

Effectiveness of Shading Air-Cooled Condensers of Air-Conditioning Systems

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ABSTRACT

In air-conditioning (A/C) systems with air-cooled condensers, the condensing unit has to be kept in the open for easy access to outdoor air in order to efficiently dissipate heat. During daytime, the solar radiation falling on the surfaces of the condenser and the high ambient temperatures can be detrimental for the energy performance. The effectiveness of shading the condensing unit to mitigate this adverse impact is investigated in this paper. A limiting analysis compares the performance of several A/C systems with ideal shade to those with ideal solar heat gain. The comparison is based on a theoretical model and data from equipment catalogs. The theoretical increase in the coefficient of performance (COP) due to shading is found to be within 2.5%. Furthermore, this small improvement in ideal efficiency decreases at higher ambient temperatures, when enhancements to efficiency are more needed. The actual efficiency improvement due to shading is not expected to exceed 1%, and the daily energy savings will be lower.

KEYWORDS: Energy saving, shading, air-conditioning, energy efficiency, electrical demand, coefficient of performance.

INTRODUCTION

Substantial amounts of energy are consumed in hot climates to provide comfort cooling. In a country like Kuwait, air-conditioning (A/C) accounts for nearly 70% of the electricity demand during peak hours and 45% of the annual consumption. Therefore, savings in energy consumed by A/C systems are critical for meeting energy demands and reducing harmful environmental emissions. Such savings can be achieved by reducing the cooling loads of buildings and improving the efficiency of A/C equipment. The condensing units of A/C systems with air-cooled condensers have to be kept in the open to allow access to outdoor air and efficiently dissipate heat from the condenser. During daytime, the solar radiation falling on the condenser surfaces can reduce system efficiency. In addition, the

ambient temperatures in hot climates significantly degrade the A/C performance by as much as 30% (ElSherbini and Maheshwari, 2010). This paper investigates the effectiveness of shading the condensing unit in order to mitigate the adverse impact of solar radiation.

Shade trees have direct and indirect effects on energy consumption, as summarized by Akbari (2002). Donovan and Butry (2009) studied shade trees in Sacramento, California, and estimated that trees on the west and south sides of houses save 5.2% of summertime electricity use. These savings result from reductions in cooling loads. The potential impact of shading on the efficiency of A/C systems can be attributed to two effects: reducing condenser inlet air temperature and decreasing the solar heat gain by the condenser. These two effects can potentially reduce the condensing temperature and improve system efficiency. However, measurements indicate that the first effect is not significant. Wray and Akbari (2008) examined the impact of cool roofs with reflective coatings on air temperatures around rooftop condensers and found the reduction in condenser inlet air temperature to be within 0.3°C. Also, the measurements of Parker et al. (1996) showed the change in condenser inlet air temperature caused by direct shading to be insignificant.

The energy impact of shading the A/C systems was measured by Parker and co-workers for 3 sites. They obtained mixed results with average efficiency enhancement of 0.1%. Some negative impact on efficiency was attributed to the shading method, which led to recirculation of hot exhaust air into the condenser inlet. A similar problem was encountered by Waly et al. (2005) who tested three methods to improve A/C system efficiency. Due to the recirculation, shading degraded system performance.

Thus, although the use of shade trees around buildings showed notable energy savings, the impact of shading air-conditioning systems on their energy performance demonstrated mixed results. Negative effects of shading on A/C efficiency were partly

blamed on the unsuccessful implementation of the shading devices themselves. The website of the Energy Efficiency and Renewable Energy program of the U.S. Department of Energy states that direct sunshine on the condenser reduces the A/C efficiency by up to 10% (EERE, 2010). The goal of this article is to evaluate the potential opportunity for utilizing condenser shading to enhance the energy efficiency of A/C equipment and reduce their power demand.

APPROACH

The shading of A/C condensers can potentially improve system efficiency by reducing the solar heat gain to the condenser. This study considers a limiting analysis to estimate the maximum potential for enhancing the A/C efficiency through the shading of condensers.

The analysis compares the performance of A/C units when operated under shaded and un-shaded conditions. For the un-shaded condition, it is assumed that all the energy available due to solar radiation is gained by the condenser. For the un-shaded condition, the shade is assumed to block all the energy from solar radiation without obstructing air flow or causing recirculation of hot exhaust air from the condenser. The change in refrigerant condensing temperature between the two conditions and the corresponding change in efficiency are then estimated.

