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Performance analysis of a single-cylinder type steam turbine with a capacity of 3.5 mw using enthalpy drop method

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Abstract

The performance capability of the steam turbine under factory conditions will experience changes that can be caused by operating or environmental factors. Therefore, it is necessary to analyze the performance of the steam turbine during the actual condition so that it can be compared with the performance of the steam turbine from the manufacturer using mass and energy balance equations on HP heater #1 and deaerators and iteration methods. The research was conducted by looking at the phenomena that occur in the steam turbine using mathematical models and theories when the unit operates according to the heat balance design parameters. Feedwater flow from the calculation of the iteration method based on the equation of the water heater obtained a value of 17,961.58 kg/h. The performance steam turbine experienced a decrease in efficiency with a value for isentropic efficiency of 72.73% down 6.54% from the design value of 79.27% and thermal efficiency of 26.88% down 1.75% from the design value of 28.64%. Meanwhile, the steam rate value of 5.03 kg/kWh increased by 0.44 kg/kWh from the design value of 4.59 kg/kWh, and the turbine heat rate of 3198.83 kcal/kWh, an increase of 196.08 kcal/kWh from the design value of 3002.75 kcal/kWh.

Keywords:
Efficiency;
Heat Balance;
Iteration;
Performance;
Steam Turbine;

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INTRODUCTION

Energy needs have become human needs in the word because energy is covered all aspect of everyday human life. In Indonesia, the government have the project to increase domestic electricity generation capacity by 35,000 MW [1]. In the steam generator, chemical energy available in fossil fuel is converted to heat energy by combustion. The thermal energy if the steam is converted to mechanical energy and then to electrical energy in the steam turbine and generator. The steam power plant working is based on Rankine cycle, where the increasing of the superheated steam temperature lead to improving the thermal efficiency of cycle as thermodynamics process [2, 3, 4].

A steam turbine was important equipment for a thermal power plant. A steam turbine is a prime mover in which the potential energy of the steam is transformed into kinetic energy and later in its turn is transformed into the mechanical energy of rotation of the turbine shaft. A steam turbine is consisting of high pressure, low pressure, and moderate pressure [5, 6, 7, 8].

To optimize the operating conditions the temperature and pressure of the steam inlet and exhaust pressure of the turbine can significantly affect the performance of the turbine. The variation of these parameters can affect the steam consumption in the turbine and also the efficiency of the turbine.

Where the ability of the turbine when in factory conditions will certainly experience changes to performance when operating. These changes can be caused by operating or environmental factors [9, 10, 11].

Therefore, it is necessary to analyze the performance of a single cylinder steam turbine with a capacity of 3.5 MW to determine the actual performance of the steam turbine to serve as a performance reference when the unit operates routinely.

Steam turbine performance analysis is generally carried out based on the Standard of ASME PTC 6 as a standard of test to prove the performance of the steam turbine with design values. Performance tests carried out according to ASME PTC 6 are an accurate method for determining the performance of a steam turbine.

The standard ASME PTC is contained rules and procedures for the implementation and reporting of steam turbine tests and measurement methods, test techniques, and methods for calculating test results [12][13]. Performance parameters that can be determined from the test include heat rate, generator power, steam flow, steam rate, and feedwater flow. Therefore, it is necessary to analyze the performance of a single-cylinder type steam turbine with a capacity of 3.5 MW in a steam power plant based on a test method according to the ASME PTC 6 standard. To determine the performance of a single-cylinder type steam turbine with a capacity of 3.5 MW will be compared with the performance of the manufacturer.

METHOD

This research will be conducted on a coal fire steam power plant with a capacity of 3.5 MW. The research will use the method mass and energy balance to determine feedwater flow and steam flow as per the following ASME PTC 6 Steam Turbine Performance on the water heater, while for the performance of the steam turbine use the enthalpy drop method. The research will compare the actual performance of the steam turbine with the manufacturing design at a rated load of 3,5 MW.

