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Criterion to evaluate the convenience of implementing evaporative precooling in air-cooled chillers

Criterio para evaluar la conveniencia de implementar preenfriamiento evaporativo en chillers enfriados por aire

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ABSTRACT: This study presents a criterion to determine if local conditions of meteorology and the cost of energy and water favor the use of evaporative precooling in air-cooled chillers. It has been found that when the energy saved per unit of water consumed is higher than the ratio between the cost of water and electricity, it is economically attractive to operate the chiller with evaporative precooling. Furthermore, we found that the energy savings are proportional to the annual average wet-bulb depression (AWBD) temperature. As a case study, we tested this criterion by comparing it with results of monitoring every ten minutes and for more than five months, the operation of a frequently used chiller (82 RT) working in northern Mexico. Considering the past six years of hourly meteorological conditions of this region, we found that, on average, 4.4% of the annual energy consumption can be saved by evaporative precooling. That saving could be up to 23% at some hours of the year. These results represent a potential saving of 35.7 MWh/year. However, it requires the use of 1,759 m^3/year of water to moisten the air. Considering the current water and energy prices in the study region, the evaporative precooling represents a saving of USD 2,704/year. This monetary saving is relevant considering that many companies and buildings use tens of these chillers in their production line or air conditioning systems.

RESUMEN: Se presenta un criterio para determinar si las condiciones locales de meteorología y el costo de la energía y el agua favorecen el uso de preenfriamiento evaporativo en chillers enfriados por aire. Cuando la energía ahorrada por unidad de agua consumida es mayor que la relación entre el costo del agua y el costo de la electricidad es económicamente atractivo operar chillers con preenfriamiento evaporativo. El ahorro de energía es proporcional a la temperatura promedio anual de depresión de bulbo húmedo (AWBD). Como caso de estudio, se verificó este criterio con los resultados de monitorear cada diez minutos y durante más de cinco meses, la operación de un chiller de uso frecuente (82 RT) operando en el norte de México. Se encontró que, en promedio, el 4,4% del consumo anual de energía se puede ahorrar mediante preenfriamiento evaporativo. Ese ahorro podría ser de hasta un 23% en algunas horas del año. Estos resultados representan un ahorro potencial de 35,7 MWh/año. Sin embargo, requiere el uso de 1.759 m^3/año de agua para humedecer el aire. Teniendo en cuenta los precios actuales del agua y la energía en la región de estudio, el preenfriamiento evaporativo representa un ahorro de USD 2.704/año. Este ahorro monetario es relevante teniendo en cuenta que muchas empresas y edificios utilizan decenas de estas enfriadoras en su línea de producción o sistemas de aire acondicionado.

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1. Introduction

The world's consumption of energy for cooling has increased considerably in the last decades due to diverse

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factors such as population growth, global warming, and industry requirements. A large percentage of this energy is consumed by air conditioning equipment in buildings to maintain adequate conditions of comfort in a more demanding society. Large quantities of energy for cooling are also needed to satisfy the demands of several processes in the chemical, food, pharmaceutical, and manufacturing industries [1].

Chillers are the most common technique deployed to provide chilled water for air conditioning systems of commercial and residential buildings and some industrial processes [2]. They are preferred because of their lower maintenance cost and the simplicity of their operation. The operation of chillers is linked to a large proportion of the electrical energy consumed by buildings [1]. Their operation is based on the vapor compression cycle where a refrigerant is compressed and expanded to remove heat from a water flow that circulates in a heat exchanger. A condenser is used to dissipate the removed heat to a flow of ambient air (air-cooled chillers). At full load operation, the air-cooled chillers have typical coefficient of performance (COP) values between 2.7 and 3.2 [3]. The COP of this type of chiller can be improved by precooling the inlet ambient air using different methods, such as direct evaporative cooling with water mist generated by spray nozzles [4].

Previous works have shown that the performance of air-cooled chillers improves by precooling the ambient air at the inlet of the condenser using analytical models based on thermal energy balances and statistical analyses using experimental data. Most of them focus on chillers used for air conditioning of residential and commercial buildings in subtropical regions in Asia. Experimental works report low savings in energy consumption (<25%), while analytical works report savings of up to 50%. Next, we acknowledge some of those works.

Experimental studies

In 2012, an experimental facility of three R134 air-cooled chillers with water mist evaporative precooling was implemented in Hong Kong, China. Results showed that the air temperature decreased by up to 9.4 oC, and the chiller COP was enhanced by up to 18.6% [5].

In 2015, a 4-ton supersonic vaporization air-cooled chiller with a fuzzy control system was proposed in Taiwan. An air temperature difference of 5.4°C was observed, along with 25% of energy savings [6].

In 2017, in a study developed in Egypt, water-cooled by the chiller was used for attaining the water mist precooling. The air temperature dropped by up to 9.4°C, and the chiller's COP improved by 18.6% [7].

In 2018, the operative variables of a 282 kW (COP of 2.8 at 100% load) air-cooled chiller of an office building and a hotel in a subtropical climate in Hong Kong, China, was monitored every 5 min during seven months. It was found that precooling the condenser air by mist increased 0.36–8.86% and 0.34–10.19% of the chiller's COP under the normal and variable fan speed modes, respectively. The annual electricity savings were found to be 2.5-2.94%. Based on a regression analysis, the authors found that the change in cooling effectiveness was influenced mainly by the wet bulb temperature, indicating that cooling effectiveness depended more on the weather variables than the controlled variables of the chiller [8, 9].

