

Huang, Chung-Neng; Ye, Ying-Han

**Article**

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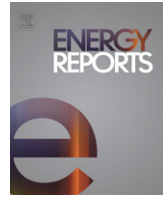
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# Development of a water-mist cooling system: A 12,500 Kcal/h air-cooled chiller



Chung-Neng Huang\*, Ying-Han Ye

Graduate Institute of Mechatronic System Engineering, National University of Tainan, Taiwan

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## ABSTRACT

Global warming and energy exhaustion problems are becoming a severe problems, of which energy conservation and carbon reduction are the most critical. Between 40% and 48% of the total electricity used in a building is consumed by air conditioning systems. The development of a supersonic water-misting cooling system with a fuzzy control system is proposed to optimize existing condenser noise, space, and energy consumption, as well as to address problems with cooling capacity resulting from improper control between compressors and condensers. An experimental platform was established for conducting tests, observing cooling efficiencies, and calculating power saving statuses. Comparing the observed cooling efficiency, a temperature difference of 5.4 °C was determined before and after the application; this is significant regarding efficiency. The method produces no pollution or water accumulation. When compared with fixed frequency air-cooled water chillers, an exceptional energy saving of 25% was observed. The newly developed supersonic mist-cooled chiller is an excellent solution to increasing water and electricity fees.

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## 1. Introduction

The air-cooled water chillers, as combined with the water-mist cooling system, variable speed condenser fans and condensing temperature control, the chiller coefficient of performance (COP) can increase by 12.1%–110.4% or improve further (Yu and Chan, 2006). Water-spray air-cooled water chillers that are currently available on the market mainly depend on water mist to cool the system; this tends to rust base frames and accumulate water around the unit. This study was intended to maintain the performance of the water-spray type air-cooled water chiller while mitigating its shortcomings. Based on the nozzle diameter and the distance from the nozzle to the test surface affecting the critical heat flux (Hsieh and Tien, 2006), three different surface areas/shapes and nozzle angles were used in studying the behavior of spray cooling (Slik et al., 2006). The cooling performances of spray cooling and thin film cooling on the surfaces of heated steel plates were compared (Celata et al., 2009), concluding spray cooling to have the better cooling effect. The effects on heat-plate behaviors were analyzed using various volumes of atomization, spray angles, and nozzle-to-object distances (Mzad and Tebbal, 2009).

Spray-cooling experiments were performed on high-temperature metal surfaces, revealing that the flow rate of liquid significantly increased heat conductance (Sozbir et al., 2003) and that increases in the volume of atomization are significant during heat transfer (Nakayama et al., 1988). Over a distance of 1.2 m, heat transfer increases; for 0.3 m, heat transfer first increases and subsequently decreases (Hamlin et al., 1998). In a spray system, water quality is critical (Abdalla and Narendran, 1991). R-134a was used with water to research the cooling behavior of droplets on a hot plate (Hsieh et al., 2004). Three types of radiator were compared and analyzed: air-cooled, water-cooled, and evaporative cooled (Hosoz1 and Kilicarslan, 2004). The literature has shown that spraying water mist is an effective cooling method and that the small water molecules comprising water mist do not cause pollution; however it is not used in air-cooled water chillers. This study was intended to investigate its use in air-cooled water chillers; a supersonic atomizer was used as the major cooling mechanism.

Because of shortcomings in air-cooled water chillers, such as complex peripheral components, environmental pollution, and easily rusted frameworks, supersonic oscillating vaporization was used as the main cooling method in this study. Atomized mist vaporizes easily in the air because of the small diameter of its particles. When spread over a condenser with the help of a condenser fan, no water accumulation occurs. To increase efficiency, the condenser is thicker than usual, which also enables a longer retaining time for water mist on the condenser. An

\* Corresponding author.

E-mail address: [kosono@gm2.nutn.edu.tw](mailto:kosono@gm2.nutn.edu.tw) (C.-N. Huang).

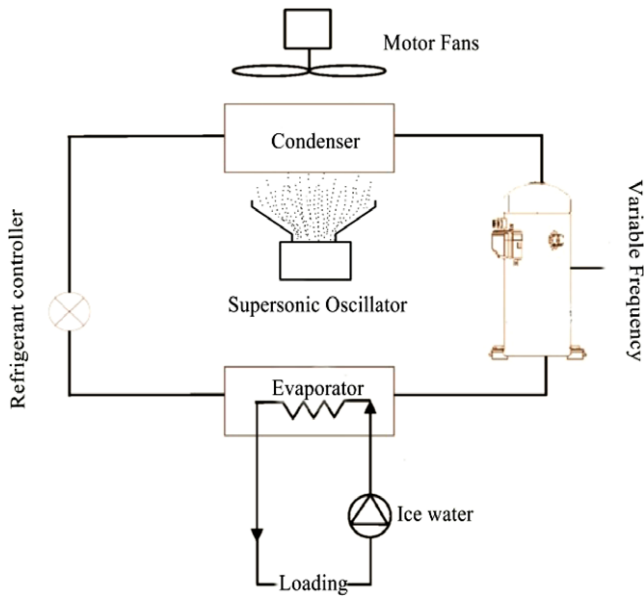


Fig. 1. Flow chart of the air-cooled water chiller components.

additional human–machine interface was provided for real-time observation of the machine’s operation, as well as for remote monitoring.