ANALYSIS

Consider an air-conditioning system with an air-cooled condenser that is operating under an “ideal” shade, as shown schematically in Fig. 1. The evaporator can be air-cooling as in direct expansion (DX) systems or water-cooling as in chillers. The shade blocks all energy from solar radiation without restricting air flow. The figure also shows another condenser without the shade. It is assumed that all energy from solar radiation will be gained by the condenser. The amount of heat to be rejected through the unshaded condenser, Q_{cu} , is increased by the radiation gain, and is express as

$$Q_{cu} = Q_{cs} + q_{sol}A_c \quad (1)$$

where Q_{cs} is the heat rejected at the shaded condenser, q_{sol} is the solar heat flux reaching the condenser, and A_c is the condenser face area. For the shaded case, the rise in air temperature across the condenser can be determined from

$$T_{os} - T_i = \frac{Q_{cs}}{m_a c_a} \quad (2)$$

where T_{os} is the outlet air temperature, T_i is the inlet air temperature, m_a and c_a are the mass flow rate and specific heat of air. The inlet air temperature, T_i , is considered the same as the ambient temperature. Similarly, the outlet air temperature for the unshaded case, T_{ou} , can be estimated,

$$T_{ou} - T_i = \frac{Q_{cu}}{m_a c_a} \quad (3)$$

The log mean temperature difference for the condenser, ΔT_{LM} , is calculated from

$$Q = UA\Delta T_{LM} \quad (4)$$

where Q is the amount of heat transfer, U is the overall heat transfer coefficient, and A is the heat transfer area of the condenser. For the shaded condenser, the condensing temperature, T_{cs} , can be estimated from the log mean temperature difference,

$$\Delta T_{LMs} = \frac{(T_{cs} - T_i) - (T_{cs} - T_{os})}{\ln [(T_{cs} - T_i)/(T_{cs} - T_{os})]} \quad (5)$$

The two condensers are expected to have the same UA value. Therefore,

$$\frac{Q_{cs}}{\Delta T_{LMs}} = \frac{Q_{cu}}{\Delta T_{LMu}} \quad (6)$$

where ΔT_{LMu} is the log mean temperature difference for the unshaded condenser. The condensing temperature for the unshaded case, T_{cu} , can be determined from

$$\Delta T_{LMu} = \frac{(T_{cu} - T_i) - (T_{cu} - T_{ou})}{\ln [(T_{cu} - T_i)/(T_{cu} - T_{ou})]} \quad (7)$$

For a given A/C unit, equations (1) to (7) can be solved to obtain the change in condensing temperature due to solar radiation. The change in system efficiency is then estimated based on the difference in condensing temperatures. For this limiting analysis, the efficiency is represented by the ideal coefficient of performance (COP) for an equivalent Carnot cycle. Thus, the efficiency for the shaded case is

$$COP_{is} = \frac{T_e}{T_{cs} - T_e} \quad (8)$$

where T_e is the evaporating temperature. Similarly, the efficiency for the unshaded case is

$$COP_{iu} = \frac{T_e}{T_{cu} - T_e} \quad (9)$$

The improvement in COP due to shading becomes

$$COP_{inc} = \frac{COP_{is} - COP_{iu}}{COP_{iu}} = \frac{T_{cu} - T_e}{T_{cs} - T_e} - 1 \quad (10)$$

RESULTS AND DISCUSSION

The analysis described above was implemented on several A/C units to estimate the maximum potential improvement in efficiency due to shading. Data were collected from manufacturers' catalogs, including nominal capacity at standard rating conditions (AHRI, 2008), and condenser face area and air flow rate. The data also included the cooling capacity and compressor power at different ambient temperatures, especially at 48 °C. This temperature represents operation in hot weather and is currently the design ambient temperature for A/C equipment in Kuwait (MEW, 2010). The heat rejected at the condenser is estimated from an energy balance for the system, assuming no losses. The solar heat flux reaching the unshaded condenser is set at its peak of 1 kW/m². The evaporating temperature is assumed to be 5 °C for air-cooling evaporators (DX units), and 0 °C for water-cooling evaporators (chillers). The evaporating temperature is fixed for both the shaded and unshaded A/C systems. For the condensing temperature, a fixed "temperature split" is assumed. The temperature split, T_{ss} , is defined as the difference between the condensing and ambient temperatures,

$$T_{ss} = T_{cs} - T_i \quad (11)$$

where T_{cs} is the condensing temperature for the shaded case. A condenser split of 15 °C is adopted for typical condensers (Ananthanarayanan, 2005).