In 2020, a study carried out in Tianjin, China, the authors adopted a two-phase swirl nozzle in the precooling state. Their experimental results showed that the chiller's COP increased by 4%–8%, contributing to electricity savings of 2.37%–13.53% [10].

In 2021, it was explored the feasibility of using seawater for evaporative cooling and concluded that seawater has slightly lower cooling performance compared to the case of using fresh water. This conclusion is relevant for coastal areas where access to freshwater is limited [11].

Finally, in 2022, researchers in China developed an experimental investigation on the performance of a hollow fiber membrane evaporative cooler in hot–dry regions under laboratory conditions. The maximum air temperature drop was 7.5°C [12]

Modelling studies

In 2011 (Hong Kong, China), researchers conducted transient simulations with the DOE2 software to investigate the effect of the dry bulb temperature on the COP of an air-cooled chiller with mist precooling. They found that chillers using mist precooling could increase their COP between 17.1- 61.7% with respect to normal operation. These improvements could represent around an 18% reduction in the annual electricity consumption of a chiller system serving a reference hotel in a subtropical climate [13].

In 2012 (Hong Kong, China), it was developed a thermodynamic model and validated it with measured data. The study analyzed the effect of the energy efficiency of air-cooled chillers with a water mist system for an office building in a sub-tropical climate, obtaining an improvement in the chiller's COP of 51.5% [14]

In 2013 (Hong Kong, China), the software (Energy Plus) and experimental data were employed to estimate the energy consumption of an air-cooled chiller under different weather scenarios (2020, 2050, 2080). Results showed a reduction in the electricity energy consumption of the chiller of 16.96-18.58% using a mist precooling strategy and variable air conditioning fan speeds were included [15].

Finally, in 2019, it was modeled the heat transfer that occurs in a hybrid evaporative precooling air-conditioning system. The heat exchanger was used to precool ambient hot and fresh air before the conventional air conditioning unit using evaporative water mist along and cool exhaust indoor air. They concluded that the hybrid system achieved energy savings by reducing the cooling load for the vapor compression unit [16].

Objectives and contribution of the present work

Previous experimental works required the implementation of the water mist evaporative precooling technology on a chiller to conduct the desired study. This action produced irreversible modifications on the chillers being tested. Therefore, these works limited their scope to the specific chiller technology tested and the specific meteorological conditions under which they were conducted. These works highlighted the need for further studies to evaluate the effects of the meteorological and operating conditions on the performance of the air-cooled chiller when they use water mist evaporative precooling. It is desirable to know in advance if the local meteorological conditions of a given region are appropriate for implementing the water mist evaporative precooling technology. Furthermore, it would be desirable to know the actual effects of precooling on the energy efficiency of a given chiller technology.

Aiming to address these needs, in this work, we present a criterion to determine if the prevailing local conditions of meteorology and the local cost of energy and water favor the use of water mist evaporative precooling in air-cooled chillers. We also present a methodology to confirm experimentally the effects of using evaporative precooling on the energy performance of any technology of air-cooled chillers, based on the continuous monitoring of the actual operative conditions of the chiller, without implementing the water mist precooling. Finally, we illustrate the use of the suggested criterion and methodology for the case of a chiller operating in a region with a mix of favorable and unfavorable meteorological conditions for applying evaporative precooling.

2. Methodology

Aiming to develop a criterion to determine if the local meteorological conditions and the cost of energy and water favor the use of evaporative precooling, we first developed a model in which the electrical power consumed by air-cooled chillers is estimated as a function of the ambient meteorological conditions. Next, we added the use of water mist evaporative precooling to that model. Then, we selected a typical medium-sized chiller working in a region with potentially favorable meteorological conditions and monitored its operation for a long time ($\sim$ 5 months). The collected data was used to calibrate the model. Subsequently, we deployed the calibrated model to assess the 6-year average energy and water consumption with and without evaporative precooling. Finally, we performed a financial analysis to determine a metric to measure when the implementation of this technology is attractive. Next, we describe in detail each step.

2.1 Energy consumption of chillers as a function of meteorological conditions

A steady-state thermodynamic model was developed to estimate the energy consumed by air-cooled chillers as a function of the ambient air temperature under which they operate. Figure 1a illustrates the components of the refrigeration cycle of the chiller, and Figure 1b shows its corresponding pressure vs. enthalpy diagram. An energy balance for each of these components was carried out.

Evaporator: The chiller load demand (*L*) is defined by the mass flow of cold water $(\dot{m}_w)$ and the temperature difference of this water at the inlet (T_5) and at the output (T_6) (Equation (1)], where *h* is enthalpy). (T_6) is defined by the process where the chiller is used. It remains constant regardless of the chiller load demand. In our case of study, it is 7°C.

