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Effects of Cooling Tower Performance to Water Cooled Chiller Energy Use: a Case Study toward Energy Conservation of Office Building

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***Abstract*—This paper presents results of a study on effects of cooling tower performance to energy consumption of a water cooled chiller system of an office building in Jakarta the capital city of Indonesia. The building was recorded as a less efficient office building with energy use intensity reaching 271 kWh m^{-2} year^{-1}. The study was conducted by running a water cooled chiller with alternately two different cooling towers of similar specified capacity. Energy and temperature performances of the cooling towers were tested and evaluated. Performance parameters of the chiller that rejected heat to each cooling tower were evaluated, and then the chiller performances involving its energy use were calculated. It was found that one cooling tower had less air flow rate. Its efficiency was only 38% which was much lower than the efficiency of another cooling tower of 61%. Performance of the chiller to be operated with lower efficiency cooling tower, decreased by 5.5% and power consumption increased by 4.1%. The result of this study also showed that cooling tower performance was an important parameter that could make an office building less-energy efficient.**

***Keywords*—cooling tower, performance, water cooled chiller, energy conservation**

I. INTRODUCTION

A study on energy consumption of air conditioning (AC) systems (chiller system) for hotel and office buildings has been reported in [1,2]. AC systems were found to consume the highest electrical energy among other facilities. Therefore, by improving energy efficiency of the chiller systems would significantly contribute to energy conservation and reduce operational cost of the buildings. Reducing energy consumption would also affect environmental impact of the buildings.

Strategies in improving energy efficiency of chiller systems in commercial buildings have been reported in [3-5]. The strategies include waste heat recovery systems, implementation of thermal energy storage in minimizing temperature instability of heat recovery system and integration of heat pump and water cooled chiller system to improve energy-saving opportunity of the buildings.

Another strategy to reduce energy use of chiller systems is by enhancing the process of heat rejection in condenser. For central water cooled chiller systems, heat is rejected to the environment through cooling towers. Optimization of heat rejection in the cooling towers would be one of key roles in improving energy use efficiency of chiller systems. Ghazani *et al.* [6] reported that cooling towers were integrated parts of energy systems. Energy-saving strategies could be obtained by enhancing the overall performance of energy systems including cooling towers. Optimization heat transfer in cooling towers could significantly contribute to energy saving strategy due to cooling towers have been widely used in water cooled condenser. There are several types of cooling towers in which the forced draft counter flow cooling tower is most commonly used in commercial buildings. Cooling towers work using the concept of evaporative cooling where ambient air is humidified and hot water is cooled as a result of heat and mass transfer interactions between air and water. Heat transfer in a cooling tower is potentially driven by temperature difference between the ambient air and the water. While for mass transfer is driven by their vapor pressure difference.

Many researchers have developed mathematical models for estimating energy performance of cooling towers [7-12]. By using the mathematical models, researchers could optimize performance parameters of the cooling towers. Recent research on correlations between mass transfer coefficient and moisture effectiveness as well as heat transfer coefficient and thermal effectiveness in a cooling tower has also been reported in [13]. Further optimization was found that reversibly used cooling towers presented great potential for energy saving in subtropical areas [14].

Some results of the study on cooling towers have not been properly implemented by building managers due to lack of capability to transfer research results to the building operational practices. It is often to be found in commercial buildings, the managers keep operating chillers with inefficient cooling towers until serious problems occur. This would generally affect the energy use of the chiller as well as energy use intensity (EUI) of the buildings.

