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 Field-based Analyses on Approach Temperatures for Performance Evaluation of Centralized Air Conditioning System in a Shopping Mall Building I N Suamir1,*, I N G Baliarta, M E Arsana, Sudirman and I M Sugina 1Mechanical Engineering Department, Bali State Polytechnic, Bali, 80364, Indonesia *Email: nyomansuamir@pnb.ac.id Abstract. This paper presents field analyses on the influences of condenser and evaporator approach temperatures of water cooled air conditioning system for a shopping mall. The mall building comprises food and non-food retail stores and uses a centralized air conditioning (AC) system to condition the entire building. The AC system comprises three chillers with the same cooling capacity. Chillers’ performance parameters included power consumption, condensing and evaporating temperatures, evaporator-condenser approach temperatures, pressure drop and cooling capacity parameters were hourly recorded for a period of one year. Performance characteristics of each chiller were evaluated at different condenser and evaporator approach temperatures and regression analyses were also established to examine the correlations and influences of the approach temperatures on the chillers’ performance. The analyses results showed that the increase of condenser approach temperature could increase the power consumption and reduce the coefficient of performance (COP) of the chillers. While evaporator approach temperature was found to have insignificant effect to the chiller performance. The results also showed that for the investigated chillers with condenser and evaporator approach temperatures maintained below 2 K, the approach temperatures had negligible correlation to the power consumption and the overall performance of the chillers. At this operational conditions, the water cooled air conditioning systems could operate at their best possible performance. 1. Introduction In developed countries, both residential and commercial sectors are likely to consume more energy and recently both sectors have been reaching a value from 20% up to 40% [1]. In Indonesia, commercial building sector alone which includes shopping malls has consumed for about 5.3% of the country total energy use with energy consumption growth of 5.68% per year [2]. The commercial sector has energy saving potential in the range between 10% and 30% [3-6]. Shopping mall buildings as part of the commercial sector which are group into energy intensive buildings with energy use intensity from 500 to 1000 kWh/m2.y [7]. For food retail stores, the energy use intensity could range between 346 and 700 kWh/m2.y and for non-food retail stores ranging from 146 up to 293 kWh/m2.y [8]. More study on energy-efficiency strategies in food and non-food retail stores have been published in [7,9-11]. Since the number of shopping malls is quickly growing, studies on energy performance of AC systems and factors that may influence for energy saving potential evaluation seems to be attractive for researchers. One factor that may restrict the efforts to achieve energy saving was shortness of knowledge of operators about critical-operation parameters such as evaporator and condenser approach temperatures. The increase of approach temperatures in the evaporator and condenser heat exchangers indicates that heat transfer has restricted. The AC systems would run at lower evaporation and higher condensation temperatures. Consequently, temperature lift and energy consumption of the AC systems become high. The increase of approach temperatures could also provide hints that the condenser and evaporator heat exchangers have to be descaled in order to sustain optimum temperature and energy performances. Descaling can also prevent the condenser and evaporator heat exchangers from further damage [12]. The approach temperatures could be influenced by fouling on the surface of condenser and evaporator heat exchanger pipes. Zhao et al. [13] reported methods to detect fouling on the surface of condenser pipe. The report was demonstrated causes of damage in a water cooled AC system which included cooling water shortage in condenser, lacking chilled water in evaporator, low or over refrigerant charging and condenser fouling. This investigation was found that condenser fouling provided the highest potential to initiate impairment on an AC system. Due to fouling, approach temperatures have strong influence on heat transfer capacity of the heat exchangers and so the overall performance of an AC system. Condenser approach temperature was reported to have more significant influence to AC systems performance compared with approach temperature of the evaporator. When the condenser approach temperature was not tightly checked, condenser pipes could crack and leak. While evaporator approach temperature is not considerably affected by fouling. In combination with hot gas line superheat, evaporator approach temperature can be practically used to determine optimum refrigerant charge in a water cooled AC system [12]. A control strategy could reduce effects of condenser approach temperature. The controller regularly reset temperature of the cooling water to prevent the approach temperature influences