Material

This research was conducted using coal fuel with the specification as follows High Heating Value (HHV) 3800 kcal/kg, Moisture (Mr) 36.28 %, Ash (As) 4.67 %, Sulfur (S) 0.16 %, Carbon (C) 50.96 %, Hydrogen (H) 3,76 %, Nitrogen (N) 0.71 %, and Oxygen (Ox)15.58 %. This test material is used as a test sample**.**

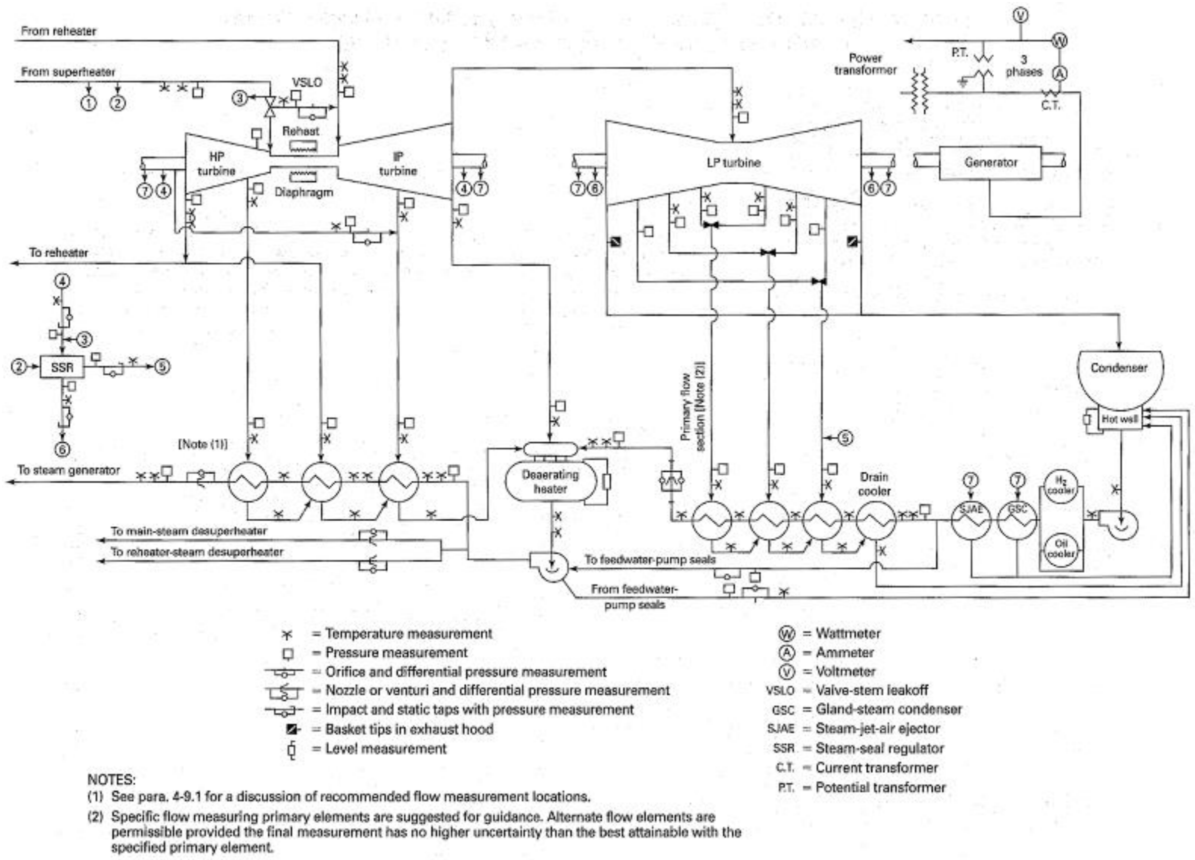

Figure 1. Location and Types of Test Instrumentation

Standard ASME PTC 6 – Steam Turbine Performance Test Method

The accuracy of the test results depends on the isolation of the generating system so that when testing the unit must be operated in an isolated condition so that there is no incoming and outgoing fluid flow. Isolation of the system is carried out before the test which is carried out by closing the valve whose flow must be isolated [12]. isolation deals with flows that enter or leave the turbine cycle, such as condensate make-up or boiler blowdown flow. This system isolation shall be affected so that the difference between the sums of the measured storage changes and entering and leaving flows is minimized.

The parameter measurements that will be used for this research will follow the rules as recommended by the ASME PTC 6 standard. For location and type of instrumentation will use during performance can show the location on Figure 1. If the feedwater cycle has a deaerator, it is recommended that condensate flow entering it be measured as primary flow. This eliminates the possibility of any heater tube leakage recirculating through the flow measuring device [12].