For energy conservation, it is crucial to regularly monitor and examine energy use level of the buildings. One way to assess energy use is through measuring and identifying current year energy use intensity (EUI) and then comparing the results against similar building type from published building energy benchmarking. A report of commercial building energy benchmarking has been published by Building and Construction Authority [15]. The report also involved energy benchmarking of office buildings. The average EUI of 180 large office buildings (gross floor area more than 15,000 m^2) was 247 kWh m^{-2} year^{-1}. The report categorized the office buildings into: top quartile (EUI $\leq$ 160 kWh m^{-2} year^{-1}), second quartile (EUI more than 160 up to 209 kWh m^{-2} year^{-1}), third quartile (EUI more than 209 up to 272 kWh m^{-2} year^{-1}) and bottom quartile (EUI more than 272 kWh m^{-2} year^{-1}). In Indonesia, energy levels of office buildings were classified and labeled in accordance with [16] which comprised: very efficient (EUI $\leq$ 102 kWh m^{-2} year^{-1}), efficient (EUI more than 102 up to 168 kWh m^{-2} year^{-1}), quite efficient (EUI more than 268 up to 222 kWh m^{-2} year^{-1})

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and inefficient (EUI more than 222 kWh m^{-2} $year^{-1}$). Study on energy use intensity of office buildings in the United States of America, Europe and around the world have been reported respectively in [17-19. It was reported that around 75% of Europe's buildings were not energy efficient [18].

This paper reports results of onsite investigation on effects of cooling tower performance to energy consumption of water cooled chiller systems. This paper also provides a testimony of the influences of cooling tower performance to energy consumption of an office building located in Jakarta, Indonesia. The building is a large office building with gross floor area 17,400 m^2. Recent main problem occurred in the building was that energy consumption tended to increase since past three years. Energy use intensity (EUI) year 2017 increased for about 4.4% compared with EUI year 2016. This has also caused significant increase in energy cost. In addition of that, some tenants have also complained to the building management that their office temperatures could not achieve thermostat set points especially during midday (feeling uncomfortable).

Evaluation on the energy records of the building was found that energy consumptions of the building in the years 2016 and 2017 were 4,519 MWh and 4,719 MWh respectively. There was an increase of about 4.4%. Considering gross floor area (GFA) of the office building, energy use intensity (EUI) can be calculated for two consecutive years 2016 and 2017. The EUIs are 259.71 kWh m^{-2} $year^{-1}$ and 271.18 kWh m^{-2} $year^{-1}$ respectively for year 2016 and 2017.

According to regulation [16], the investigated office building can be grouped into inefficient office buildings. In order to improve the energy performance of the building toward energy conservation, some recommendations for optimization on the cooling tower parameters are also presented in this paper.

II. WATER COOLED CHILLER AND METHODS

A. Water Cooled Chiller

The investigated central chiller plant is for air conditioning (AC) system of an office building. The plant comprises two water cooled chiller system, distribution pumps and two cooling tower systems. Pump systems consist of pumps for cooling water distribution system and pumps for chilled water system. Both chiller and pump systems are located in a central plant room. The cooling tower systems are situated on the roof of the building. Detailed schematic diagram of the chiller systems completed with pumps, cooling and loading systems can be seen in Fig. 1.

Fig. 1 shows the chiller plant which constitutes three main systems, namely: refrigeration, cooling water and chilled water systems. The refrigeration system consists of two water-cooled chillers which absorb heat from the chilled water and reject heat to the cooling water. Chiller 1 and chiller 2 are hermetic centrifugal chillers with R-134a refrigerant of cooling capacity 400 TR (Tons of Refrigeration) each.. The chiller plant provides cooling to the service facilities in the building. Number of chillers in operation is usually only 1 and another chiller will be in standby mode as a backup chiller.

The cooling water system of the chiller plant consists of two cooling towers (CT-1 and CT-2) with heat rejection capacity specified for 500 TR each. Two pumps are installed to circulate the cooling water. The main function of the cooling water system is to remove heat from the condenser and reject it to the ambient air through cooling tower system. While the chilled water system comprises three pumps and cooling load units which constitute fan coil units (FCUs) and air handling units (AHUs). Chilled water from chillers streams down to a chilled water header and then to be pumped to AHUs and FCUs. There are about 18 units AHUs and several units FCU to provide cooling into the building.