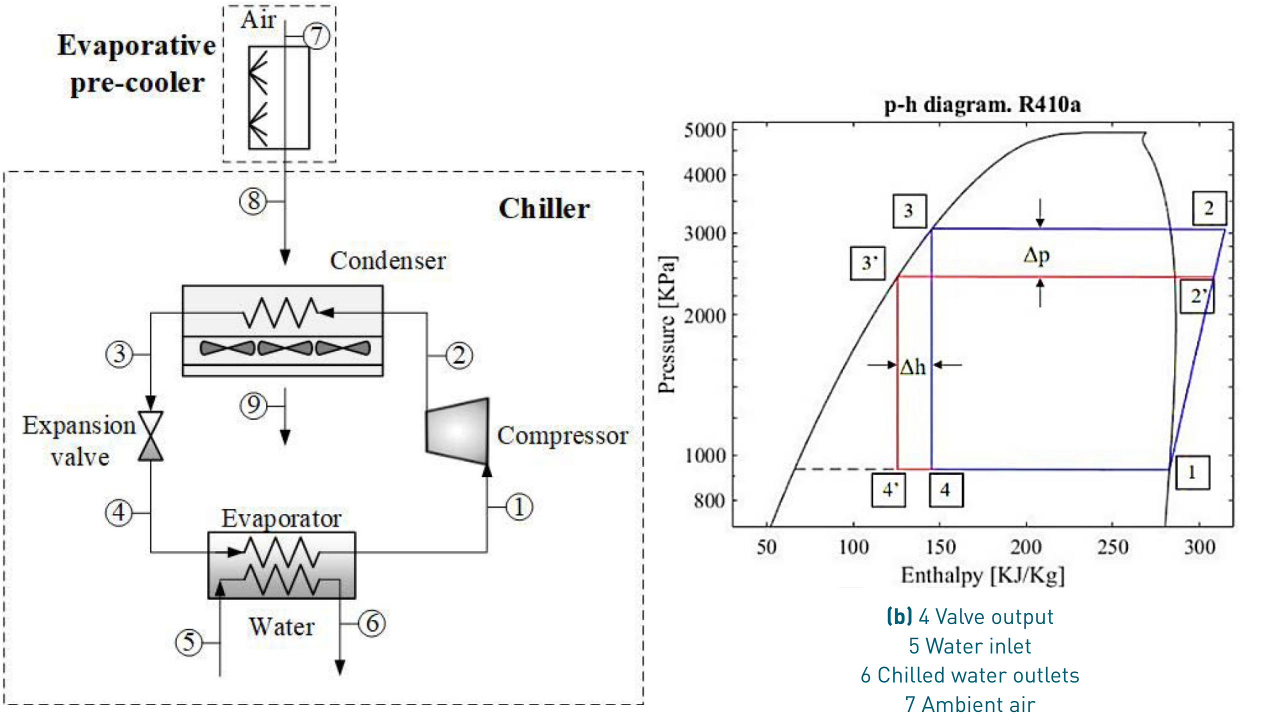
The thermal chiller load demand is provided by the refrigerant when it passes through the evaporator $(\dot{Q}_e)$. The refrigerant temperature at the outlet of the evaporator (T_1) is equal to the temperature of the cold water (T_6). The refrigerant comes out as saturated vapor at the evaporator outlet (state 1). The state of the refrigerant at the evaporator inlet (state 4) is defined by the expansion process at the expansion valve. Therefore, Equation (2) describes the average refrigerant coolant flow rate $(\dot{m}_r)$ required to meet the load requested to the chiller.

$$L = \dot{m}_w \left(h_6 - h_5\right) \tag{1}$$

$$\dot{Q}_e = \dot{m}_r \left(h_1 - h_4\right) \tag{2}$$

Compressor: Assuming that the second law efficiency of compression, or isentropic efficiency (η_s), and the mechanical efficiency of the compressor (η_m) are known, the compression work ($\dot{W}$) is given by equations (3) and (4). In Equation (4), h_2^* is the isentropic enthalpy of the refrigerant at the same pressure as state 2, which is defined by the refrigerant condensation process.

$$\dot{W} = \dot{m}_n \underline{(h_2 - h_1)} \tag{3}$$



(a) 1 Evaporator outlet
2 Compressor output
3 Condenser output

(b) 4 Valve output
5 Water inlet
6 Chilled water outlets
7 Ambient air
8 Air inlet to the condenser
(wet air if using evaporative precooling)
9 Condenser output

Figure 1 Thermodynamic cycle of a chiller with a water mist evaporative precooling system. a.) Components of the chiller and of the water mist evaporative precooling system. b.) pressure vs. enthalpy diagram of the refrigeration cycle, showing the effect of precooling the air on the condenser side of the refrigeration cycle

$$\eta_s = \frac{h_2^* - h_1}{h_2 - h_1} \tag{4}$$

Condenser: The condensation temperature (T_3) is defined by the energy balance that occurs between the refrigerant and the ambient air at the condenser. According to Hundy *et al.* [17], heat transfer in air-cooled condensers ($\dot{Q}_C$) is directly proportional to the difference between the refrigerant condensation temperature (T_3) and ambient air temperature (T_8). This constant of proportionality (*K*) depends on the condenser technology and must be obtained experimentally. The refrigerant leaves the condenser as a saturated liquid. Therefore, Equations (5) and (6) define the temperature and pressure in the condenser.

$$\dot{Q}_c = K\,(T_3 - T_8) \tag{5}$$

$$\dot{Q}_c = \dot{m}_r\,(h_3 - h_2) \tag{6}$$

Expansion valve: We consider that the flow of refrigerant through the valve follows an isenthalpic process ($h3 = h4$). This process, plus the fact that T_4, T_6, and T_1 are known, defines state 4.

