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Energetic and exergetic performance computation of coal-fired steam power plant using IAPWS IF-97 formulation for target variable datasets generation in machine learning based performance prediction

A Y E Risano[1,*], A D Prabowo[1]

[1] Department of Mechanical Engineering, Faculty of Engineering, Universitas Lampung, Gd. H Lt 2, Jalan Prof. Soemantri Brojonegoro No. 1, Bandar Lampung, 35143 Indonesia

[*] E-mail: ayerisano@gmail.com

Abstract. More than 50% of power plants in Indonesia are Coal-Fired Steam Power Plants. According to the Ministry of Energy and Mineral Resources of Indonesia, coal reserves in Indonesia will run out in 67 years. Fuel saving can be done by operating the system at the highest efficiency operating conditions. These conditions can be determined by analysing the operating history of the system along with the energetic and exergetic performance produced using machine learning algorithm. Unfortunately, energetic and exergetic performance calculation of the Coal-Fired Steam Power Plants system that is not easy results in lack of system performance target datasets generated from the history of the Coal-Fired Steam Power Plants operation, so that the Steam Powerplant performance data generation software written using the Python programming language is created in this paper to calculate the Coal-Fired Steam Power Plants energetic and exergetic performance using IAPWS IF-97 formulation quickly and accurately. Accuracy of the software written in this paper was tested using the Coal-Fired Steam Power Plants performance values calculated manually as a comparison and result difference between the two types of calculations below 1% and able to cut manual calculation time from 142.46 minutes to 14.34 minutes using the software which is feasible to generate target variable datasets needed for performance prediction using machine learning algorithm.

Keywords: coal-fired steam power plant, performance, IAPWS IF-97, machine learning

1. Introduction

More than 50% of the power plants in Indonesia are Coal-Fired Steam Power Plants. Coal is a non-renewable natural resource and according to the Ministry of Energy and Mineral Resources of Indonesia, coal reserves in Indonesia will run out in 67 years [1]. Therefore, if Indonesia is not ready to utilize other energy sources, then half of Indonesia will suffer a power outage. Using coal in an efficient way is needed to extend the time of coal fuel usage.

In order to commit coal fuel saving, operating coal-fired steam power plant at the highest efficiency condition is needed. Steam power plant performance can be determined analytically by the function of

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complete operating parameters datasets [2]. Based on Tarahan coal-fired steam power plant heat rate test report, some operating parameters such as LP turbine steam quality, turbine outlet steam quality, regenerator drain properties are not available and boiler emission properties are only available once a year so that analytical method will result low accuracy [3].

Another method to determine the highest efficiency operating condition is using machine learning algorithm with thousands of operating parameters datapoints. Researches show that this method results high accuracy with less operating parameter needed but required huge amount of the power generated target variable and operating parameter function variable datapoint as data feed [4,5]. In order to get more advanced result, more target variable such as turbine, boiler, condenser, pump, and regenerator performance based on energy balance and exergy are needed.

Adding these new target variables cannot avoid analytical calculation so that analytical and machine learning method need to be combined. Performance target and operating condition variable correlation can be determined without completing the data needed as analytic method but the performance target variable datasets still need to be calculated analytically. Unfortunately, these analytical calculations are not easy, consuming a lot of time and require special competencies that yield lack of datapoint. To solve the problem, a fast computation is needed to generate the variable target datasets corresponding to Coal-Fired Steam Power Plants PT PLN Persero Tarahan Generation Sector 100 MW which is the steam power plant object used in this paper.

2. Materials and Method

Coal-Fired Steam Power Plants PT PLN Persero Tarahan Generation Sector 100 MW is a type of regenerative Rankine cycle with 5 preheating levels through heat exchangers before feed water enters the boiler where the heat source comes from turbine extraction vapor. The specification has 23 main conditions [6] with the graph of the Rankine regenerative cycle as follows