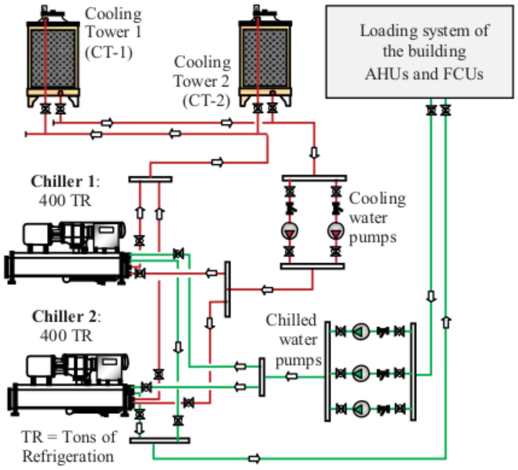

Fig. 1. Schematic diagram of the investigated central chiller plant

In the cooling load units, heat from the facilities is absorbed which results in temperature of the chilled water increases. The chilled water then returns to the evaporator of the chiller system where the heat is transferred to the refrigerant and finally the heat is rejected to the atmosphere through condenser, cooling water circuit and cooling towers.

B. Cooling Towers

Technical specifications of the cooling towers are presented in Table I. It can be seen that the CT-1 is actually smaller in term of fan power input and diameter of 'spray filled'. Smaller fan power would provide less airflow rate which meant smaller air mass flow rate and lower heat rejection rate. Fan power consumption of CT-1 is 16% smaller than CT-2 as shown in Table I. Airflow rate of CT-1 was 32.5 $m^3 s^{-1}$. This flow rate can be optimized by adjusting fan pitch and modifying fan blades. Maximum optimization obtained by implementing fan law, however, would improve the airflow rate up to 40.4 $m^3 s^{-1}$. This would still smaller than the airflow rate of CT-2 which was 47.8 $m^3 s^{-1}$.

TABLE I. TECHNICAL SPECIFICATION OF THE COOLING TOWERS

No	Parameters	CT-1	CT-2
1	Heat rejection capacity (TR)	500	500
2	Running current (Ampere)	15.2	18
3	Power input (Hp)	11.4	13.5
4	Voltage (V)	380	380
5	Phase	3	3
6	Air flow rate ($m^3 s^{-1}$)	32.5	47.8

CT = Cooling tower, TR = Tons of Refrigeration, Hp = horse power
Value of the parameters specified by manufacturer

C. Methods

The tests were carried out in the plant room and on the roof of the building respectively for the chiller and cooling tower units. The tests were performed in two stages. The first stage, chiller-1 was operated with CT-2 (the cooling tower with higher thermal efficiency) referred to as the first test method. The test was continued to the second stage where the chiller-1 was consecutively operated with CT-1 (the cooling tower with lower thermal efficiency) referred to as the second test method.

Data of the chiller parameters such as high and low pressures of the refrigerant, chilled and cooling water temperatures were directly obtained from chiller monitoring system. Other data include refrigerant temperature, water mass flow rate, air temperature and relative humidity (RH) were measured using instrumentation systems specifically prepared for the tests. The measurement system consisted of some sensors which include temperature sensors of accuracy better than ± 1°C, RH sensor (accuracy ± 3 unit), mass flow meter (accuracy ±1%) and air velocity meter with accuracy 10%; data logging system (Labtech software and DataScan modules) and recording system (computer set and monitor). Power consumption of the chiller system was also monitored and recorded. The instrumentation systems used for the tests can be seen in Fig. 2.


Data logging system
(DataScan Logger)

Power measurement

Fig. 2. Measurement systems with data logger and power analyzer

The main purpose of conducting direct measurements and observations is to obtain accurate data based on actual operating conditions. Some parameters such as temperatures of the cooling towers, FCUs and AHUs, as well as water and air flow rate were measured using handheld measurement tools where data were recorded manually.

Data of the tests were recorded in every 10 seconds. This interval provided possibilities to examine the measurements in more detailed. The recorded data were processed and analyzed and performance parameters such as energy consumption, cooling capacity, approach temperatures, coefficient of performance (COP) of the chiller, efficiency of the cooling towers were calculated.

Further calculations were processed by using spread sheet and EES (*Engineering Equations Solver*) programs. With these programs, energy performance of the chillers can be investigated and simulated. The program can also be used to estimate performance of the chillers and cooling tower at different operating conditions.