Overall performance of chillers: Equations (1)-(6) model thermodynamically the cooling cycle used in chillers. The coefficient of performance (COP, Equation (7)) evaluates the energy performance of chillers. In Equation (7), *W* is the electric energy consumed by the chiller.

$$COP = \frac{L}{W} \tag{7}$$

Evaporative precooling: Figure 1 illustrates the chiller running with evaporative precooling. In this case, ambient air goes through a previous process of isenthalpic humidification ($h_7 = h_8$) before passing through the condenser. Considering that, in practice, it is not possible to saturate the air at 100% of relative humidity, a humidification efficiency, given by Equation (8), was used.

$$\eta_h = \frac{T_7 - T_8}{T_7 - T_{wb7}} \tag{8}$$

This equation defines the new air temperature (T_8) entering into the condenser. We used η_h = 80%, taking into consideration that this value has been observed in previous works [7, 11, 13]. In Equation (8), T_{wb} is the saturation temperature at 100% of humidification or wet bulb temperature, which is calculated from the meteorological data of ambient temperature (T_7) and ambient relative humidity (ϕ), considering an isenthalpic humidification process.

Finally, Equation (9) determines the water flow ($\dot{m}_w$) needed to achieve the level of humidification required. In this equation, the specific humidity (ω) is calculated through Equation (10), where P_s is the water saturation pressure at the temperature considered, P is the total ambient pressure, and $\dot{m}_a$ is the mass of air flowing through the condenser.

$$\dot{m}_w = \dot{m}_a \left(\omega_8 - \omega_7\right) \tag{9}$$

$$\omega = \frac{0.622\phi P_s}{P - \phi P_s} \tag{10}$$

This model was implemented and solved in the Engineering Equation Solver (EES), which has a database of the thermodynamic properties of water and of the refrigerants frequently used in chillers. In this case, we used the refrigerant 410A. The implemented model does not take into account the additional energy required for the operation of the chiller, such as i.) The energy used by the fans that force the airflow through the condenser, and ii.) The energy consumed by the control system. Additionally, these equations include unknown constants (Equation (5)) that need to be determined experimentally.

2.2 Monitoring the operation of a typical chiller

The metropolitan area of Monterrey was selected as a case study. Monterrey is a city in Northern Mexico with a semi-arid climate. It is characterized by a notorious seasonal behavior with low humidity, high temperatures in summer (~40°C), and low temperatures in winter (~0°C). In order not to lose generality in the conclusions, results will be presented as a function of the measured meteorological conditions.

For this study case, we used an industrial medium-size chiller (YLAA0089SE), which is equipped with hermetic scroll compressors. It uses R410A and exhibits a nominal capacity of 82 refrigeration tons (RT). It supplies between 25 and 100 m^3/h of chilled water (7°C) using a double cooling circuit, six scroll compressors in parallel (3 for each circuit), and a condenser cooled by 60,000 cfm of air generated by four fans (Figure 2). This chiller operates 24 hours/day all year round in the metropolitan area of Monterrey, providing cold water for the industrial process of a glass manufacturer.

An electronic system was developed to monitor the operation of the chiller every ten minutes and to send the collected data to the cloud automatically via 3G. The technical features of these sensors are shown in Table 1. Sensor calibration was checked periodically (once per month). We monitored: i.) the temperatures of the water at the inlet and outlet of the chiller; ii.) The temperature of evaporation, condensation, and discharge of the refrigerant; iii.) The temperature and relative humidity of the air at the inlet and outlet of the condenser, and iv.) the electrical power consumed by the chiller.

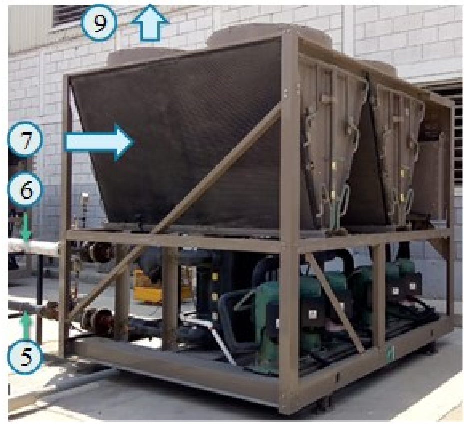


Figure 2 Illustration of the chiller monitored in this study. The numbers shown correspond to the locations defined in Figure 1

The operation of this chiller was monitored under normal operating conditions for five months (June to October). The data obtained was filtered to disregard spurious data. Outliers were also disregarded, including ambient temperature above 45°C or an ambient relative humidity value higher than 100% or less than 5%,

3. Results

3.1 Modeling of the chiller's performance

We used the model described above to estimate the electric energy consumed by the chiller as a function of the ambient air temperature. We considered different levels of loads in consideration of the fact that, in practice, chillers are rarely used at 100% of their nominal capacity.
We defined the reference power as the power consumed by the chiller at 25°C of ambient air temperature under each load level and expressed results as power ratio, i.e., the fraction with respect to the respective reference power. Figure 3a shows that the power ratio depends linearly on the ambient temperature ($R^2 > 0.96$). Figure 3a shows that this power ratio is mostly independent of the load level. Similarly, we define the reference (COP_{ref}) as the COP reported by the manufacturer, which was obtained at a load of 100% and 25°C of ambient air. Figure 3b shows that according to this model, the chiller's COP decreases with ambient temperature, and it is also independent of the load level.