Balance of Mass and Energy High Pressure Heater and Deaerator

If the primary flow is measured in the condensate flow, then the feedwater flow must be calculated using the mass and energy balance method in the water heater[14]. As per the design heat balance of the steam power plant with a capacity of 3.5 MW has a high-pressure heater and deaerator, which can show in Figure 2 and Figure 3.

The feedwater flow from deaerator is calculated by mass and energy balance around the deaerator. From mass balance design of heat balance [15, 16, 17], as in (1).

$$G_{fw} = G_{e1} + G_{e2} + G_{cw} \tag{1}$$

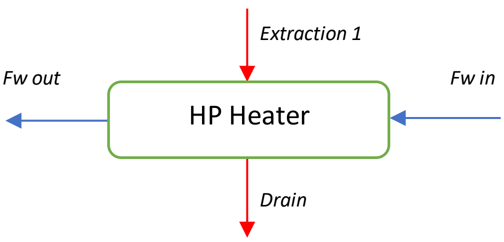

Figure 2. Mass Balance of High-Pressure Heater

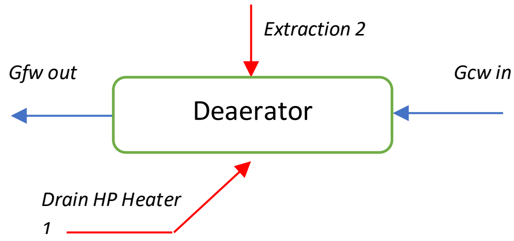

Figure 3. Mass Balance of Deaerator

From mass and energy balance the equation from high-pressure heater in the design of heat balance [17][18][19], as in (2).

$$G_{e1} = G_{fw} \times \left(\frac{H_{wo1} - H_{wi1}}{H_{e1} - H_{d1}}\right) \tag{2}$$

From mass and energy balance the equation from deaerator in the heat balance, as in [17][18][19].

$$G_{e2} = \frac{G_{fw} \times H_{fw} - G_{cw} \times H_{cw} - G_{e1} \times H_{d1}}{H_{e2}} \tag{3}$$

The value of the condensate flow will use the orifice flow nozzle measurement results from DCS.

The main steam flow from boiler is given by, as in

$$\dot{m} = G_{fw} - G_{leak} \tag{4}$$

During the testing of isolated steam and water cycle conditions, the assumption for the leakage value (G_{leak}) is 0.

Fixed-Point Iteration Numeric Method

Fixed point iteration is a method for solving an equation of the form f(x) = 0. The method is carried out by rewriting the equation in the form [20, 21, 22].

$$x = g(x) \tag{5}$$

When x is solution of f(x) = 0, the left side and the right side are equal. The numerical value of the solution is determined by an iterative process. The value of g(x) that is obtained is the new (second) estimate for the solution. The second value is then substituted back in g(x), which then gives the third estimate of the solution. The iteration formula is thus given by [21][22]

$$x_{i+1} = g(x_{i+1}) \tag{6}$$

The approximate error for this equation can be determined using the error estimator as in:

$$\varepsilon_a = \left|\frac{x_{i+1} - x_i}{x_{i+1}}\right| 100\% \quad (7)$$

Performance Steam Turbine

Turbine efficiency is the ratio of mechanical work output in kCal (or kJ) to the total heat available across the turbine in kCal (or kJ) expressed as a percentage. The introduce the isentropic turbine efficiency, refer to Figure 4, which show a turbine expansion on a Mollier diagram [23, 24, 24]

With assumptions, heat transfer between the turbine and its surrounding is ignored, the mass and energy rate balance reduce, at steady state, to give the work developed per unit of mass flowing through the turbine[23][24], as in.

$$\frac{\dot{W}_{cv}}{\dot{m}} = h_1 - h_2 \quad (8)$$

Since state is fixed, the specific enthalpy h_1 is known. Accordingly, the value of the work depends on the specific enthalpy h_2.