condensation temperature. The control strategy causes the increase of fan speed in the cooling tower to match the requirement of heat rejection in condenser when the approach temperature increases. Consequently, energy consumption of the cooling tower also increases. However, the strategy was found to provide annual energy efficiency of about 4% [14]. For commercial buildings, such as shopping malls, which consumed large amount of energy was suggested to always observe performance of the AC systems in order to detect early indication of performance fall due to fouling in the condenser heat exchanger. Operational variables should be strictly monitored to improve AC system performance [15,16]. This paper presents results of field-based analyses on condenser and evaporator approach temperatures for performance evaluation of water cooled AC system in a shopping mall building. AC system performance parameters included power consumption, condensing and evaporating temperatures, evaporator-condenser approach temperatures, pressure drop and cooling capacity are hourly presented for a period of one year. Results of performance characteristic evaluation which include results of regression analyses are also presented at different approach temperatures. The correlations and influences of the approach temperatures on the AC system performance are also discussed. 2. Methods Field-based study was conducted in a modern fully air conditioned shopping malls. The mall was equipped with a centralized air conditioning (AC) system which comprises:

(i) three water cooled chillers; (ii) a heat rejection system: cooling water system and cooling tower; and (iii) loading systems: chilled water system, air handling units (AHUs) and fan coil units (FCUs). Centrifugal compressors with R-134A refrigerant are applied for all three chillers. The chillers are specified for COP and overall efficiency of 6.24 and 0.56 kW/TR respectively. Hourly operational data of the AC system for a period of one year were collected which include dependent variables such as: power consumption, cooling capacity and coefficient of performance (COP) and independent variables which are: approach temperatures, temperatures of evaporation and condensation, temperatures of chilled and cooling water, temperature of ambient, pressure drop, flow rate of chilled and cooling water. Some da were directly retrieved from chillers' monitoring systems and other system instrumentations include water flow meters, power meters for chillers and thermometer for ambient temperature measurement. Data were recorded hourly into data sheets, then, analyzed the effects of approach temperatures on AC system performance and their correlation to the waterside pressure drop of condenser and evaporator. 3. Results and Discussion 3.1. Approach Temperatures and Energy Performance Figure 1 shows daily variation of three operation parameters include ambient, condensation and evaporation temperatures. Condensation and evaporation temperatures are slightly fluctuated throughout the year with annual average 33.5 ºC and 5.4 ºC respectively. There is small variation appears on the temperature of condensation and evaporation although ambient temperature significantly changes. This indicates that the condensation and evaporation temperatures are not directly following the ambient temperature. 40 35 Temperature (ºC) 30 25 20 T_c on T_a mb T_e va 15 10 5 0 0 20 40 60 80 100 120 140 160 180 200 220 240 260 280 300 320 340 360 Days (in a year) Figure 1. Operational parameters of the AC system include condensation, evaporation and ambient temperatures presented daily for a period of one year Figure 2 shows condenser approach temperature of the chillers presented daily for one year. From the figure, it can be seen the condenser approach temperature periodically changes for about in 60 days. In one period, the condenser approach temperature daily increases from about 0.1 (chiller-1), 0.3 K (chiller-2), 0.5 K (chiller-3) and reaches the highest value ranging from 1.5 K to 2 K then the next period starts. This shows that condenser approach temperature rapidly increases due to fouling with an increase rate can reach 0.03 K per day. The periodic change of condenser approach temperature indicates a regular descaling process has been done for the condenser pipes. The descaling process was periodically performed whenever the condenser approach temperature reaching closed to 2 K. The building management has implemented regular maintenance program based on approach temperature record in order to maintain the AC system energy performance. This is in agreement with recommendation given in [12]. 3.0 Approach Temperature 2.5 of condenser (K) 2.0 1.5 1.0 0.5 0.0 Chil ler-1 Chil ler-2 Chil ler-3 0 20 40 60 80 100 120 140 160 180 200 220 240 260 280 300 320 340 360 Days (in a year) Figure 2. Daily condenser approach temperature of the chillers 1.40 Approach Temperature of evaporator (K) 1.12 Chil ler-1 Chil ler-2 Chil ler-3 0.84 0.56 0.28 0.00 0 20 40 60 80 100 120 140 160 180 200 220 240 260 280 300 320 340 360 Days (in a year) Figure 3. Daily evaporator approach temperature of the three chillers While evaporator approach temperature relatively constant as shown in Figure 3. There are no significant changes occur during the investigation period. The annual average of evaporator approach temperature for chiller-1, 2 and 3 are respectively 0.6 K, 0.4 K and 0.7 K. This shows that evaporator approach temperature is not considerably affected by fouling. In the year of investigation, descaling process has never performed for the evaporator pipes. Compressor power (kW) 800 700 600 500 400 300 200 Chil ler-1 Chil ler-2 Chil ler-3 0 20 40 60 80 100 120 140 160 180 200 220 240 260 280 300 320 340 360 Days (in a year)