Table 1 Technical characteristics of the sensors used to monitor the operation of the chiller

Sensor	Range	Accuracy	A/D	Installation	Supply
Temperature	-55 to 125°C	± 0.5°	D	Contact	3–5v
Humidity	-20 to 70°C 0-95%RH	±0.5°C/2% RH	D	Environment	3.3-5v
Flow	-	±1%	A/D	Contact	24v
Current	0–800A	0.5%	D	Contact	-

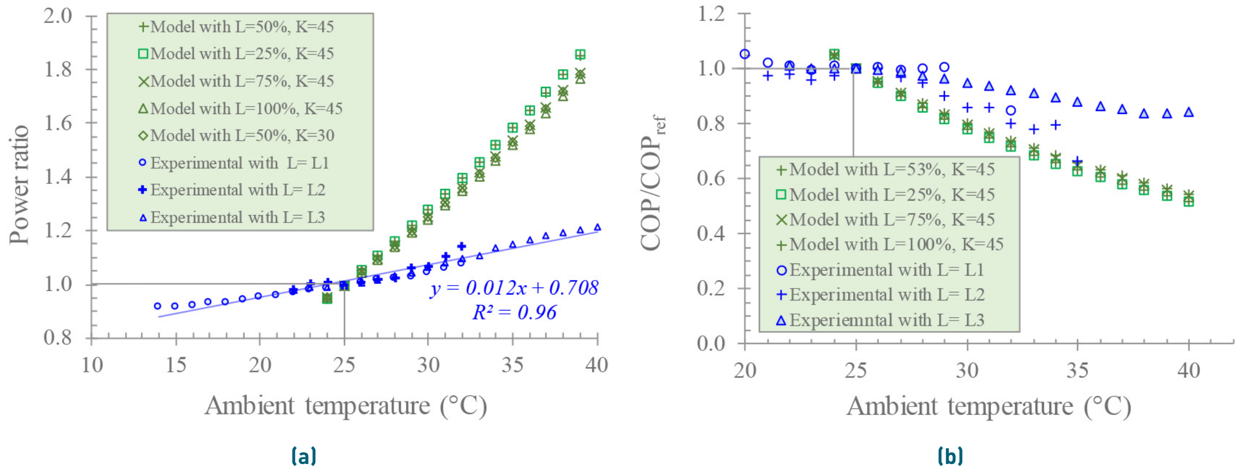


Figure 3 Results of the chiller's model and experimental measurements as a function of ambient temperature. a.) Power consumed by the chiller expressed as a fraction of the reference power. b.) Chiller's COP as a fraction of the reference COP

3.2 Monitoring the chiller's performance and calibration of the model

As described above, our model does not consider mechanical efficiencies and assumes arbitrary values for the heat transfer constant and the isentropic efficiency of the compression process. It does not consider the secondary energy consumptions required for the operation of the chiller, such as the fans and the control system. Therefore, this model needs to be calibrated for each type of chiller with experimental data obtained at different working load conditions and ambient temperatures.

Toward that end, we used the 82 RT industrial medium-size chiller described above as a case study. This chiller was instrumented and monitored every ten minutes for five continuous months of operation. Figure 4a shows the daily variation of ambient temperature during the monitored time. This figure shows that during this period, in the region of study, the ambient temperature varied between 20 and 41°C, corresponding to the operating range of the chiller. Vertical lines in Figure 4a indicate one standard deviation of the temperature at each hour of the day, which varied from 3.0 to 4.3°C.

This chiller worked predominantly under three operative conditions described next during this period. Two trends of temperature differences (inlet and outlet) of the chilled water (ΔT's) were observed: between 1.4 and 3.5°C and between 4.9 and 6.0°C (Figure 4b). Part of the time, the chilled water flow remained constant at approximately 18 m^3/h. These working conditions led to two load levels of approximately L_1=26% and L_2=43% of the nominal chiller power (82 RT), respectively. We also identified a third working condition when 4.9<ΔT <6.0°C and the chilled water flow rate was $\sim$22 m^3/h, which leads to a load of approximately L_3=53% (Figure 4c).

Then, we plotted the experimental results as the power ratio vs. ambient temperature for the three working loads (Figure 3a). We observed that, independently of the working load, experimental data collapsed into a single line, which agrees with the conclusion obtained from the analytical model. This figure also shows that the actual demand in power consumption is linearly correlated (R^2>0.95) with ambient temperature and that power consumption increases by 1.21% per degree of ambient temperature.

As described above, the analytical model must be adjusted by a calibration constant in order to reproduce experimental data. We developed a correlation analysis between the model's results and experimental data for that purpose. Figure 4d shows that they are highly