A variable frequency control was employed to eliminate the frequent starting and stopping of the compressor. It is capable of controlling the temperature, as well as providing a power saving operation and allowing the supersonic atomizer system to adjust the volume of atomization in coordination with the compressor loading status. Because supersonic atomization has mostly been used in the cooling of electronic chips and small components, and the literature has shown that atomization is capable of carrying away a large amount of heat through the vaporization of water mist, this study was intended to design an experiment platform to measure the data and compare the atomization efficiency with that of traditional air-cooled water chillers.

Fig. 1 shows the main components of the air-cooled water chiller cycle. The variable frequency controls the compressor, condenser, and evaporation controller (a capillary tube or an expansion valve). As the medium of refrigerant in the system, the cycle repeats endothermically as well as exothermically.

## 2. Design of the experiment platform and parameter set up

### 2.1. Equipment

The design of the supersonic vaporization chiller is shown in Fig. 2(a) and a photograph of its implementation is shown in Fig. 2(b). Fig. 2(a) also shows the experiment platform of the air-cooled water chiller. Its components are (1) a fan; (2) a condenser; (3) a water-mist spray outlet; (4) a Man–machine interface/circuitry assembly; (5) a Refrigerant controller; (6) supersonic atomizer; and (7) a compressor.

Their main functions are as follows:

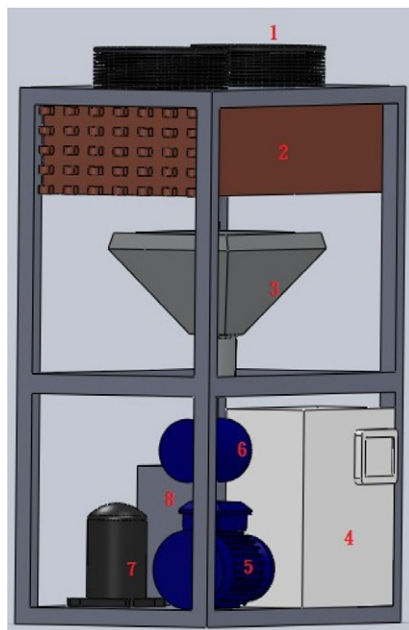
1. Fan: driving water mist to distribute it evenly over the condenser surface.

2. Condenser: exchanging heat with air (heat dissipation), using the air to carry heat away from the refrigerant inside the condenser so that the high-temperature and high-pressure gaseous refrigerant transforms into a hyper-cooled high-pressure liquid refrigerant of normal temperature.

3. Water-mist spray outlet: outputting required mist for cooling and with a function of preventing from mist leaked out of the effective heat-exchangeable area of condenser.

4. Man–machine interface/circuitry assembly: viewing the status of machine operation, including chilled water temperature, condenser temperature, and operation load.

5. Refrigerant controller: regulating the flow rate of refrigerant entering the evaporator, so that the quantity of liquid refrigerant entering the evaporator equals the quantity of vaporized refrigerant in the evaporator. Another function is to maintain the system pressure difference between the high-pressure side and low-pressure side, to provide the low-pressure required in the evaporator and the high-pressure required in the condenser. The unit uses a capillary as the controller.



(a) System design.



(b) System setup.

Fig. 2. Supersonic vaporization chiller system.

**Table 1**  
Supersonic vaporization chiller parameters.

Condenser length	1.2 m
Condenser width	1.1 m
Condenser thickness	0.4 m
Condenser power	15,000 Kacl/h
Volume of atomization	10 L/H
Air-cooled water chiller length	1.5 m
Air-cooled water chiller width	1.4 m
Air-cooled water chiller thickness	2 m

6. Supersonic atomizer: water is atomized into mist through supersonic vibration and spreads in the air. This apparatus includes a set of supersonic transducers and controllers, via tuning the alternating voltage of relatively high frequency, which can effectively adjust the volume of mist. This was the basic cooling setup of the study.

7. Compressor: The system uses a volute-type compressor, mainly for compressing the refrigerant to generate the high-pressure and low-pressure necessary for the refrigeration cycle. The low-pressure and low temperature gaseous refrigerant is compressed to form high-pressure and hyper-heated refrigerant vapor, which is delivered into the condenser to perform heat-exchange.

8. Evaporator: performing heat exchange of the refrigerant and the water chiller system. Evaporators commonly used in water chillers are the dry expansion type and flooded type. Structurally, heat-exchangers can be categorically divided into shell, pipe, and plate types. This unit uses a plate heat exchanger.

## 2.2. Parameter settings

An air-cooled water chiller with the characteristic of cooling capacity at 14.52 kW, COP at 3.41, and rated power of compressor at 2.984 kW, was adopted in this study and under the operational conditions of entering air temperature under 36.5 °C and entering/leaving chilled water temperatures at 8.09/5.6 °C. The experimental approach achieved a volume of atomization in relation to the heat dissipation, which corresponded to the heat dissipation characteristics of the supersonic vaporization chiller. The supersonic vaporization cooling system parameters are displayed in Table 1.