Table 1 presents the results for 5 packaged air-conditioning units and a chiller. The packaged units span a capacity range of 5 to 10 Tons of Refrigeration (TR; 1 TR = 3.517 kW), and the chiller represents large machines with a capacity of 458 RT. The increase in ideal COP for the 6 systems ranged between 0.6 and 1.9%. This result is a reflection of the small decrease in condensing temperatures due to shading, which ranged between 0.4 and 1.0 °C. Thus, the maximum theoretical improvement in efficiency resulting from shading these A/C systems is less than 2%.

The different system capacities presented in Table 1 demonstrate that the potential improvement in COP is not significantly affected by the size of the A/C unit. A more important variable is the heat rejected per face area of the condenser, q_s . This parameter ranged between 17 and 37 kW/m² for the selected systems. The increase in COP due to shading is plotted against q_s in Fig. 2. The figure shows that the impact of shading is more diminished as q_s increases. As the condenser heat per unit area increases, the contribution of the solar heat gain (1 kW/m²) becomes less noticeable. Therefore, the impact of removing the solar gain by shading is insignificant.

The effect of ambient temperature on the present analysis was examined. The ideal increase in efficiency due to shading was calculated for a single machine at different ambient temperatures. Figure 3 shows that the improvement in COP decreases at high ambient temperatures. It is worth noting that the anticipated improvement in efficiency by shading is most needed at these high temperatures. Figure 4 presents the change in COP with ambient temperature for the shaded and unshaded cases as percentages of the nominal value. The figure demonstrates that the theoretical decrease in COP due to solar radiation is small compared to the degradation due to the rise in ambient temperature. Thus, for nighttime operation, the drop in ambient temperature is the dominant factor improving A/C efficiency, rather than the lack of solar radiation.

The sensitivity of the results to the assumed temperature split was evaluated. The temperature split is a function of the condensing temperature, which depends on the effectiveness of heat transfer at the condenser. For a given duty and ambient temperature, a condenser with a higher UA has a lower condensing temperature, smaller split, and higher system COP. Thus, a lower temperature split is favorable for higher A/C efficiency. If an A/C unit is shaded, the impact of the temperature split on the theoretical increase in COP is shown in Fig. 5. The improvement in COP due to shading decreases for lower values of T_{ss} . However, the COP improvement due to shading is still small, and the impact of the temperature split on it is not significant.

The actual effect of shading A/C condensers is expected to be lower than the theoretical impact. Condenser coils typically have vertical or inclined orientations, and the solar angle of incidence is far from zero for most of the time. Moreover, coil configurations usually have more than one side, such as a U shape. This results in the solar radiation not

reaching all the condenser face area at a given time. Therefore, the actual improvement in efficiency due to shading is not expected to exceed 1%. The daily energy savings will be much smaller than this maximum, since the radiation drops to zero at night. The very small savings prohibit a detailed consideration of hourly savings for different solar angles. It is also important to note that shading can result in performance degradation, if the shading method itself led to partial obstruction of the air flow out of the condenser.

CONCLUSIONS

The effect of shading the condensers on the efficiency of air-conditioning systems was investigated. A limiting analysis was conducted to estimate the maximum potential improvement in system COP when condensers are shaded. The analysis compared the performance of several A/C systems with ideal shading to those with ideal solar heat gain. The results showed the theoretical increase in COP due to shading to be only within 2.5%. The improvement in COP was found to decrease as the heat rejected per face area of the condenser increases. This finding was explained by the diminishing share of the solar heat at higher values of q_s . A sensitivity analysis was carried out to examine the impact of some assumed values on the results. The small improvement in theoretical COP due to shading was not significantly affected by the ambient temperature, nor the condenser temperature split. The improvement in COP was found to be slightly lower at higher ambient temperatures, when it is needed most, and at lower temperature splits. The actual increase in efficiency due to shading is not expected to exceed a maximum of 1%. Actual daily and seasonal savings in energy will be even lower. The findings of this study suggest that shading alone, without evapo-transpiration, is not an effective measure to improve A/C efficiency or reduce electrical demand.