III. RESULTS AND DISCUSSION

A. Cooling Tower Performaces

A cooling tower is a specialized heat exchanger in which two fluids (air and water) are brought into direct contact with each other to affect the transfer of heat. Heat rejection process is accomplished by spraying water into a rain-like pattern, through which an upward moving mass flow of cool air is induced by the action of a fan. Therefore, performance parameters would be influenced by water and airflow through the cooling tower.

In order to examine the performance of cooling towers (CT-1 and CT-2), two numerical models were developed in EES program. Models were used to process data and comprehensively provided outputs such as performance parameters. Input data were obtained from tests and operational records of the chiller. Input parameters include temperature and RH (relative humidity) of air, temperature of water entering and leaving the CT, flow rate of air and water. Other input such as hardness of cooling water and make up water, operation time and flow rate of makeup water.

Main output performance parameters of the cooling towers include heat rejection capacity, efficiency, range, approach and COC (Cycle of Concentration). Other output parameters are total flow rate of air, blow-down rate, evaporation rate and drift. Table II shows performance comparison between cooling tower CT-1 and CT-2 resulted from the EES models. Heat rejection capacity of CT-1 was found to be smaller than CT-2 of about 6.9%. Convective heat rejection of CT-1 was bigger than CT-2 because of dry bulb temperature of exit air for CT-1 was higher.

TABLE II. TECHNICAL SPECIFICATION OF THE COOLING TOWERS

No	Performance Parameters	CT-1	CT-2
1	Heat rejection capacity (TR)	330.2	354.7
2	Evaporation heat (kW)	980.2	1077.0
3	Convective heat (kW)	181.2	170.5
4	Cooling Water inlet Temperature (ºC)	33.8	30.3
5	Cooling water outlet Temperature (ºC)	29.8	26.0
6	Ambient wet bulb Temperature (ºC)	23.3	23.3
7	Range (K)	4.0	4.3
8	Approach (K)	6.5	2.7
9	Efficiency (%)	37.85	60.96
10	Evaporation water (m^3 day^{-1})	18.3	20.0
11	Drift loss (m^3 day^{-1})	0.2	0.2
12	Blow down water (m^3 day^{-1})	3.5	3.8
13	Makeup water (m $^3day^{-1}$)	22.0	24.0
14	COC	5.21	5.21

CT = Cooling tower, TR = Tons of Refrigeration, COC = cycle of concentration.

Evaporation heat rejection of CT-1, however, was smaller of about 9.9% compared with CT-2. This provides indication that CT-1 works with lower efficiency than CT-2. The efficiencies of CT-1 and CT-2 were found to be 37.85% and 60.96% respectively as shown in Table II.

B. Water Quality of the Cooling Tower

Quality of the cooling water can also gradually affect the performance of the cooling towers and the chillers. For example high hardness and alkalis in the cooling water can form salt scale on the heat transfer surface of the condenser which then increases thermal resistance of the condenser pipe and reduces heat transfer from the refrigerant to the cooling water. It consequently reduces the heat rejection capacity of the condenser. Tests on the quality of cooling water were also carried out. Results of the test are presented in Table III.

TABLE III. WATER QUALITY OF THE COOLING TOWERS

No	Item Parameters	**Max. Conditions	*Cooling water	Unit
1	TDS	700	2165	ppm
2	Conductivity	1000	-	μS cm^{-1}
3	Sulphate Ions	200	163.62	ppm
4	All Iron (as Fe)	0.5	0.0722	ppm
5	M Alkalis (as $CaCO_3$)	100	1008.3	ppm
6	All Hardness (as $CaCO_3$)	200	795.72	ppm
7	Silica (as SiO_2)	50	8.05	ppm
8	Chloride Ions (as Cl)	150-400	181.94	ppm
9	pH at 25°C	6-9	8.19	pH

TDS Total Dissolved Solids
* Tested by Analytic Lab. of Udayana University
**Recommended by chiller manufacturer

From Table III, it can also be seen water characteristics of the cooling tower recommended by chiller manufacturer. Three parameters of the cooling water (TDS, M Alkalis, and hardness) did not comply with the recommendation. The water used for cooling towers contains high hardness, alkalis and dissolved solid. This, however, would provide COC of the cooling towers in the range of 3 to 10 as recommended by manufacturer. Too low COC value would increase flow rate of the make-up water due to requirement of high blow-down rate. While high value COC would increase the formation of salt-scale on the surface of condenser pipe. Therefore, it is also recommended to continuously check and monitor the quality of the cooling water and maintain the COC value between 5 and 7.

