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Thermodynamic Analysis of Centrifugal Water Chiller Refrigeration Performance at PT X

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***Abstract* - Water chiller is a crucial air conditioning unit in various industries, tasked with efficiently cooling large spaces. It utilizes two refrigerants, primary and secondary, during its cooling process. A well-functioning air conditioning system not only ensures human comfort but also benefits machinery and the overall environment. However, one significant issue leading to excessive electricity consumption is the mismatch between the refrigeration system's initial design and its real-world operation. To ensure energy efficiency, it's essential to evaluate the chiller's performance meticulously. To analyze the water chiller's performance, data was collected from its control panel over three days. This data includes water pressure and temperature both entering and exiting the evaporator, set point ampere, and compressor power. With this data, the actual Coefficient of Performance (COP) can be calculated and compared against the design COP. The research findings reveal that between January 23, 2023, and January 25, 2023, the chiller's actual COP falls below the design COP at 05:00, 08:00, 11:00, and 21:00. However, at 23:00, the actual COP surpasses the design COP. In conclusion, the water chiller demonstrates less efficient cooling during specific hours, resulting in heightened energy consumption.**

Keywords: Thermodynamic, Centrifugal, Water Chiller, Refrigeration Performance, COP, energy consumption.

I. INTRODUCTION

As technology develops, air conditioning systems are increasingly being used in industries such as power generation, oil and gas, food and beverage, pharmaceuticals, and others. An air conditioning system is important because a good air conditioning system will produce fresh air that makes people, machines and the surrounding environment comfortable[1]. The main purpose of using an air conditioning system is to control and maintain temperature stability. In general, the working principle is to absorb heat from a room and release it to the environment.

One of the air conditioning systems that is widely used is a water chiller. Water chiller infers that the compressor, condenser and chiller with internal piping and controls are combined into a single unit[2]. Water chiller may range in size from small capacity reciprocating compressor units with air or water cooled condensers up to large units incorporating centrifugal or screw compressor. The water chiller is one of the main components of central AC which is tasked with cooling the air that will flow into the room. Central AC is widely used in large buildings (office buildings, shopping centres, hotels, hospitals, universities and factories) because it has a bigger cooling capacity than other types of AC. The larger the room, the greater the cooling load borne by the cooling machine[3].

The water-cooled chiller is used more often than air-cooled chiller (other types of chiller with air as a cooling medium for the condenser) because water is a more space-efficient heat transfer medium than air, and therefore works well in space-constrained applications such as high-rise buildings. One pound of water can store about four times as much thermal energy as the same mass of air, and because water is much denser than air, a pound of water has a much smaller volume than the pound of air[4].

The proportion of power consumption for air conditioning equipment in buildings is about 23–56%. If people's daily air conditioning use is not included, the proportion is about 45–56%, which shows that the central air conditioning system is the most energy-consuming piece of equipment in most buildings[5]. The excessive use of electrical energy can have a negative impact on the environment and high operational costs. Its energy consumption can cover 70% of energy consumption under the worst operating conditions[6]. The mismatch between the system's operating pattern during design and actual conditions is one of the causes of high electricity consumption [7]. The power consumption of the chiller compressor is the highest, accounting for about 50-60% of the total air conditioning system[5]. Reducing the power consumption of chiller compressors while also improving their operational efficiency has become an important energy-saving direction.

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Therefore, it is necessary to analyze the cooling performance (Coefficient of Performance/COP) to find out how efficient the machine is in using electrical energy. By carrying out this analysis, corrective maintenance can be taken to increase efficiency, thereby reducing operational costs and greenhouse gas emissions into the environment. Futhermore, it detect where waste takes place, identify the most critical points and discover opportunities where energy consumption can be reduced [8].

II. RESEARCH METHODOLOGY

The following is a flowchart of the steps involved to determine the water chiller Coefficient of Performance (COP). Figure 1 shows the flowchart of COP calculation.

