJ/kg ^o K	uw	0.000109542
conductivity	0.6545	W/m ^o K	u/uw	1.098574364
density	841	kg/m ³		
Re	378101.8737			
hi	35689.62707	W/m ² ·K		

perhitungan ho Tw diketahui				
Tfilm	265.3014338	C	538.3014	K
Tsteam	312.5	C	585.5	K
Properties				
u,s	8.84988E-05	kg/ms	pr	1.03625
cp,s	5.9815	kJ/kg ^o K	k,f	0.60637
k,s	0.050653	W/m ^o K	Rho,f	771.312
Rho,s	27.094	kg/m ³	u,f	0.000103089
r*	0.012367646			
ho	9526.380571	W/m ² ·K		

Perhitungan U dan UA yang pakai Tave	
Overall U	4888.52824 W/m ² ·K
Overall UA	10510335.72 W/ ^o C

Table 6. Result Calculation HPH 3

Tw	500.4176707	K	227.4177	C
Perhitungan hi				
Properties				
u (viscosity)	0.00014249	kg/ms	pr	0.92077
cp	4.3911	kJ/kg ^o K	uw	0.00012053
conductivity	0.679	W/m ^o K	u/uw	1.1821855
density	881.9	kg/m ³		
Re	319445.9467			
hi	33720.8915	W/m ² ·K		

perhitungan ho Tw diketahui				
Tfilm	249.550753	C	522.5508	K
Tsteam	315.95	C	588.95	K
Properties				
u,s	8.74827E-05	kg/ms	pr	1.051775
cp,s	6.06085	kJ/kg ^o K	k,f	0.6239
k,s	0.047353	W/m ^o K	Rho,f	794.675
Rho,s	7.5073	kg/m ³	u,f	0.00010955
r*	0.010269005			
ho	10516.39598	W/m ² ·K		

Perhitungan U dan UA yang pakai Tave	
Overall U	5018.106956 W/m ² ·K
Overall UA	8530781.825 W/ ^o C

After the simulation runs well without any errors, it will give the remaining steam output and the heated feedwater.

Table 7. Result Simulation

Variable	Parameters	Unit	Value
Feedwater Output	Temperature	°C	264.7
	Pressure	bar	199.1
	Mass flow	kg/h	2002000
Steam Output	Temperature	°C	209
	Pressure	bar	19.49
	Mass flow	kg/h	370500

4.2. Heat Mass Balance

From the two analyzes of the heat mass balance calculation, it shows a low error value. This shows that the 3-level HPH system is running well.

Calculation of heat mass balance will be carried out from the input stream and the output of the product, which is the goal. Of course, the heat mass balance is expected to be equivalent to the resulting product, but generally, other factors cause the system to be not optimal. The data needed for the calculations are listed in table 8.

Table 8. Data For Calculation Heat Balance

Variable	Tube	Shell	Unit
Temperatur Input	179.2	420	Celcius
Temperatur Output	264.6	209	Celcius
Enthalpy Input	769.6	893.2	KJ/Kg
Enthalpy Output	1156.3	3226.8	KJ/Kg
Cp	4.5969	7.8036	kJ/Kg.K
Mass flow	573.361	141.429	Kg/s

The data above is the data obtained in the steam entering the system at HPH 1 and the steam output system when in HPH 3. In comparison, the feedwater data is obtained from the input tube for HPH 3 and the output tube for HPH 1. According to the operational configuration, namely, crossflow. Then the value of the data above is obtained. Furthermore, the calculation of the heat mass balance of the HPH system.

$$q_{shell} = \dot{m}_{shell}(h_{shell\ in} - h_{shell\ out}) \quad (9)$$

$$q_{shell} = 141.429 \frac{Kg}{s} \times \left(893.2 \frac{kJ}{Kg} - 3226.8 \frac{kJ}{Kg} \right)$$

$$q_{shell} = -238027.2 \frac{kJ}{s}$$

The shell side will have a negative value because the shell fluid will provide heat to the tube fluid so that the heat transfer value will always be greater than the tube side. Negative is a symbol of the work of the hot fluid flowing into the cold fluid.