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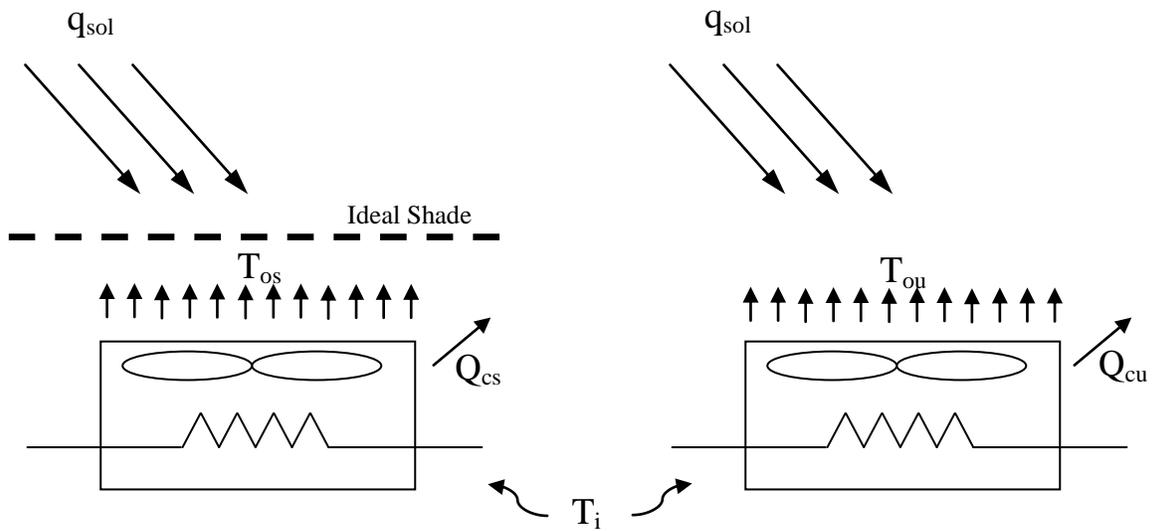


Fig. 1. Schematic diagram representing the two cases of shaded and unshaded condensers.

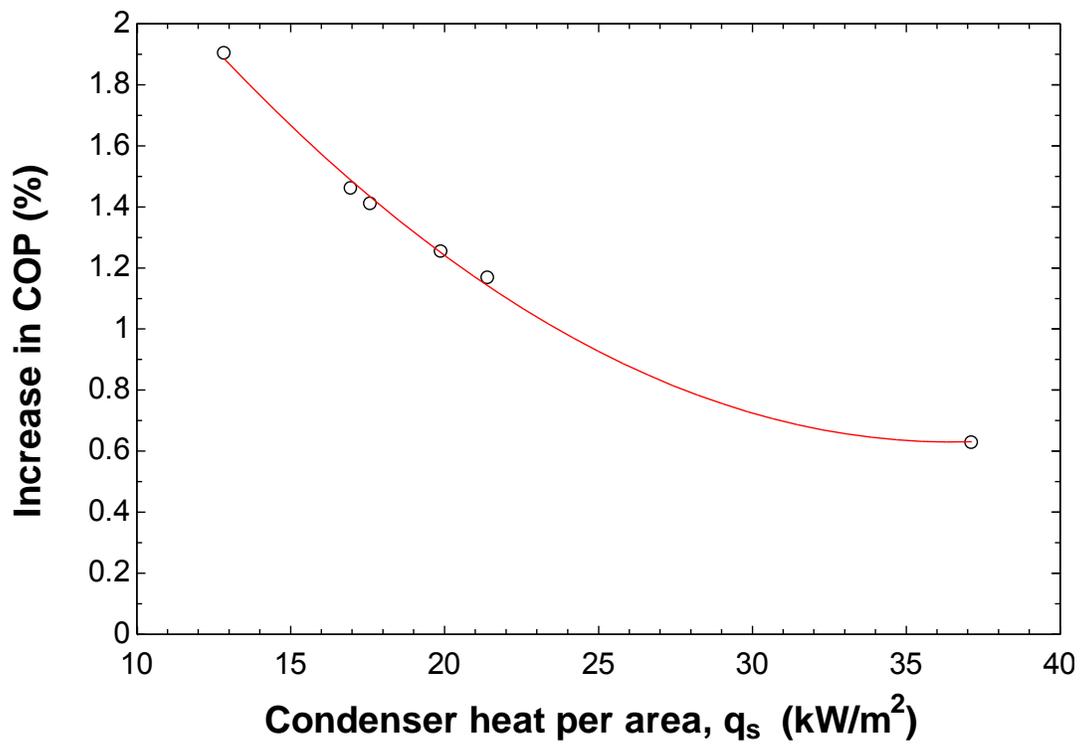


Fig. 2. Increase in efficiency due to shading as a function of condenser heat rejected per unit area