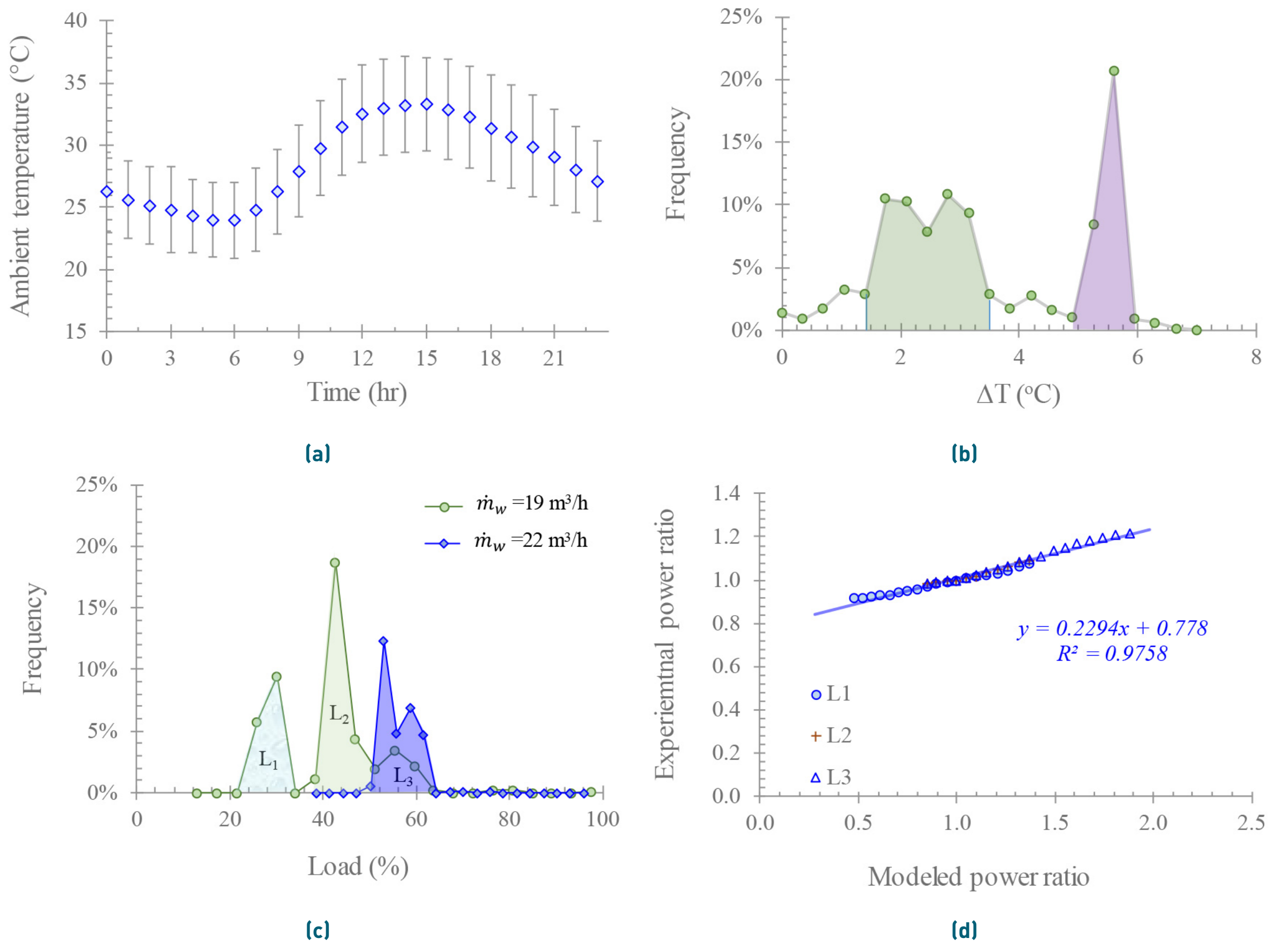


Figure 4 Results of monitoring the operation of an 82 TR chiller under the meteorological conditions of Monterrey every ten minutes. a.) Hourly variation of ambient temperature. Vertical lines indicate one standard deviation of the temperature. b.) Frequency distribution of the difference between the inlet and outlet temperature of the chilled water (ΔT). c.) Frequency distribution of the chiller's working loads for the two predominant ΔT levels observed in Figure 4b. d.) Correlation analysis between the measured electrical power consumed by the chiller and the estimated by the model

correlated (R^2>0.96) and that the calibration constant is 0.23 with an offset of 0.778. We highlight that this calibration constant is valid only for the specific chiller used in this study.

3.3 Use of the calibrated model to evaluate the savings that could be obtained by evaporative precooling over six years of operation

Aiming to estimate the energy savings and water consumption of chillers when evaporative precooling is employed over a long time, the chiller used in this work and the local meteorological conditions for the past six years were considered. Historical Meteorological data was obtained from the Mexican Meteorological Center [17].
Figure 5a shows the variation in average daily ambient temperature throughout the six years considered. It highlights the temperature seasonal behavior in Monterrey. Figure 5b shows the time-frequency distribution of ambient temperature and relative humidity. This figure shows the predominance of medium temperatures (∼25°C) and high humidity (∼90%), which could be unfavorable for using evaporative precooling in this region.

Then, for each hour of the year, we used the calibrated model and estimated the power consumed by the chiller at the respective ambient temperature. Also, ambient air humidity at the same hour was used to calculate the temperature that would be achieved by precooling this ambient air through a water mist evaporative process. A humidification efficiency of 80% (Equation (8)) was considered. Subsequently, the calibrated model was used again to recalculate the power consumed by the chiller, assuming that it operates under this new ambient