$$q_{Tube} = \dot{m}_{Tube}(h_{Tube\ out} - h_{Tube\ in}) \quad (10)$$

$$q_{Tube} = 573.361 \frac{Kg}{s} \times \left(1156.3 \frac{kJ}{Kg} - 769.6 \frac{kJ}{Kg} \right)$$

$$q_{Tube} = 221696.7 \frac{kJ}{s}$$

Calculation for Efficiency.

$$\eta = \frac{Energy\ tube}{Energy\ shell} \quad (13)$$

$$\eta = \frac{221696.7 \frac{kJ}{s}}{238027.2 \frac{kJ}{s}}$$

$$\eta = 0.93$$

While on the tube side, it receives heat from the shell side, so it is positive. But theoretically, the heat transfer shell and tube must be the same. However, there is a difference in this value. To validate the calculation, it is calculated using another method to get the heat transfer value validation and be calculated as follows.

Another calculation

$$q_{Shell} = \dot{m}_{shell} \times Cp \times (\Delta T_{shell}) \quad (11)$$

$$q_{shell} = 141.429 \frac{Kg}{s} \times 7.8036 \frac{kJ}{Kg.K} \times (-211\ ^\circ C)$$

$$q_{shell} = -232871.2 \frac{kJ}{s}$$

$$q_{Tube} = \dot{m}_{tube} \times Cp \times (\Delta T_{tube}) \quad (12)$$

$$q_{Tube} = 573.361 \frac{Kg}{s} \times 4.5969 \frac{kJ}{Kg.K} \times (85.46\ ^\circ C)$$

$$q_{shell} = 225257.5 \frac{kJ}{s}$$

Calculation for Efficiency.

$$\eta = \frac{Energy\ tube}{Energy\ shell} \quad (13)$$

$$\eta = \frac{225257.5 \frac{kJ}{s}}{232871.2 \frac{kJ}{s}}$$

$$\eta = 0.96$$

4.3. Heat Loss and Efficiency

The difference in the value of the heat transfer at this HPH affects the system's performance in operation. Under ideal conditions, the HPH goal is to produce feedwater with a high temperature to reduce the workload of the steam generator or boiler fuel. The output tube is a crucial result.

Table 9. Heat Loss

Variable	Value	Unit	Efficiency
Calculation 1	16331.43	$\frac{kJ}{s}$	0.93
Calculation 2	7613.70	$\frac{kJ}{s}$	0.96

The heat mass balance calculation shows that the fluid does not completely absorb the energy on the shell side on the tube side. This error difference under normal field conditions occurs because the shell side must have a larger value. Energy can be channeled because there is a potential difference in power. The cause of the difference or unabsorbed residual energy is some field errors or unit damage like leaking tube that can affect the heat transfer.

Efficiency has a value of $\eta < 1$, but the existing value still shows a good value if it is assumed that there is normal heat loss in the field because the perfect system does not exist in field conditions, but this must still pay attention to other analyzes such as leaking, slugging, or uncondensate fluid.

In addition to operational analysis, this HPH system can evaluate operational performance compared to the initial design, as in the table below.

Table 10. Result & Design Operations

Variable	Parameters	Unit	Design	Result
Feedwater Output	Temperature	°C	310	264.7
	Pressure	bar	280	199.1
Steam Output	Temperature	°C	290	209
	Pressure	bar	23	19.49

When viewed from a design perspective, the difference between operational and design will look different. The value of the design is certainly more significant than the operational results. The purpose of this modeling will also be to evaluate how good the performance is when viewed from the HPH design. The previously calculated heat loss results can cause this difference. Besides, the operational value must be below the design because if the system overloads or

exceeds the work, it will pose a risk to worker safety and the system's durability of HPH.

5. CONCLUSIONS

From this research and observations from the results of the heat mass balance on the three stages High-Pressure Heater, the heat loss value is 7613.70 kJ/s to 16331.43 kJ/s. This is thought to be due to operational errors and minor unit damage so that the difference in value is still within reasonable limits. The value of heat loss results can be used to carry out corrective maintenance or for future data as a preventive measure on high-pressure heaters.

AUTHORS' CONTRIBUTIONS

This research will contribute to the energy generation business because it is able to provide an evaluation for cost savings.

ACKNOWLEDGMENTS

The author is very concerned about researching so that it can be helpful in industrial power plant. Further research is recommended to find out how much the loss is financially based on the consumption of coal or other fuels in the power plant industry.

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