The state labeled "2_s" on Figure 4 would be attained only in the limit of no internal irreversibility. For fixed exit pressure, the specific enthalpy h2 decreases as the specific entropy s2 decreases. The smallest allowed dor h2 corresponds to state 2s, and maximum value for turbine work as in;

$$\left(\frac{\dot{W}_{cv}}{\dot{m}}\right)_s = h_1 - h_{2s} \quad (9)$$

In an actual expansion through the turbine $h_2 > h_{2s}$, and thus less work than the maximum would be developed. This difference can be gauged by isentropic turbine efficiency defined by

$$\eta_{is} = \frac{W_{cv}/\dot{m}}{(W_{cv}/\dot{m})_s} = \frac{h_1 - h_2}{h_1 - h_{2s}} \quad (10)$$

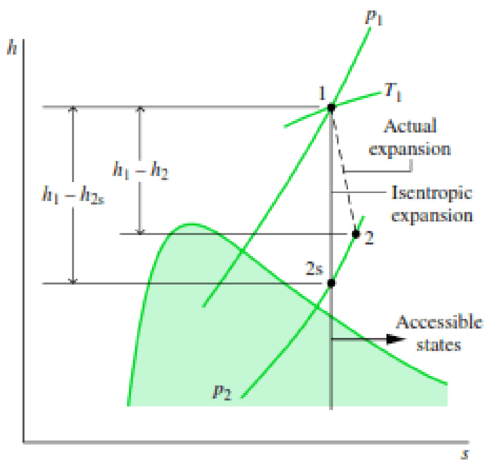

Figure 4. Comparison of actual and isentropic expansions through a turbine.

For turbine with regenerative feed heating, the thermal efficiency is the significant criterion. It is defined as the ratio of power output to heat added to the cycle from external sources [25][26].

$$\eta_t = \frac{P}{\sum(\dot{m}\,\Delta h_j)} \quad (11)$$

The heat rate traditionally has been used and is still used for the same objective as thermal efficiency, which is applied in these rules [25][26].

$$HR = \frac{3600}{\eta t} \quad (12)$$

The steam rate traditionally has been used as a performance criterion for turbines. It is defined as the ratio of initial steam flow rate to power output and is connected with thermodynamic efficiency [26][27] as follows in.

$$SR = \frac{\dot{m}}{P} = \frac{1}{\eta_{td}\,\Delta h_s} \quad (13)$$

RESULTS AND DISCUSSION

In the first stage, using the fixed-point iteration method to determine the feedwater flow is to assume the value of the feedwater flow based on the design value of the heat balance is 16.069.00 kg/h.

The result of the computation of feedwater flow using the fixed-point iteration method is shown in Table 1. From Table 1. where computation progresses repeated condition of these methods always results in closer estimates of the true value of the root so these methods are said to be convergent. Notice that the percent relative error on iteration 7th of Table 1. is zero percent.

The iteration process in 7th is the result of the value of feedwater flow which value is 17,961.58. Where the test conditions are in isolated, it can be assumed that there is no leakage in the system so that the main steam flow ($\dot{m}$) is the same as the feedwater flow value of 17.961.58 kg/h. The results of the difference in the measurement and Iteration method for feedwater and steam flow can be seen in Figure 5.

Table 1. Process Iteration of Feedwater Flow

Iteration	x1	x2	e
1	16,069.00	17,800.75	0.097285
2	17,800.75	17,947.91	0.008199
3	17,947.91	17,960.42	0.000697
4	17,960.42	17,961.48	0.000059
5	17,961.48	17,961.57	0.000005
6	17,961.57	17,961.58	0.00000043
7	17,961.58	17,961.58	0.000000000