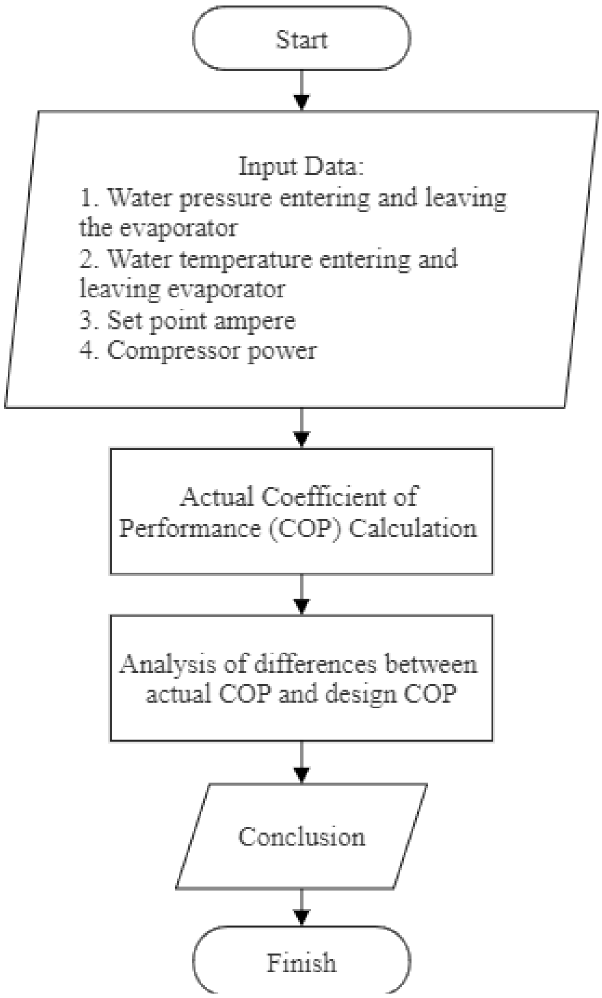

Figure 1: Flowchart of COP Calculation

2.1 Chiller Specification

Type: Centrifugal Water Chiller
Cooling Capacity: 2905 kW
Voltage/Phase/Frequency: 380V-3PH-50Hz
Input Power: 513 kW
Refrigerant: R134a
Refrigerant Weight: 709 kg
The chiller design performance output can be seen in the following Table 1.

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Table 1: Chiller Design Performance Output

Output Type	Percent Load						
	100%	90%	80%	70%	60%	50%	46%
Chiller Capacity	825 Tons	742 Tons	660 Tons	578 Tons	495 Tons	413 Tons	379 Tons
Chiller Input kW	513 kW	450 kW	403 W/	381kW	350 tiW	317 kW	300 kW
Chiller Input Power	0,177 ikW/kW	0,172 ikW/kW	0,174 ikW/kW	0,188 ikW/kW	0,201 ikW/kW	0,218 ikW/ kW	0,225 ikW/kW
Chiller COP	5,7	5,8	5,8	5,3	5	4,6	4
Cooler							
Entering Temp.	12 C	11,49 C	10,99 C	10,49 C	10 C	9,5 C	9,3C
Leaving Temp.	7 C	7 C	8 C	9 C	10 C	11 C	12 C
Flow Rate	138,6 L/s	138,6 L/s	138,6 L/s	138,6 L/s	138,6 L/s	138,6 L/s	138,6 L/s
Pressure Drop	99,2 kPa	99,4 kPa	99,5 kPa	99,7 kPa	99,8 kPa	100 kPa	100 kPa
Condensor							
Entering Temp.	37 C	36,5 C	36,01 C	35,56 C	35,08 C	34,62 C	34,43 C
Leaving Temp.	32 C	33 C	34 C	35 C	36 C	37 C	38 C
Flow Rate	164,3 L/s	164,3 L/s	164,3 L/s	164,3 L/s	164,3 L/s	164,3 L/s	164,3 L/s
Pressure Drop	94,3 kPa	94,5 kPa	94,5 kPa	94,6 kPa	94,7 kPa	94,8 kPa	94,8 kPa

2.2 Chiller Plant Layout

The chiller plant consists of 4 chillers, 4 cooling towers, 4 chilled water supply pump, and 4 chilled water return pump and the layout is presented in Figure 2.