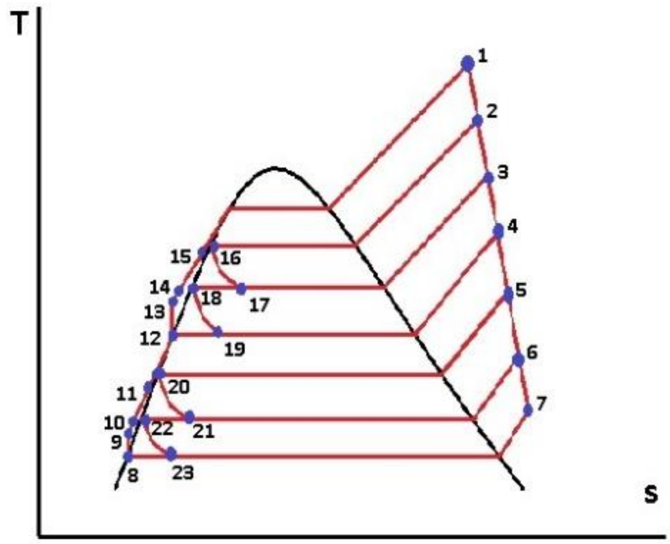


Figure 1. Tarahan Coal-Fired Steam Power Plants Rankine diagram

In order to calculate the performance of the main components of the Coal-Fired Steam Power Plants system, enthalpy and entropy values are needed which are functions of temperature and working fluid pressure. Manual enthalpy and entropy calculations can be done with the help of the Computer Aided Thermodynamics Table program as an alternative to the calculation by interpolating the values in the table of water-steam properties. While enthalpy and entropy calculations can automatically be done by creating an algorithm based on the IAPWS IF-97 standard which divides the water properties diagram into 5 areas [7] where each area has a different equation as shown below.

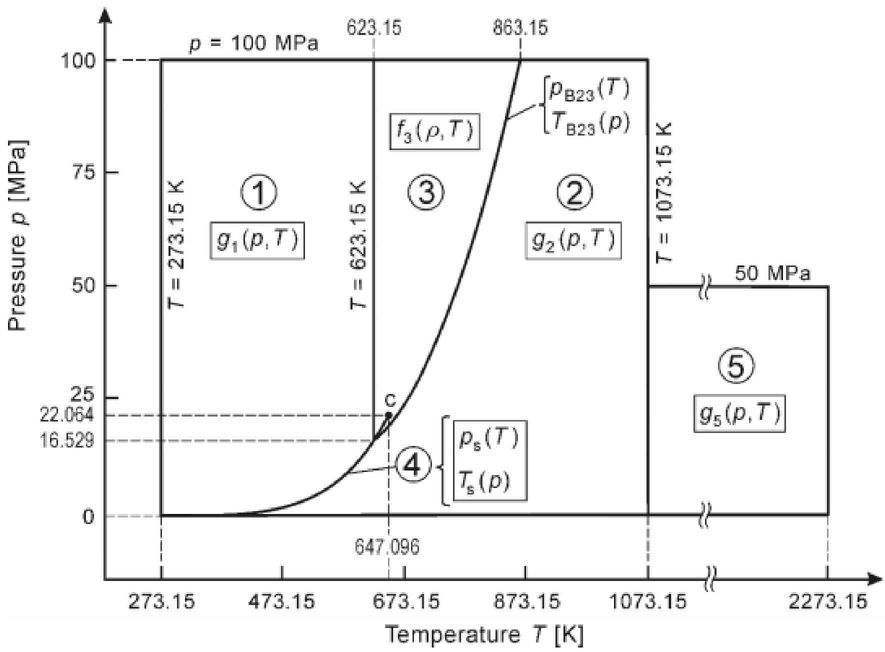


Figure 2. IAPWS IF-97 Diagram

Turbine performance can be obtained by calculating isentropic efficiency which is a comparison between actual work and isentropic work and exergetic efficiency which is a comparison of actual work with reversible work [8].

$$\eta_s = \frac{w_{aktual}}{w_s} \times 100\% \quad (1)$$

$$\eta_{II} = \frac{w_{aktual}}{w_{rev}} \times 100\% \quad (2)$$

Where:

η_s : Isentropic efficiency (%)
η_{II} : Exergetic efficiency (%)
w_{aktual} : Actual work (kW)
w_s : Isentropic work(kW)
w_{rev} : Reversible work (kW)

Steam turbine performance calculation with 5 extraction points is divided into 6 segments based on the mass flow difference. this division occurs because the mass flow of steam through the turbine decreases due to the steam extraction, so it is necessary to calculate the amount of steam extracted at each extraction point using the principle of energy balance [8]. Pump performance is obtained by calculating isentropic efficiency and exergetic efficiency which is almost identical to the turbine but the actual work is in the lower section.