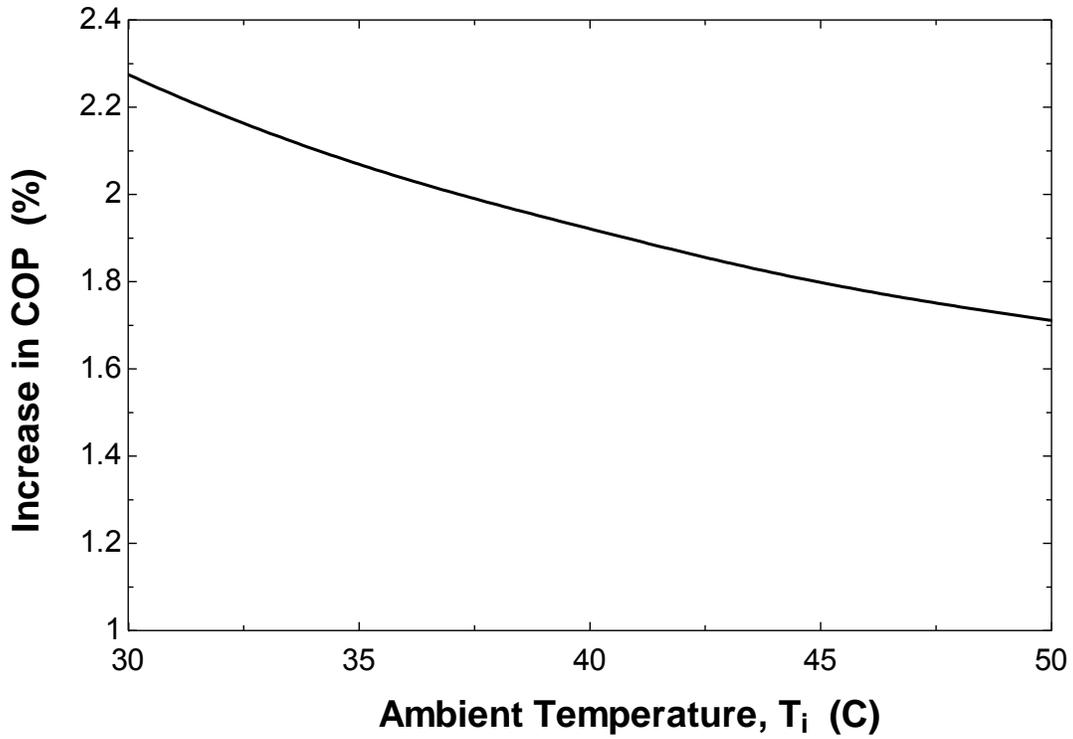


Fig. 3. Increase in efficiency due to shading as a function of ambient temperature