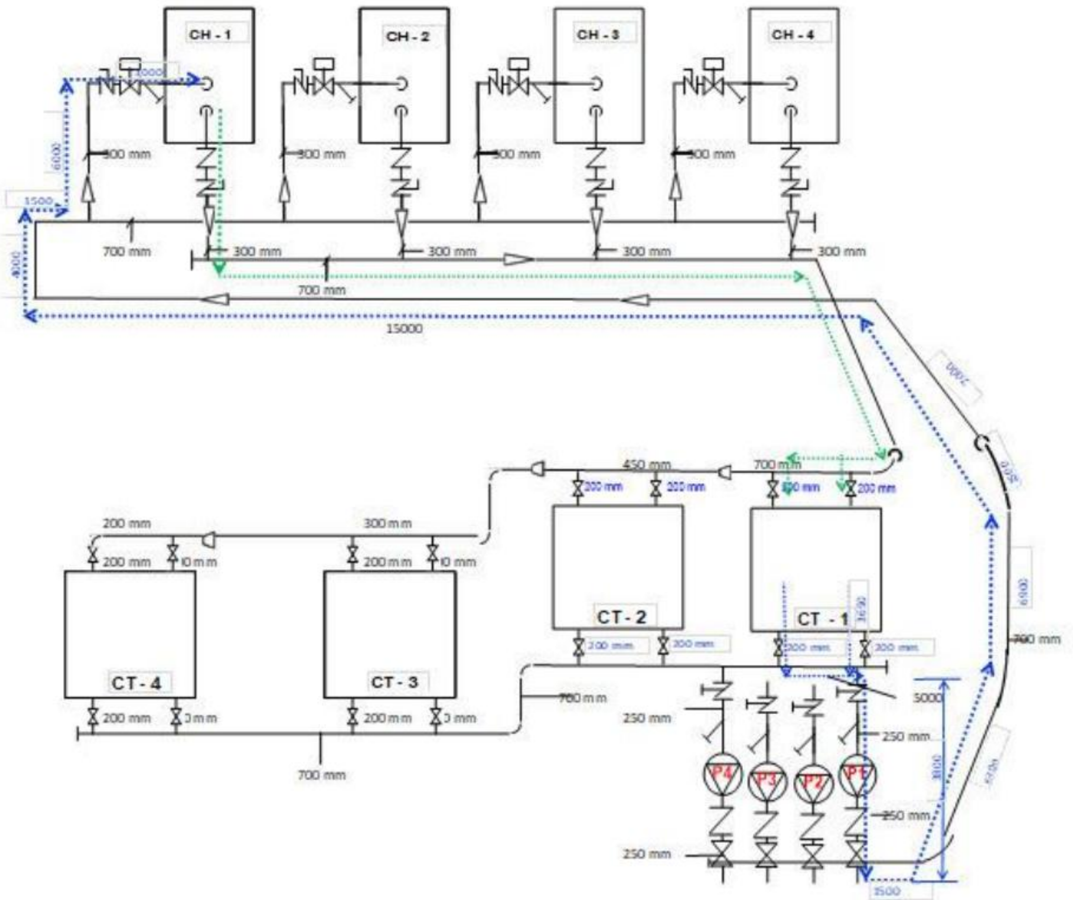

Figure 2: Chiller Plant Layout

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2.3 Observation Result

From observations made from 23 to 25 January 2023, data was obtained on the chiller control panel. Table 2, Table 3, and Table 4 show the data taken.

Table 2: Chiller Operational Data 23 January 2023

Item Check				Standard	05.00	08.00	11.00	17.00	21.00	23.00
Chiller Unit	Cooler	1	Entering chilled water (CHW in)	14-19°C	13,3	13,7	12,6	14,8	14,6	14,3
		2	Leaving chilled water (CHW out)	10-12,5°C	8,6	9,5	8,6	10,7	10,4	10
		3	Evaporator refrigerant temp.	6,5-7,8°C	7,1	8	7,1	9,3	8,9	8,8
		4	Evaporator pressure	240-315 kPa	284	299	279	303	299	294
		5	Evaporator approach	1-2°C	1,5	1,5	1,5	1,4	1,5	1,2
	Condensor	6	Entering condensor water (CHW in)	28-32°C	32,9	33,6	33,6	33,8	33,6	33,7
		7	Leaving condensor water (CHW out)	33-37°C	37,6	40	39,6	39,8	39,8	40
		8	Condensor refrigerant temp.	34-38°C	39,8	40,3	39,8	40,1	40,1	40,4
		9	Condensor pressure	650-850 kPa	909	946	906	919	922	929
		10	Condensor approach	< 4°C	2,2	0,3	0,2	0,3	0,3	0,4
	Compressor	11	Set point ampere	85%	78	71	69	68	69	72
		12	Oil pressure	190-270 kPa	240	247	248	245	246	247
		13	Oil temperature	52-55°C	56	56	56	56	56	56
		14	Compressor discharge temp.	< 85°C	46	48	49	49	48	48
		15	Bearing temperature	< 85°C	64	64	63	64	64	64
		16	Motor winding temp.	< 104°C	17	21	19	18	19	22
	Power	17	Actual line current	460-884 A	696	649	614	610	632	697
		18	Actual line voltage	380 V	401	388	386	384	382	380
		19	kW	513 kW	439	396	374	372	381	390
Cooling Tower		20	Cooling water pump (CDP) 1	55 A	49	45	43	43	43	43
		21	Cooling water pump (CDP) 2	55 A	51	45	44	44	44	44
		22	Pressure supply	1,2-1,8 bar	1,5	2,7	2,7	2,7	2,7	2,7
		23	Pressure return	0,2-0,8 bar	0,6	2	2	2	2	2
Chilled Water Pump (CCP)		24	Chilled water pump (CCP)	36 A	32	33	33	33	33	33
		25	Chilled water pump (CCP)	36 A	37	31	31	31	31	31
		26	Pressure supply	0,1-0,15 MPa	0,15	0,15	0,14	0,14	0,14	0,14
		27	Pressure return	0,003-0,008 MPa	0,04	0,02	0,02	0,02	0,02	0,02
		28	Temp Ambient	27-37°C	31	31	30	32	31	31