Boiler performance is obtained by boiler energetic efficiency calculation with the direct method or directly comparing the energy stored in the steam produced with energy stored in fuel and indirect methods that analyze the components that cause energy loss in the boiler [11]. Boiler performance is also calculated based on exergetic efficiency which is a comparison between exergy flow of steam with exergy of fuel and combustion air [10].

$$\eta_{II\ boiler} = \frac{\psi_{steam}}{\psi_{fuel+}\psi_{air}} \times 100 \tag{3}$$

Where:

$\eta_{II\ boiler}$: Exergetic efficiency of boiler (%)
ψ_{steam} : Steam exergy flow (kJ/kg)
ψ_{fuel} : Fuel exergy flow (kJ/kg)
ψ_{air} : Air exergy flow (kJ/kg)

The exergy of coal fuel is obtained by analyzing the chemical exergy of coal constituent substances using this following equation [9].

$$\psi_{ch} = \left[\left(NCV + 2442.\, m_{H_2O}\right)\varphi_{dry}\right] + 9417.\left(\frac{m_S}{100}\right) \tag{4}$$

Where:

ψ_{ch} : Fuel exergy flow (kJ/kh)
m_{H_2O} : water-fuel fraction
φ_{dry} : dry fuel exergy (kJ/kh)
m_s : Sulphur-fuel fraction
NCV : Net Caloric Value fuel (kJ/kg)

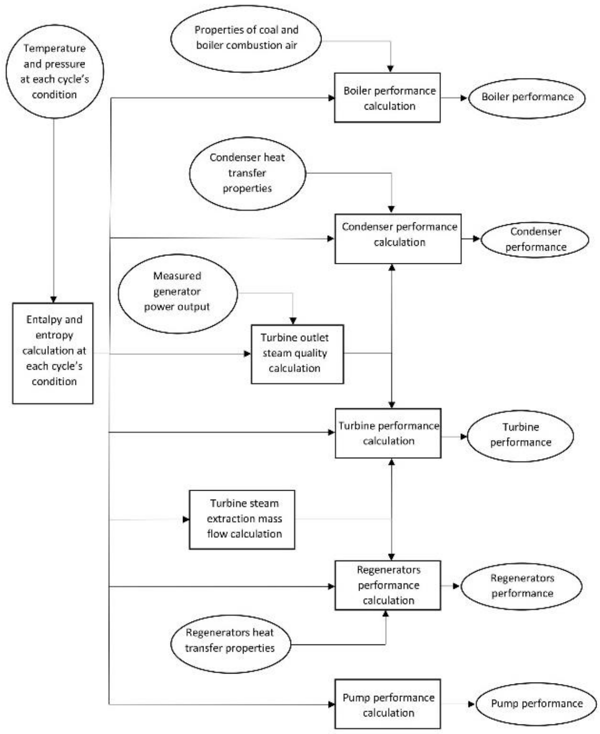
The condenser and regenerator are heat exchangers. The performance of the components is obtained from the effectiveness calculation of heat exchanger. The effectiveness of a heat exchanger is a comparison between the actual operating heat load and the maximum heat load that can be transferred by a heat exchanger [12]. The objectives of this study is to create a software that is able to calculate energetic and exergetic performance of Coal-Fired Steam Power Plants PT PLN Persero Tarahan Generation Sector with a maximum value of 1% difference compared to manual calculation and significantly reduce calculation time to make combined analytical and machine learning method feasible to conduct.

3. Results and Discussions

3.1. Header and footers

The software was written in Python 3 programming language with additional Scipy libraries to do scientific calculations, Pyqt5 library for building user interfaces, and iapws libraries to obtain enthalpy and entropy values from temperatures and pressures based on IAPWS IF-97 standards.

The program algorithm starts by calculating the enthalpy and entropy values from the temperature and pressure values entered based on the IAPWS IF-97 standard with corresponding filter created to minimize input error, then the enthalpy and entropy values generated are used as parameters in the Coal-Fired Steam Power Plants performance calculation as shown in the Fig. 3.