C. Energy Consumption and Performance of the Chiller

The data from direct measurements were processed and analyzed by using spreadsheet and EES (*Engineering Equations Solver*) programs. For data processing and investigation of the chillers performance, two simple refrigeration cycle models were developed. Input parameters of the models include high and low pressures, temperatures of refrigerant at suction and discharge line of the compressor and at refrigerant liquid line, chilled and cooling water temperatures as well as cooling water flow rate.

The chiller systems use R-134a as their heat transfer fluid. The refrigerant flow through the refrigeration system range from 5.77 kg s^{-1} up to 5.91 kg s^{-1} with cooling capacity varied with the methods of the tests. The chillers were operated at load factor of 87%. This load factor was based on the measured power consumption and maximum power of the chiller specified by the manufacturer. Maximum cooling capacity at full load operating conditions (load factor 100%) was found to be about 302 TR accounting for 75.5% of specified capacity. It can be noticed that the actual capacity of the chiller was significantly lower of about 24.5% than the specified cooling capacity of 400 TR.

The simulation results also showed that the flow-rates of cooling water and chilled water are relatively stable. The cooling water circulated through condenser with flow rate of 4206 LPM (Liter per minute) or equivalent to 69.72 LPS (liter per second) or mass flow rate of 69.79 kg s^{-1}. This flow rate provided water velocity of 2.19 m s^{-1}, which was in the range of manufacturer specification between 1.02 m s^{-1} and 3.66 m s^{-1}. While the flow rate of chilled water was 3901 LPM equivalent to 65 kg s^{-1} mass flow rate. The velocity of chilled water is about 2.04 m s^{-1} (specified range from manufacturer between 0.91 and 3.66 m s^{-1}).

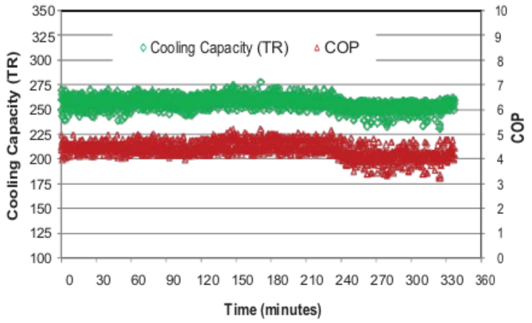

Fig. 3. Chiller cooling capacity in tons of refrigeration (TR) and COP

Pressure drops at waterside of condenser and evaporator were also investigated. Test results were in agreement with recorded data from the chiller operation log sheet. Pressure drop of cooling water at condenser was ranging from 0.8 to 1 bar (80 to 100 kPa) and for chilled water at evaporator was in the range of 1.7 to 2 bar (170 to 200 kPa). The pressure drops of cooling and chilled water at test conditions specified by manufacturer are 75 kPa and 100 kPa respectively.

Performance parameters of the chiller are shown in Figs. 3, 4, and 5. The figures showed that investigated parameters (cooling capacity, power consumption, Coefficient of Performance (COP), condenser temperatures) seem to be stable during the first four hours (the first test method) and then significantly change in the last 1.5 hours (the second test method). This happened due to the chiller operated with different cooling towers. At the first test method, the chiller was in operation with CT-2 and then at the second test method CT-2 was subsequently replaced with CT-1. Ambient temperature during the test was ranging from 25 °C to 28 °C.