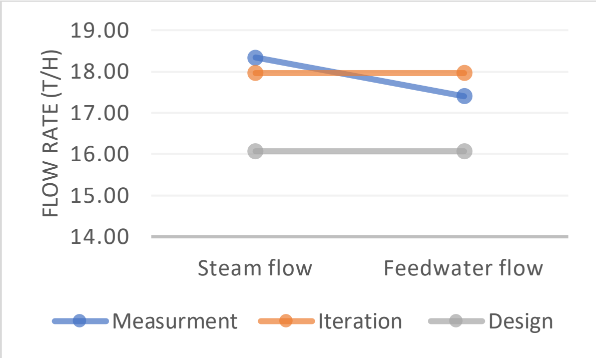

Figure 5. Graph of Feedwater and Steam Flow Comparison Chart

Based on Figure 5. Theoretically, the feed water flow value is equal to or less than the main steam flow value, but for the measurement results, the main steam flow value is higher than the feed water flow with a large difference of 0.94 T/h. While the results of the main steam flow and feedwater flow with the iteration method are higher than the manufacturer's design with a difference of 1.89 T/h. In Figure 6 and Figure 7 h-s diagrams, the result of the isentropic efficiency of the turbine is the result of a comparison between the turbine work achieved under isentropic conditions, namely the entropy value of the turbine inlet is equal to the value of the turbine exit (Ws) with the value of the actual work (Wa). Regarding the results of the isentropic efficiency values and calculations, it can be seen in Table 2. Steam turbine enthalpy drop at the manufacturer's design conditions and Table 3. Turbine enthalpy drop during actual condition.

In Table 2, it is known that steam enters the turbine (no. 1) at a pressure of 4.9 MPa(a) and a temperature of 470 oC and from the steam table the enthalpy value is 3365.4 kJ/kg and the entropy value is 6.8949 kJ/kg.K.

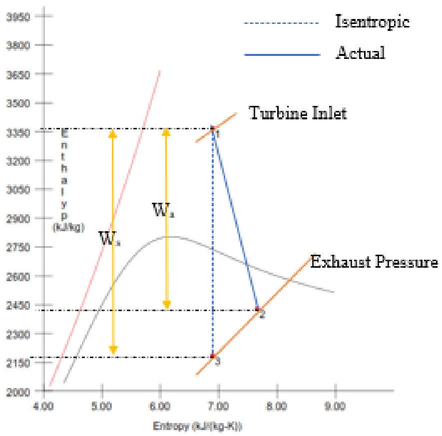

Figure 6. h-s Diagram Design Condition

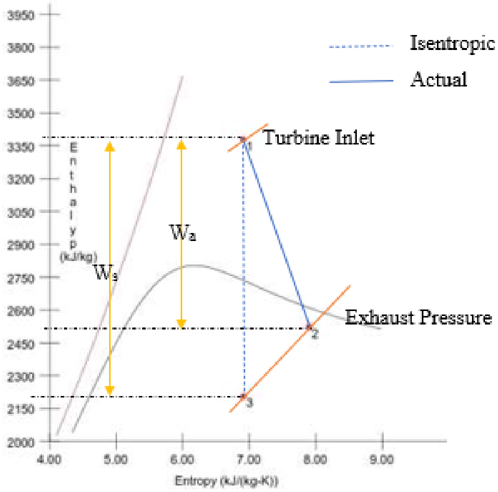

Figure 7. h-s Diagram Actual Condition

The steam leaving the turbine (no. 2) at a pressure of 0.01 MPa(a) and a temperature of 45.8 oC and for the actual enthalpy value is 2428.9 kJ/kg and the isentropic enthalpy value at the same entropy as the incoming steam (no. 1) is 6.8949 kJ/kg.K the isentropic enthalpy value (no. 3) is 2183.96 kJ/kg. so that the value of the isentropic enthalpy drop is 1181.44 kJ/kg and the actual enthalpy drop is 936.5 kJ and the isentropic efficiency is 79.27%.

In Table 3, it is known that steam enters the turbine (no. 1) at a pressure of 4.923 MPa(a) and a temperature of 475,879 oC and from the steam table using the interpolation equation, the enthalpy value is 3379.02 kJ/kg and the entropy value is 6.91079 kJ/kg K. actual of the steam turbine exit (no. 2) at a pressure of 0.0114 MPa(a) and a temperature of 47,322 oC and for the actual enthalpy value at 2523.74 kJ/kg and isentropic enthalpy value (no. 3) at the same entropy as the steam inlet (no. 1) is 6.91079 kJ/kg K, the isentropic enthalpy value is 2203,029 kJ/kg. so the value of the isentropic enthalpy decrease is 1175.99 kJ/kg and the actual enthalpy decrease is 855.28 kJ and the isentropic efficiency is 72.73%. Turbine work is the difference between the enthalpy value entering the turbine minus the enthalpy value coming out of the turbine, where the difference in the value of the heat energy will be converted by the steam turbine to be used as electrical energy.

The decrease in the isentropic efficiency value in the actual condition results in an increase in the amount of steam consumed to produce 3.5 MW of power. This is due to an increase in the pressure value on the condenser side where the manufacturer's design value should be 10 kPa(a) to 11,442 kPa(a).