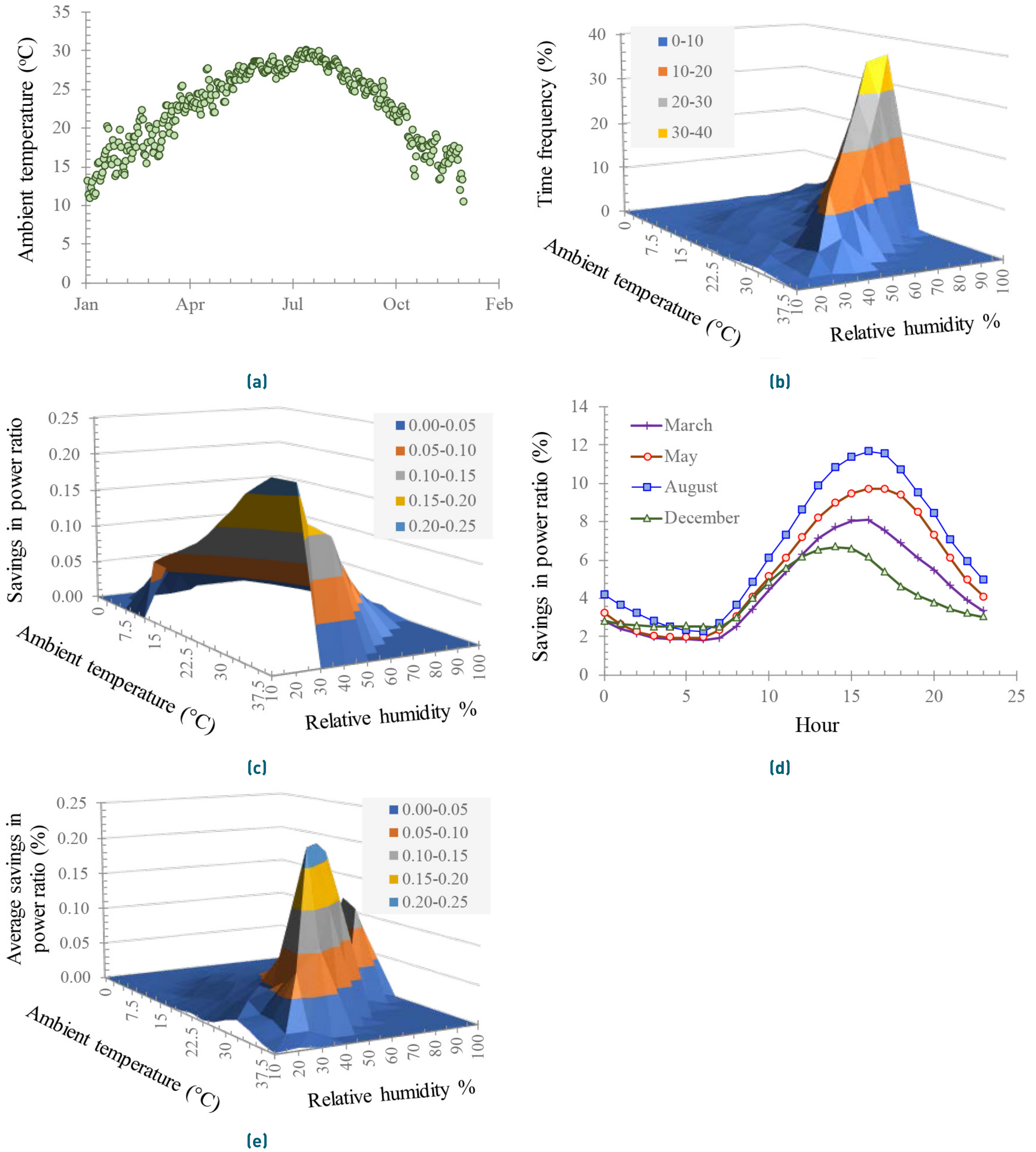


Figure 5 Results of the use of evaporative precooling in an 82 RT industrial chiller based on the meteorological conditions of the last six years in Monterrey. a.) Average daily ambient temperature b.) Time-frequency distribution of ambient temperature and humidity. c.) Energy savings as a function of temperature and humidity in the chiller operation expressed as power ratio. d.) Hourly average savings expressed as power ratio per month of the year. e.) Six-year average savings in power ratio as a function of temperature and relative humidity

temperature. The difference between these two powers is the power saving achieved by evaporative precooling. In addition, we calculated the amount of water used in the air-cooling process (Equation (9). Figure 5c shows the savings, expressed as power ratio and as a function of the temperature and humidity of the environment. As expected, the most significant savings were achieved at high temperatures and low humidity conditions. The shape of Figure 5c is independent of the chiller's technology and of the meteorological conditions. The values of power savings could be affected by a single scale factor that depends on the chiller's technology.

The savings in the total annual energy consumption depend on the actual load demanded to the chiller, which depends on the industrial process that the chiller serves. Then, to keep the generality of our results, we report the savings as the six-year average savings in power ratios. It can be obtained by multiplying (dot product) results shown in Figure 5b (local meteorological conditions) by the results shown in Figure 5c (general behavior of chillers) or just by a simple average of the hourly savings during the six years considered. Following these two procedures, we found an average saving of f_s =4.4% (Figure 5d, Table 2) for the chiller considered in this study, working under the meteorological conditions of the study region for the past six years. Thus, the total energy saved is obtained by multiplying this percentage of savings by the total energy currently consumed by the chiller. For the 82 RT chiller considered in this study, assuming L=100%, the estimated saving was 4.08 kW, which means an annual energy saving of 35.7 MWh. Considering the local cost of electric energy (C_e) of USD$ 0.10/kWh, which is close to the average cost of electricity in the USA of USD$ 0.12/kWh [18], this result represents a saving of USD$ 3,729/year. These figures could be considered small; however, at least in Monterrey, many companies and buildings use several of these chillers in their production line or air conditioning system.

Figure 5d shows the hourly average power ratio saved per month of the year. It shows that for the meteorological conditions of the study region, operating the chiller with evaporative precooling is most favorable in August, the hottest month of the year in this region. However, the level of energy savings depends not only on the ambient temperature but also on the humidity level.