$T_1>T_2$ $P_1>P_2$
$T_2>T_3$ $P_2>P_3$
$T_3>T_4$ $P_3>P_4$
$T_4>T_5$ $P_4>P_5$
$T_5>T_6$ $P_5>P_6$
$T_6>T_7$ $P_6>P_7$
$T_7>T_8$ $T_8<T_9$
$P_8<P_9$ $T_9<T_{10}$
$P_9>P_{10}$ $T_{10}<T_{11}$
$P_{10}>P_{11}$ $T_{11}<T_{12}$
$P_{11}>P_{12}$ $T_{12}<T_{13}$
$P_{12}<P_{13}$ $T_{13}<T_{14}$
$P_{13}>P_{14}$ $T_{14}<T_{15}$
$P_{14}>P_{15}$ $T_{15}<T_1$

Figure 3. Software architecture and Input data filter

3.2. Validation and Software Testing

Validation of the software output values performed by comparing the Coal-Fired Steam Power Plants performance values generated by the program with the performance values of manual calculation. The operation procedure of the software starts by entering the temperature, pressure, and mass flow values needed as well as the coal constituent substances as shown on Fig. 4.

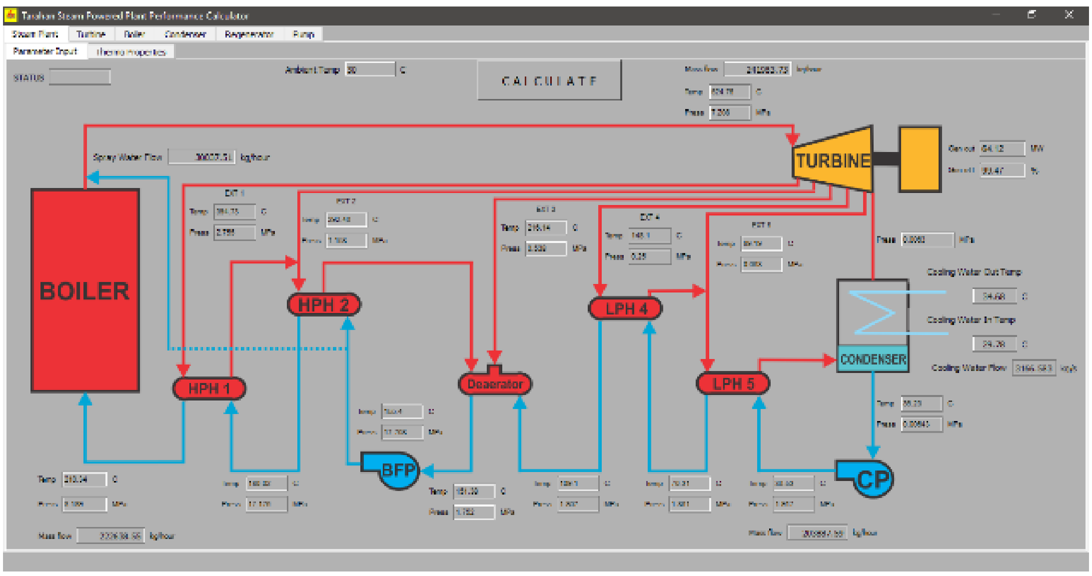


Figure 4. Input page of the software

The data used is the annual performance test results of PT PLN PERSERO Tarahan Generation Sector in 2017 with load variations of 64.12 MW, 74.25 MW, 86.02 MW, and 100.82 MW. As all the required data has been inputted, by clicking the calculate button, the calculation algorithm starts running and the performance value of the PLTU components will appear on each component's page. Re-checking the software input data is performed by looking at the status bar that is correct if the status "PASS" appears and somethings are incorrect if the "RECHECK" status appears.

The Coal-Fired Steam Power Plants main components performance values generated by the software are compared with the performance value obtained by manual calculations using the same operating data so that the difference between the two calculation methods are obtained as the following Table 1 to Table 6.

Table 1. Comparison of the calculation of steam turbine performance manually and using software.