Table 3: Chiller Operational Data 24 January 2023

Item Check				Standard	05.00	08.00	11.00	17.00	21.00	23.00
Chiller Unit	Cooler	1	Entering chilled water (CHW in)	14-19°C	12,9	14,1	14,3	14,1	13,7	13,4
		2	Leaving chilled water (CHW out)	10-12,5°C	8,1	9,8	10,2	10,1	9,4	8,1
		3	Evaporator refrigerant temp.	6,5-7,8°C	7,1	8,4	8,8	8,7	8	7,7
		4	Evaporator pressure	240-315 kPa	281	291	297	296	281	281
		5	Evaporator approach	1-2°C	1	1,4	1,4	1,4	1,4	0,4
	Condensor	6	Entering condensor water (CHW in)	28-32°C	33,2	33,6	33,7	33,6	33,3	33,3
		7	Leaving condensor water (CHW out)	33-37°C	39,6	40	39,8	39,7	39,7	39,6
		8	Condensor refrigerant temp.	34-38°C	40,1	40,5	40,1	40	40,2	40,1
		9	Condensor pressure	650-850 kPa	919	930	922	917	921	919
		10	Condensor approach	< 4°C	0,4	0,4	0,3	0,3	0,4	0,4
	Compressor	11	Set point ampere	85%	72	71	68	68	72	72
		12	Oil pressure	190-270 kPa	248	248	246	245	248	248
		13	Oil temperature	52-55°C	55	56	56	56	56	56
		14	Compressor discharge temp.	< 85°C	48	48	48	47	48	48
		15	Bearing temperature	< 85°C	63	64	64	61	64	64
		16	Motor winding temp.	< 104°C	22	21	19	18	22	23
	Power	17	Actual line current	460-884 A	653	640	618	617	642	601
		18	Actual line voltage	380 V	389	387	386	380	383	380
		19	kW	513 kW	401	393	378	371	390	398
Cooling Tower		20	Cooling water pump (CDP) 1	55 A	43	43	43	43	43	43
		21	Cooling water pump (CDP) 2	55 A	45	45	45	45	45	45
		22	Pressure supply	1,2-1,8 bar	2,7	2,7	2,7	2,7	2,7	2,7
		23	Pressure return	0,2-0,8 bar	2	2	2	2	2	2
Chilled Water Pump (CCP)		24	Chilled water pump (CCP)	36 A	33	33	33	33	33	33
		25	Chilled water pump (CCP)	36 A	31	31	31	31	31	31
		26	Pressure supply	0,1-0,15 MPa	0,12	0,12	0,12	0,12	0,12	0,12
		27	Pressure return	0,003-0,008 MPa	0,02	0,02	0,02	0,02	0,02	0,02
		28	Temp Ambient	27-37°C	30	30	30	32	32	31

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Table 4: Chiller Operational Data 25 January 2023