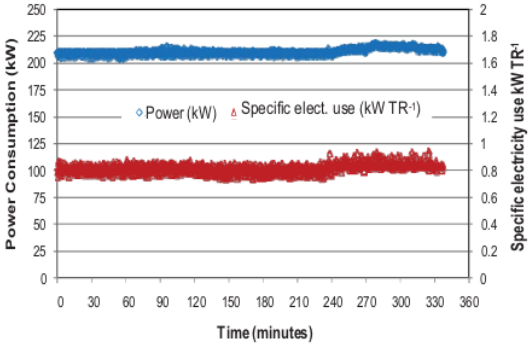

Fig. 4. Chiller power consumption and spesific electricity use

Figs. 3 and 4 show performances of the chiller drop at the second test method. Cooling capacity decreased by 4 TR, power consumption increased for about 8.7 kW, COP reduced by 0.24 and specific electricity consumption went up for about 0.05 kW TR^{-1}. This was caused by the increase of cooling water temperature due to low thermal efficiency of the cooling tower.

With regards to the condenser of the chiller, Fig. 5 shows that condenser operates with low approach temperature (0.5 K). This indicates that condenser is clean. By maintaining the approach temperature of the condenser as low as possible can make the chiller operate at lower condensing temperature and better energy performance [20].

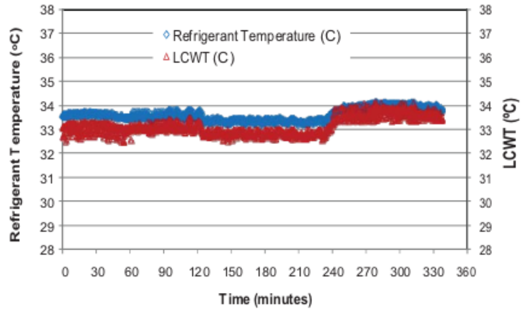

Fig. 5. Temperature of refrigerant and leaving cooling water in condenser

Comprehensive results have been obtained from this study. Effects of cooling towers with 60.96% and 37.85% efficiencies to the investigated water-cooled chiller have been identified which can be described below:

- Cooling capacity decreases by 1.6%;
- Coefficient of performance (COP) reduces by 5.5%;
- Power consumption increases of about 4.1%;
- Specific electricity use (kW TR^{-1}) increases 5.8%;
- Condensing temperature as well as cooling water temperature leaving the condenser increased for about 1.4 K.

In this study, the increase of chiller power consumption caused by less efficient cooling tower could reach 4.1%. The value is very close to the increase of energy consumption of the office building (4.4%). The results provide indication that chiller or air conditioning system is the most significant energy consumption facility of the building. This is in agreement with [21] which reported that energy consumption of air conditioning system in office building was nearly 51% of total energy use. Therefore, improving the quality and energy efficiency of cooling towers as well as chiller system offers a considerable energy saving opportunity.

In order to improve energy efficiency of the cooling tower, optimization on the airflow rate is required. Optimization can be done by adjusting fan pitch and modifying fan blades. This optimization can increase airflow rate from 32.5 $m^3 s^{-1}$ to 40.4 $m^3 s^{-1}$. Further optimization can be prepared by replacing fan of the cooling tower with one that can provide minimum air flow rate of 47,8 $m^3 s^{-1}$. Additionally water quality of the cooling tower should also be improved so that it can meet the requirements recommended by chiller manufacturer.

IV. CONCLUSIONS

Energy consumption of a water cooled chiller operated with different performance cooling towers for office building application has been examined. Chiller performance decreased of about 5.5% when it was operated with a lower efficiency cooling tower. The study was also found that critical effect of using inefficient cooling tower to the chiller was that the chiller would operate at higher condensing temperature (increased by 1.4 K) due to the increase of cooling water temperature leaving the cooling tower. This caused the chiller to consume 4.1% more energy. Moreover, low efficiency cooling tower would cause mismatch between heat rejection in the cooling tower and cooling load of the chiller and it consequently could affect the energy performance of the chillers. Maintaining quality and efficiency of cooling towers would offer a substantial energy-saving opportunity for chiller operation and energy conservation of the building.

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