Table 2. Stage Group Efficiency Enthalpy Drop Method Design Condition

Location	Description	Pressure MPa (a)	Temperature °C	Enthalpy kJ/kg	Entropy kJ/kg. K
1	Turbine Inlet	4.9	470	3365.4	6.8949
2	Turbine Outlet	0.01	45.8	2428.9	
3	Turbine Outlet			2183.96	6.8949

Table 3. Stage Group Efficiency Enthalpy Drop Method During Actual Condition

Location	Description	Pressure MPa (a)	Temperature °C	Enthalpy kJ/kg	Entropy kJ/kg. K
1	Turbine Inlet	4.923	475.879	3379.02	6.91079
2	Turbine Outlet	0.0114	47.322	2523.74	
3	Turbine Outlet	-	-	2203.029	6.91079

Table 4. The Comparison Actual with Design Condition

No.	Item	Unit	Actual	Design
1	Generator Power Output	kW	3,5729.79	3,500
2	Isentropic Efficiency	%	72.73	79.27
3	Thermal Efficiency	%	26.882	28.635
4	Steam Rate	kg/kWh	5.03	4.59
5	Heat Rate	kcal/kWh	3,198.828	3,002.753

The results of the performance of the steam turbine in the actual condition are then compared with the performance value of the manufacturer's design which is used as a reference in analyzing the performance of the steam turbine in a steam power plant. The comparison can be shown in the Table 4. The results of the research during the Actual Condition, the value that meets the results of the manufacturer's design is the generator power output.

The measurement results for the generator power when compared with the manufacturer's design value have exceeded 72.97 kW. Where the measurement results of the generator output power during the actual condition are 3572.97 kW from the manufacturer's design value of 3500 kW.

The results for the isentropic analysis of the efficiency of the steam turbine obtained during the actual condition are 72.73% lower than the manufacturing design value of 79.27%. And for the results of the analysis of thermal efficiency at the time of actual the process is 26.882% lower than the value of the manufacturer's design thermal efficiency of 28.635%. where this value does not meet the results of the manufacturer's design.

The result of the analysis for the steam rate required for the steam turbine to produce 1 kWh of power during the actual condition is 5.03 kg/kWh which is higher than the manufacturer's design value of 4.59 kg/kWh. which results in the steam turbine requiring a higher steam rate to produce 1 kWh of power at an additional 0.44 kg/kWh than the manufacturer's design.

From the analysis, the turbine heat rate in the actual condition is 3198,828 kCal/kWh compared to the manufacturer's design value of 3002,753 kCal/kWh at 100% load. The increase in the value of the Heat Rate indicates that to produce a load of 3.5 MW, the steam turbine requires greater heat energy of 196,075 kCal/kWh [28][29].

This research was conducted at design power plant with a high-pressure water heater and deaerator and single-cylinder type turbine where without reheating. In the future, this research can be carried out on a generator with a larger capacity by using reheating where the design of the generator for the water heater will be more widely used.

CONCLUSION

Conclusions from the results of this study are as follows. The results of the analysis on the steam turbine in the actual condition where the test uses a test method based on the ASME PTC 6 standard recommendation and uses a fixed-point iteration method on the mass and energy balance equations on the HP heater and deaerator.

1. The iteration results obtained a feed water flow value of 17.961.58 kg/hour in the 7th iteration process. From the results of the value of the feed water flow, it is then used to analyze the performance of the steam turbine. where the analysis results obtained for the performance of the steam turbine have decreased when compared to the manufacturer's design value.
2. In the actual condition, the isentropic efficiency value is 72.73%, decreased by 6.54% from the design value of 79.27%, and thermal efficiency of 26.88% decreased by 1.75% from the design value of 28, 64%. While the steam rate value is 5.03 kg/kWh, an increase of 0.44 kg/kWh from the design value of 4.59 kg/kWh, and the turbine heat rate is 31988.83 kcal/kWh,

an increase of 196.08 kcal/kWh from the design value 3002.75 kcal/kWh.

To improve turbine performance, the vacuum pressure can be increased so that it is close to the design value by cleaning the tube condenser and checking for leaks in the vacuum condenser system.

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