Item Check				Standard	05.00	08.00	11.00	17.00	21.00	23.00
Chiller Unit	Cooler	1	Entering chilled water (CHW in)	14-19°C	12	12,9	13,1	12,9	12,9	12,9
		2	Leaving chilled water (CHW out)	10-12,5°C	8,6	8,6	8,8	8,8	8,6	8,7
		3	Evaporator refrigerant temp.	6,5-7,8°C	7,2	7,2	7,4	7,3	7,1	7,1
		4	Evaporator pressure	240-315 kPa	283	276	278	275	275	285
		5	Evaporator approach	1-2°C	1,4	1,4	1,4	1,5	1,5	1,6
	Condensor	6	Entering condensor water (CHW in)	28-32°C	29,2	33,4	33,3	33,1	32,9	27,9
		7	Leaving condensor water (CHW out)	33-37°C	33,1	39,8	39,7	39,2	39,4	32,1
		8	Condensor refrigerant temp.	34-38°C	34,7	40,2	40,1	40	39,8	34,3
		9	Condensor pressure	650-850 kPa	785	924	920	918	914	784
		10	Condensor approach	< 4°C	1,7	0,5	0,5	0,5	0,5	2,2
	Compressor	11	Set point ampere	85%	54	74	73	72	73	58
		12	Oil pressure	190-270 kPa	240	248	247	241	248	240
		13	Oil temperature	52-55°C	54	56	56	56	56	56
		14	Compressor discharge temp.	< 85°C	43	48	48	48	47	42
		15	Bearing temperature	< 85°C	62	63	64	62	64	62
		16	Motor winding temp.	< 104°C	11	23	22	21	22	12
	Power	17	Actual line current	460-884 A	498	662	657	642	664	533
		18	Actual line voltage	380 V	403	379	384	385	383	403
		19	kW	513 kW	312	402	400	398	402	333
Cooling Tower		20	Cooling water pump (CDP) 1	55 A	50	43	44	44	44	50
		21	Cooling water pump (CDP) 2	55 A	51	44	45	45	45	51
		22	Pressure supply	1,2-1,8 bar	1,5	2,7	2,7	2,7	2,7	1,5
		23	Pressure return	0,2-0,8 bar	0,5	2	2	2	2	0,5
Chilled Water Pump (CCP)		24	Chilled water pump (CCP)	36 A	32	33	33	33	33	32
		25	Chilled water pump (CCP)	36 A	37	32	32	32	32	37
		26	Pressure supply	0,1-0,15 MPa	0,15	0,12	0,12	0,12	0,12	0,15
		27	Pressure return	0,003-0,008 MPa	0,04	0,02	0,02	0,02	0,02	0,04
		28	Temp Ambient	27-37°C	-	30	30	32	32	-

III. RESULTS AND DISCUSSION

3.1 COP Calculation

From the data collection, the following data was obtained:

- Average set point ampere 3 days = 70%
- Entering chilled water (CHW_{in}) = 13,3°C
- Leaving chilled water (CHW_{out}) = 8,6°C
- Pressure supply (P_{1ev}) = 0,15 Mpa
- Pressure return (P_{2ev}) = 0,04 MPa
- Actual evaporator pressure drop (PD_{actual}) = 0,15 - 0,04 = 0,11 MPa = 36,80 ft
- Design evaporator pressure drop (PD_{desing}) = 99,7 kPa = 33,35 ft
- Design Flow Rate ($\dot{m}_{design}$) = 138,6 L/s = 2196,85 GPM
- Compressor power ($\dot{W}_{in}$)= 439 kW

3.1.1 Chilled Water Flow Rate

$$k = \frac{\dot{m}_{design}}{\sqrt{PD_{design}}}$$

$$k = \frac{2196,85 \text{ GPM}}{\sqrt{33,35 \text{ ft}}}$$

$$k = 380,38$$

$$\dot{m}_{aktual} = k \times \sqrt{PD_{actual}}$$

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$$\dot{m}_{aktual} = 380{,}38 \times \sqrt{36{,}80 \text{ ft}}$$

$$\dot{m}_{aktual} = 2307{,}58 \text{ GPM} = 108{,}46 \text{ kg/s}$$

3.1.2 Heat Transfer Rate at Evaporator

$$\dot{Q}_{ev} = \dot{m}_{actual} \times C_p \times (CHW_{in} - CHW_{out})$$

$$\dot{Q}_{ev} = 108{,}46 \text{ kg/s} \times 4{,}2 \text{ kJ/kg°C} \times (13{,}3\text{°C} - 8{,}6\text{°C})$$

$$\dot{Q}_{ev} = 2140{,}92 \text{ kW}$$

3.1.3 Coefficient of Performance

$$COP_{aktual} = \frac{\dot{Q}_{ev}}{\dot{W}_{in}}$$

$$COP_{aktual} = \frac{2140{,}92 \text{ kW}}{439 \text{ kW}}$$

$$COP_{aktual} = 4{,}877$$

The COP calculation can be seen in the following Table 5.