Chillers usually keep the cooling airflow constant regardless of the load level demanded to the chiller. This is because the energy consumption associated with the operation of the fans that force the ambient air to flow through the condenser is negligible compared to the total power consumed by the chiller (<2%). Therefore, we used the airflow reported by the manufacturer and estimated the water required to moisten that airflow (Equation (10)). We obtained a six-year average water consumption of W=1,759 m^3/year (Table 2). Considering the local water cost (C_w) of USD$ 0.58/m^3 [19], this result represents an extra cost of USD 1,024 per year. Therefore, using of evaporative precooling constitutes a saving of USD 2704 per year in the operative cost of an 82 RT chiller under Monterrey's meteorological conditions. However, these savings reduce to USD 952 when the chiller operates on average at *L*=53% and to zero when *L*=27.5%. Again, these results are due to the fact that the cooling airflow remains constant regardless of the load level, and therefore, the water consumption for evaporative precooling remains constant as well.

The water consumption required for precooling the air could become relevant, especially in places of low water availability or where access to this resource has a high cost. Thus, the monetary cost of water should include social aspects in this analysis.

Consequently, the water mist evaporative precooling becomes favorable when the cost of energy saved is greater than the cost of water used, i.e., where and when the energy saved per unit of water consumed is higher than the ratio between the cost of water (C_w) and the cost of electricity (C_E), it is economically attractive to operate the chiller with evaporative precooling (Equation (11)).

$$\frac{f_s L P_N}{m_w} > \frac{C_W}{C_e} \tag{11}$$

In this last equation, m_w is the water consumption, P_N is the chiller's nominal power, L the average load fraction demanded to the chiller, and f_s is the average fraction of power saved through evaporative precooling.

Equation (11) evidences the role of f_s in describing the savings in energy. We recall that f_s is dependent on the chiller technology and that it is proportional to the annual average wet-bulb depression (*AWBD*) temperature, which is the difference between the dry and wet bulb temperatures.

We suggest using Equation (11) to quantify the potential of the meteorological conditions of a region for using evaporative precooling in industrial cooling equipment.

We are developing additional work to identify regions with meteorological conditions favorable for the use of evaporative precooling (high f_s). We are also exploring the feasibility of additional savings that could be obtained by controlling the cooling airflow according to the chiller's load. Work is also required to evaluate the extra costs involved in evaporative precooling, such as implementation and maintenance. We foresee that, despite the high average atmospheric humidity, evaporative precooling is highly favorable in LATAM, especially in large hotel chains located on the nearshore from México to Perú.

Table 2 Technical characteristics of the sensors used to monitor the operation of the chiller

Item	Item	Units	Chiller's load		
			27%	53%	100%
Energy savings	Cost	USD/kWh		0.10	
	Six-year average saving	%		4.39	
	Annual energy saving	MWh	9.8	18.9	35.7
	Annual cost saving	USD/year	1,024	1,976	3,729
Water consumption	Cost	USD/m^3		0.58	
	Six-year average consumption	m^3/year		1,759	
	Annual cost	USD/year		1,024	
Annual total saving		USD/year	0	952	2,704

4. Conclusions

We developed a criterion to determine if the local meteorological conditions and cost of energy and water favor the implementation of water mist evaporative precooling technology in air-cooled chillers.

Aiming to develop such a criterion, we first developed a steady-state thermodynamic model that estimates the energy consumed by chillers as a function of the ambient temperature and the load demanded to the chiller. This model is generic but requires calibration for each chiller technology. As a case study, this model was calibrated with experimental data obtained by monitoring every ten minutes, for five months, the operation of an 82 RT chiller working in northern Mexico. This chiller was found to operate mostly at 26, 43, and 53% of the nominal power.

The methodology for assessing the energy savings of operating chillers with evaporative precooling over long periods of operation consists of using the meteorological data of the region as input for the calibrated model. At each hour of service, the ambient temperature is used to determine the power consumed by the chiller. Then, the ambient temperature and relative humidity are used again to determine the temperature of this air when it is moistened with water (with 80% cooling efficiency). The new power consumed by the chiller is then determined when it operates under the influence of this moistened air temperature. Energy savings and water consumption for moistening are determined. The process is repeated for each hour of the meteorological data considered.

We presented the conditions under which evaporative precooling is economically feasible (Equation (11)). We found that when the energy saved per unit of water consumed is higher than the ratio between the cost of water and the cost of electricity, it is economically attractive to operate the chiller with evaporative precooling. Furthermore, we found that the percentage of power ratio savings (f_s) is proportional to the annual average wet-bulb depression (*AWBD*). The wet bulb depression is the difference between the dry and wet bulb temperatures. We suggest using the *AWBD* as a metric to quantify the potential of the meteorological conditions of a given region by using evaporative precooling in industrial cooling equipment.

For the case study, we found that considering the past six years of the hourly meteorological conditions of the study region, an 82 RT industrial chiller could have saved 4.4% of the actual energy consumed. It represents a potential saving of 35.7 MWh/year. However, it requires the use of 1,759 m^3/year of water to moisten the air. Considering the current water and energy prices in the study region, the evaporative precooling represents a saving of USD 2,704/year. This monetary saving could be considered small; however, many companies and buildings, at least in the study region, use several of these chillers in their production line or air conditioning systems.

Declaration of competing interest

We declare that we have no significant competing interests including financial or non-financial, professional, or personal interests interfering with the full and objective presentation of the work described in this manuscript.

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Author contributions

J. I. Huertas-Cardozo: Conceived the project, designed the experimental work, designed the data analysis, and wrote the final version of the paper. F. E. Solano-Pérez: Collected, analyzed the data, and wrote the initial version of the paper.

Data available statement

Data associated to this paper is available under request.

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