Figure 4. Power consumption of the chillers presented daily for a period of one year Figure 4 presents power consumption of the three chillers. The instant power consumption of chiller 1, 2 and 3 vary in the range of 509-705 kW, 493-705 kW and 505-687 kW respectively. The power consumption is relatively low in July and August. In general, cooling capacities of the chillers show similar variation to the power consumption as shown in Figure 5. Annual average of the cooling capacities of the three chillers are fairly similar of about 3443, 3314 and 3442 kW respectively for chiller-1, 2 and 3. While total capacity of the AC system is found to be ranging from 5853 kW to 7630 kW (two chillers in operation simultaneously) with annual average cooling capacity of 6790 kW. Cooling capacity (kW) 4500 4000 3500 3000 2500 2000 1500 1000 Chil ler-1 Chil ler-2 Chil ler-3 0 20 40 60 80 100 120 140 160 180 200 220 240 260 280 300 320 340 360 Days (in a year) Figure 5. Cooling capacity of the chillers presented daily for a period of one year Figure 6 shows coefficient of performance (COP) of the chillers. Small variation occurs in the graph which indicates the chillers have nearly stable COP throughout the year. Annual average COP could reach 5.57, 5.59 and 5.78 respectively for chiller-1, 2 and 3. These COPs correspond to annual overall efficiency of 0.63, 0.63 and 0.62 kW/TR. From Figures 2, 3, 4 and 5 can be generally summarized that the energy performance parameters are independent of approach temperatures. This occurs because the approach temperatures of the AC system in the building have been maintained to sustain below 2 K even mostly below 1.5 K. Figure 6. Energy performances of the chillers presented daily for a period of one year Further investigation was also conducted to evaluate the relationship between approach temperatures and pressure drop at waterside of condenser and evaporator heat exchangers. The approach temperatures are very much influenced by fouling in the heat exchanger pipe. In a certain instant the fouling inside the pipes might also affect the pressure drop. Figures 7 and 8 present daily pressure drop respectively across condenser and evaporator of the AC system. 0.80 CW pressure drop across condenser (Bar) 0.70 0.60 0.50 0.40 0.30 0.20 0.10 0.00 Chil ler-1 Chil ler-2 Chil ler-3 0 20 40 60 80 100 120 140 160 180 200 220 240 260 280 300 320 340 360 Days (in a year) Figure 7. Cooling water (CW) pressure drop across condenser of the chillers evaluated daily for one- year operative time ChW pressure drop across 1.50 1.35 evaporator (Bar) 1.20 1.05 0.90 0.75 0.60 0.45 0.30 0.15 Chil ler-1 Chil ler-2 Chil ler-3 0.00 0 20 40 60 80 100 120 140 160 180 200 220 240 260 280 300 320 340 360 Days (in a year) Figure 8. Chilled water (ChW) pressure drop across evaporator of the chillers evaluated daily for one- year operative time The pressure drop at cooling water side of the condenser for all chillers is relatively stable throughout the year which varied in the range of 0.3 bar and 0.6 bar (Figure 7). The pressure drop of chilled water across evaporator is also stable but higher than the pressure drop of cooling water across the condenser (Figure 8). Chilled water pressure drop across evaporator is in the range between 0.6 and 1.1 bar. This points out that fouling in the heat exchangers especially the condenser pipes have influenced the condenser approach temperature but it has not yet influenced the flow of chilled and cooling water across evaporator and condenser. 3.2. Regression Analyses the Effects of Approach Temperatures on the Chiller Performance Figures 9-11 show regression analysis results from a spread sheet program evaluated daily for a period of one-year investigation. The analyses have been done to establish correlation between the approach temperatures particularly the condenser approach temperature and chiller performance parameters which include energy consumption, cooling capacity and COP. Figure 9 presents the regression analysis between condenser approach temperature (Tapp) and instant power consumption (Wc) of the chillers. The figure also presents the correlation equation between approach temperature and power consumption of the chillers. The results show positive correlation between condenser approach temperature and the instant power