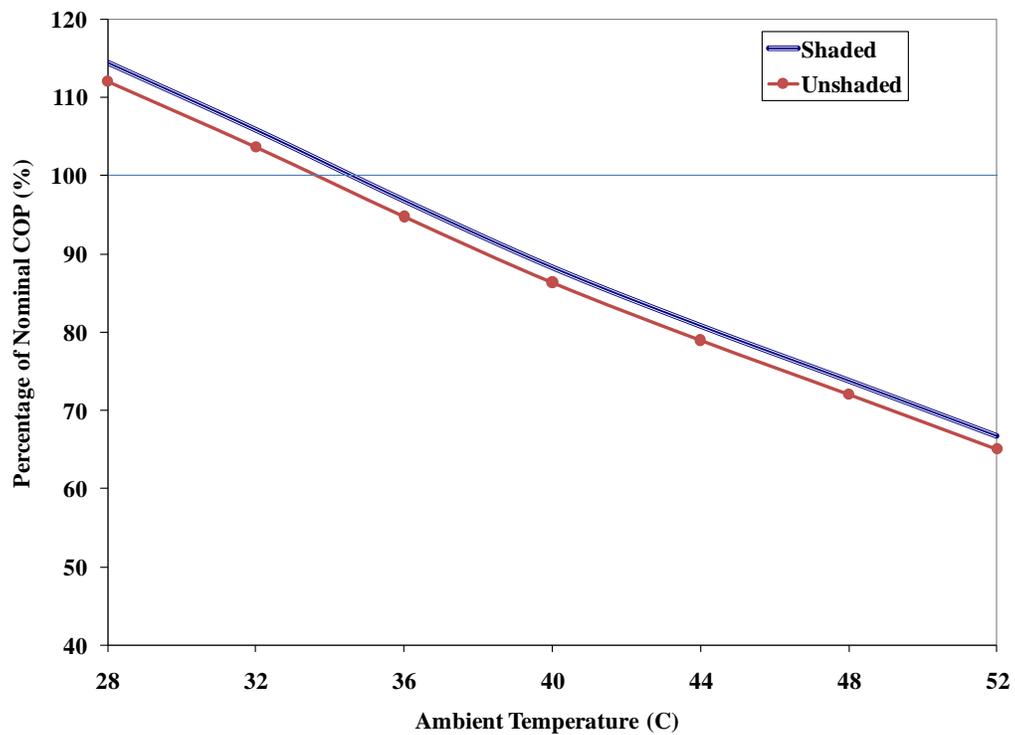


Fig. 4. Variation of COP with ambient temperature for the shaded and unshaded cases.

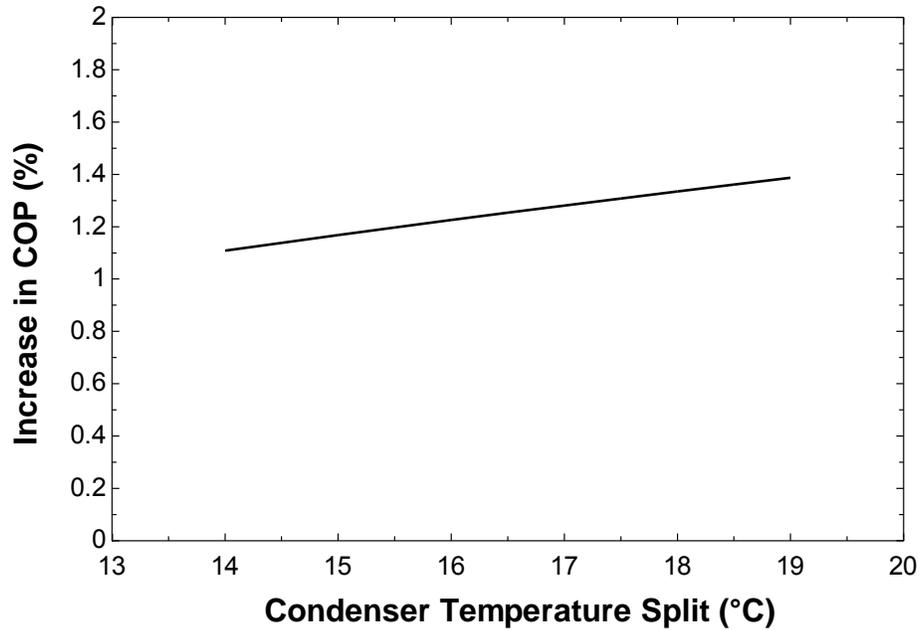


Fig. 5. Increase in efficiency due to shading as a function of condenser split temperature

Table 1. Input data and results for 6 air-conditioning systems

Parameter	Unit	Packaged Units					Chiller
		5	6.1	6.9	8.3	10.2	
Cooling Capacity - Nominal	TR	5	6.1	6.9	8.3	10.2	458
Cooling Capacity at 48°C	kW	14.5	17.1	20.3	21.3	26.9	1230
Compressor Power at 48°C	kW	6.26	7.31	9.08	10.93	18.84	552
Condenser Face Area	m ²	0.97	1.9	1.67	1.9	2.3	48
Condenser Air Flow	m ³ /s	1.415	2.88	2.88	3.05	3.05	129
Condenser Heat per Area	kW/m ²	21.4	12.8	17.6	17.0	19.9	37.1
Leaving Air Temp-Unshaded	°C	61.9	56.3	57.8	58.1	62.3	60.9
Leaving Air Temp-Shaded	°C	61.3	55.7	57.2	57.6	61.6	60.5
Condensing Temp - Unshaded	°C	63	63	63	63	63	63
LMTD-Unshaded		5.32	10.32	9.28	9.00	4.74	6.59
LMTD-Shaded		5.08	9.57	8.78	8.50	4.51	6.42
Condensing Temp - shaded	°C	62.3	61.9	62.2	62.2	62.3	62.6
Decrease in Condensing Temp	°C	0.67	1.08	0.81	0.83	0.72	0.39
Increase in COP	%	1.17	1.90	1.41	1.46	1.25	0.62