Table 5: COP Value from 23 January to 25 January

Pukul	m_aktual (kg/s)	CHW_in (°C)	CHW_out (°C)	Q_evap (kW)	P_comp (kW)	COP_aktual
23 Januari						
05:00	108,46	13,3	8,6	2140,92	439	4,877
08:00	117,90	13,7	9,5	2079,83	396	5,252
11:00	113,28	12,6	8,6	1903,08	374	5,088
17:00	113,28	14,8	10,7	1950,66	372	5,244
21:00	113,28	14,6	10,4	1998,24	381	5,245
23:00	113,28	14,3	10	2045,81	390	5,246
24 Januari						
05:00	103,41	12,9	8,1	2084,72	401	5,199
08:00	103,41	14,1	9,8	1867,56	393	4,752
11:00	103,41	14,3	10,2	1780,70	378	4,711
17:00	103,41	14,1	10,1	1737,27	371	4,683
21:00	103,41	13,7	9,4	1867,56	390	4,789
23:00	103,41	13,4	8,1	2301,88	398	5,784
25 Januari						
05:00	108,46	12	8,6	1548,75	312	4,964
08:00	103,41	12,9	8,6	1867,56	402	4,646
11:00	103,41	13,1	8,8	1867,56	400	4,669
17:00	103,41	12,9	8,8	1780,70	398	4,474
21:00	103,41	12,9	8,6	1867,56	402	4,646
23:00	108,46	12,9	8,7	1913,17	333	5,745

3.2 Analysis and Discussion

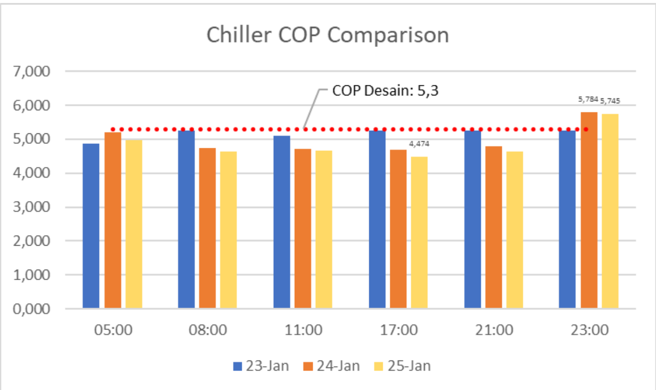

Figure 3: Comparison Chart of Actual COP with Design COP at 70% Part Load Condition

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Figure 3 shows the graph of comparison between the actual COP and the chiller design COP at 70% partial load conditions. Chiller with 70% part load refers to operational conditions where the chiller is working at 70% of its full capacity. This means some chiller components, such as the compressor, condenser, or evaporator, will operate at a lower level than under full load conditions. Chillers are generally designed to work at full load conditions (100% load), where the chiller operates at its maximum capacity. However, in many cases, the actual load on the chiller will fluctuate and often not always reach its full capacity.

In this case the chiller design COP at 70% is 5,3 according to the guidebook. Meanwhile, the actual COP is slightly below the design COP based on the calculations that have been carried out. This shows that there is a difference between the expected performance (design COP) and the actual performance (actual COP) of the chiller.

Based on the graph in Figure 3, there is a condition where the actual COP exceeds the design COP which occurred at 23.00 on January 24 and January 25, namely 5,784 and 5,785. However, at other times the actual COP of the chiller is below the design COP which shows that the efficiency of the chiller machine at PT X is not good. The smallest COP value occurred on January 25 at 17.00, namely 4.474. The causes of differences between design COP and actual COP can be caused by several factors, including:

1) The chiller does not operate under ideal conditions as assumed in the initial design (e.g. different inlet or ambient temperatures).
2) Lack of proper maintenance such as cleaning pipes on the evaporator and condenser and replacing damaged components can have a negative impact on chiller performance and reduce the COP value.
3) Measurement errors can affect the COP value. If the measurement method is less accurate or there are other factors that influence the measurement, the actual COP value may be different, such as in this case there is no flow meter to measure the flow rate of water and refrigerant in the evaporator and condenser.

IV. CONCLUSION

From this study, several conclusions were obtained regarding the topics have been described, such as:

1) On January 23, 2023 to January 25, 2023, the chiller's actual COP is below its design COP at 05:00, 08:00, 11:00, and 21:00, while at 23:00 the actual COP is the same because chiller exceeds design COP
2) The chiller does not work efficiently because the actual COP of the chiller is below its design COP. The cause of the difference between the actual COP value and the design can be caused by several factors such as the chiller not operating ideally as assumed in the initial design, lack of proper maintenance, and measurement method errors.

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