consumption. The power consumption increases when the approach temperature increases. It occurs for all investigated chillers. However, the correlations have small coefficient of determination (R2) which means the relationship of both parameters is weak. The results signify that for the investigated chillers with approach temperatures to be maintained below 2 K, the approach temperatures have negligible influence on the power consumption of the chillers. 800 Power Consumption (kW) 700 600 500 400 300 200 100 0 y 35.403x + 593.78 Wc = 3RR5².24=030.T1a6pp8+1593.78 Condenser Chiller-1 0.0 0.4 0.8 1.2 1.6 2.0 2.4 Approach Temperature (K) 800 Power Consumption (kW) 700 600 500 400 300 200 100 0 yW=c=25.914xT+app5+65767.6.699 RR²2 = 0.0787 Condenser Chiller-2 0.0 0.4 0.8 1.2 1.6 2.0 2.4 Approach Temperature (K) 800 Power Consumption (kW) 700 600 500 400 300 200 100 0 y = 36.138x + 560.05 Wc = 3R6².1=380.T0a9pp7+3560.05 R2 = 0.0973 Condenser Chiller-3 0.0 0.4 0.8 1.2 1.6 2.0 2.4 Approach Temperature (K) Figure 9. The influences of condenser approach temperature on the chillers' power consumption established from regression analyses of one-year operational data Figure 10 shows the regression analysis between condenser approach temperature (Tapp) and the cooling capacity (Qe) of the chillers. The correlation equation of both parameters is also presented in the figure. From the figure it can be noticed that between condenser approach temperature and the cooling capacity have neutral correlation. The cooling capacity is stable when the approach temperature increases. The correlations have almost zero coefficient of determination (R2) which means there is no correlation between both parameters. Figure 11 shows the regression results between condenser approach temperature (Tapp) and the COP. The correlation equation between approach temperature and the COP are also presented in the figure. The analysis results show a negative correlation between condenser approach temperature and the COP. The COP of the chillers decreases when the approach temperature increases. It occurs for all investigated chillers. The correlations also have small coefficient of determination (R2) which represents the relationship between the approach temperature and the COP is weak. The results indicate that the approach temperatures also have negligible influence on the COP of the chillers. This happens as the results of regular maintenance has been performed to the chillers. Therefore, the approach temperatures can be maintained below 2 K or even mostly lower than 1.5 K. 4500 Cooling Capacity (kW) 4000 3500 3000 2500 2000 yQe =-42.02xT+app3+4347722.9.9 1500 RR²2 = 0.0093 1000 500 0 Condenser Chiller-1 0.0 0.4 0.8 1.2 1.6 2.0 2.4 Approach Temperature (K) Cooling Capacity (kW) 4000 3500 3000 2500 2000 yQ=e=1155.2.28844xT+app3+2392898.2.2 1500 RR²2 = 0.0014 1000 500 0 Condenser Chiller-2 0.0 0.4 0.8 1.2 1.6 2.0 2.4 Approach Temperature (K) 4500 4000 Cooling Capacity (kW) 3500 3000 2500 2000 1500 1000 500 0 y = -11.185x + 3450.1 Qe = - R1R1².21=8050..T000a0p00p+223450.1 Condenser Chiller-3 0.0 0.4 0.8 1.2 1.6 2.0 2.4 Approach Temperature (K) Figure 10. The effects of condenser approach temperature on the chillers' cooling capacity developed from regression analyses of one-year operational data 7 7 7 6 6 6 5 5 5 COP 4 y = -0.3887x + 5.8509 4 y = -0.2202x + 5.8163 COP 4 y = -0.3621x + 6.1354 3 COP =R-R²0.2=3=8080.73.33T37a7p22p+5.8509 COP 3 COP = -RR0.22²=2=0020.0.T09a29pp72+75.8163 3 COP =R-0².3=6201.1T0a5pp8+6.1354 R2 = 0.1058 2 2 2 1 Condenser Chiller-1 1 Condenser Chiller-2 1 0 0 0 Condenser Chiller-3 0.0 0.4 0.8 1.2 1.6 2.0 2.4 0.0 0.4 0.8 1.2 1.6 2.0 2.4 0.0 0.4 0.8 1.2 1.6 2.0 2.4 Approach Temperature (K) Approach Temperature (K) Approach Temperature (K) Figure 11. The effects of condenser approach temperature on the COP of the chillers resulted from regression analyses of one-year operational data The study confirms that by maintaining the approach temperatures below 2 K damaging effects of fouling in the condenser and evaporator can be avoided [12]. Moreover, the AC system can be sustained at their best potential performance. This, consequently, contributes to any energy conservation programs managed to the shopping mall buildings. 4. Conclusions Performance characteristics of AC system for a shopping mall building have been evaluated at different condenser and evaporator approach temperatures and regression analyses were also established to examine the correlations and influences of the approach temperatures on the chillers performance of the AC system. The analyses results showed that the increase of condenser approach temperature could increase the power consumption and reduce the coefficient of performance (COP) of the chillers. While evaporator approach temperature was found to have insignificant effect to the chiller performance. The results also showed that for the investigated chillers, the approach temperatures had negligible correlation to the power consumption and the overall performance of the chillers. The study has confirmed that by maintaining the approach temperatures below 2 K, damaging effects of fouling in the condenser and evaporator can be avoided and the AC system can be sustained at their best potential performance.

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multivariate and data envelopment analyses Appl Energy 92, 168-174 [16] Yu F W and Chan K T 2013 Improved energy management of chiller systems with data envelopment analysis Appl Therm Eng 50, 309-317.

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