Efficiency	Load (MW)	Manual (%)	Software (%)	Difference (%)
Isentropic	64.12	83.19	83.13	0.07
	74.25	86.63	86.61	0.02
	86.02	85.48	85.44	0.05
	100.82	82.54	82.43	0.13
Exergetic	64.12	84.17	84.15	0.02
	74.25	87.74	87.73	0.01
	86.02	86.69	86.66	0.03
	100.82	83.80	83.85	0.06

Table 2. Comparison of the calculation of boiler performance manually and using software

Efficiency	Load (MW)	Manual (%)	Software (%)	Difference (%)
Energetic	64.12	80.77	80.79	0.02
	74.25	75.70	75.72	0.03
	86.02	81.08	81.11	0.04
	100.82	86.78	86.78	0.00
Exergetic	64.12	26.85	26.86	0.04
	74.25	24.90	24.89	0.04
	86.02	26.21	26.22	0.04
	100.82	28.85	28.83	0.07

Table 3. Comparison of the calculation of condenser performance manually and using software

Load (MW)	Effectiveness		
	Manual (%)	Software (%)	Difference (%)
64.12	54.94	54.92	0.03
74.25	59.84	59.81	0.04
86.02	58.63	58.62	0.02
100.82	54.53	54.52	0.02

Table 4. Comparison of the calculation of regenerators performance manually and using software.

Regenerator	Load (MW)	Effectiveness		
		Manual (%)	Software (%)	Difference (%)
HPH 1	64.12	91.01	91.06	0.06
	74.25	86.63	86.67	0.05
	86.02	84.14	84.16	0.03
	100.82	78.99	79.03	0.05
HPH 2	64.12	77.40	77.44	0.06
	74.25	73.97	74.08	0.14
	86.02	74.03	74.07	0.05
	100.82	70.40	70.46	0.08
LPH 4	64.12	82.98	82.97	0.01
	74.25	77.36	77.36	0.00
	86.02	80.51	80.51	0.00
	100.82	78.29	78.32	0.04
LPH 5	64.12	95.73	95.73	0.00
	74.25	92.19	91.95	0.26
	86.02	94.91	94.85	0.06
	100.82	93.61	93.53	0.08

Table 5. Comparison of the calculation of Condensate Pump (CP) performance manually and using software.

Efficiency	Load (MW)	Manual (%)	Software (%)	Difference (%)
Isentropic	64.12	64.75	64.88	0.02
	74.25	64.51	64.71	0.31
	86.02	69.17	69.16	0.01
	100.82	68.80	68.95	0.22
Exergetic	64.12	66.09	65.6	0.74
	74.25	65.86	65.57	0.44
	86.02	70.37	70.12	0.36
	100.82	69.86	69.77	0.13

Table 6. Comparison calculation of Boiler Feed Pump (BFP) performance (manually and software)

Efficiency	Load (MW)	Manual (%)	Software (%)	Difference (%)
Isentropic	64.12	63.89	63.99	0.16
	74.25	68.02	67.48	0.79
	86.02	86.26	86.26	0.00
	100.82	72.60	72.55	0.07
Exergetic	64.12	74.62	74.46	0.21
	74.25	77.68	77.39	0.37
	86.02	90.95	90.55	0.44
	100.82	81.09	81.05	0.05

Based on the data presented on Tables 1 to 6, there is no difference value that exceeds 1% between values obtained by manual calculation and generated by the software. Then the software operating

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speed testing was performed by 20 people with mechanical engineering background, each tested to calculate the energetic and exergetic performance manually aided with Computer Aided Thermodynamics Tables 3 and Microsoft excel filled with calculation template. Then the time consumed in manual calculation compared to the time consumed to calculate energetic and exergetic performance using software written. The result shows the software can have shortened energetic and exergetic performance calculation from 142.46 minutes manually to 14.34 minutes using the software.

4. Conclusion

A software that be able to calculate energetic and exergetic performance of Coal-Fired Steam Power Plants PT PLN Persero Tarahan Generation Sector was written. Performance value generated by the software and obtained by manual calculation was compared and found no difference value exceeds 1% and be able to shortened average calculation time from 142.46 minutes manually to 14.34 minutes using the software to generate 1 datapoints which is feasible to support combined analytical and machine learning method to conduct in future research

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