## 3. Methods

### 3.1. The principle of supersonic vibration

A rapid water flow occurs when a vibrator produces a supersonic wave in water. The liquid at the surface exerts a supersonic beam focusing effect, and forms a supersonic fountain. Because of the rapid water flow, the pressure of the liquid temporarily decreases, forming small bubbles. Internal pressure is considerably low, pulling liquid fission and forming hollowing. When the water pressure is restored, the bubbles move inward and fission collapses. A considerably small blast occurs, but the effect is a considerably large shockwave. The force from the moment of impact causes the liquid to diverge into particles and form a mist.

The latent heat required to evaporate a kilogram of water (2430.5 kJ at 30 °C) is equal to the heat required to melt 7 kg of ice. The high pressure sprays droplet sizes of 15–40 μm; the supersonic produces a micro mist diameter in the range of 3–5 μm. The larger the surface area in contact with air, the greater the cooling effect.

In atomization, cooling the droplet diameter is defined as follows:

$$R = k \left( \frac{8\pi\sigma}{\rho f^2} \right)^{\frac{1}{3}} \quad (1)$$

where  $R$  is the droplet diameter (m),  $k$  is 0.34,  $\sigma$  is the surface tension of the droplet (N/m),  $\rho$  is the droplet density (kg/m<sup>3</sup>), and  $f$  is the frequency of vibration. The droplet diameter and volume of atomization are affected mainly by the supersonic frequency. The equation shows that using the supersonic atomizer as a small mist supply source has one benefit: the diameter of water mist is related to the frequency of vibration; therefore, changing the vibration can control the volume of atomization without altering the spray quality.

Evaporative heat dissipation is defined as follows:

$$LE_0 = K \times D(T_a - T_{in}) + C_p \times \rho \times Q(T_a - T_{in}) \quad (2)$$

where  $L$  is the evaporation rate of water (kg/h),  $E_0$  is the latent heat of water evaporation (kJ/kg),  $K$  is the wall transfer coefficient (w/m<sup>2</sup> °C),  $D$  is the diffusion coefficient of water vapor in air ( $2.3 \times 10^{-5}$  m<sup>2</sup>/s),  $C_p$  is the air specific heat (1006 J/kg °C),  $\rho$  is the air density (kg/m<sup>3</sup>),  $Q$  is the ventilation rate of air (m<sup>3</sup>/s),  $T_a$  is the temperature outside the tubes (°C), and  $T_{in}$  is the exhaust temperature (°C).

### 3.2. Weber number definition and calculation

In atomization cooling, a Weber number ( $We$ ) is defined as follows:

$$We = \rho U_m^2 d_{32} / \sigma \quad (3)$$

where  $\rho$  is the droplet density,  $\sigma$  is the surface tension of a droplet,  $U_m$  is the collision velocity of droplets colliding with the heating plate, and  $d_{32}$  is the Sauter mean diameter (SMD). The relevant calculation is as follows:

(1)  $U_m$  is the collision velocity at which the droplets collide with the heating plate. From Ghodbane and Holman (1991) and Qiang and Susan (2003), we obtain

$$U_m = \left( u_0 + \frac{2\Delta P}{\rho} - \frac{12\sigma}{\rho d_{0.5}} - 2gH \right)^2 \quad (4)$$

where  $U_0$  is the droplet velocity from the nozzle to the test chamber,  $\Delta P$  is the pressure difference from the nozzle to the heating plate,  $d_{0.5}$  is the diameter of droplets that spray from the nozzle, and  $H$  is the distance from the nozzle to the heating plate.

(2)  $d_{0.5}$  is the diameter of a droplet when it exits the nozzle. Differing from the  $We$ ,  $d_{0.5}$  is the SMD provided by the manufacturer. From Ghodbane and Holman (1991), we derive

$$d_{0.5} = \frac{9.5D}{\Delta P^{0.37} \sin \beta / 2} \quad (5)$$

where  $D$  is the nozzle diameter,  $\Delta P$  is the differential pressure of the nozzle profile, and  $\beta$  is the angle of the spray cone. Calculating  $d_{0.5}$  determines the velocity at which droplets collide with the plate.

### 3.3. The program protection

To prevent the program from malfunctioning, a protection mechanism is required. The mechanism presented in Fig. 3 can identify any problems at the start of the program. If this occurs, the program does not load the machine's operating status and the fan's current protection compressor, supersonic vibrations, ice water pump, and fan motor shut down. If the program encounters an AI - 2 <= low pressure setting, the supersonic atomizer turns off, as does the fan motor after a time delay. In this study, ambient air was drawn or blown through a porous wetted surface where the air stream is cooled by water mist, and its dry bulb temperature drops to approach its wet bulb temperature. Where, DO-1 to DO-4 represents the control switches of compressor, ice water pump, supersonic vaporization, and fan motor, respectively.

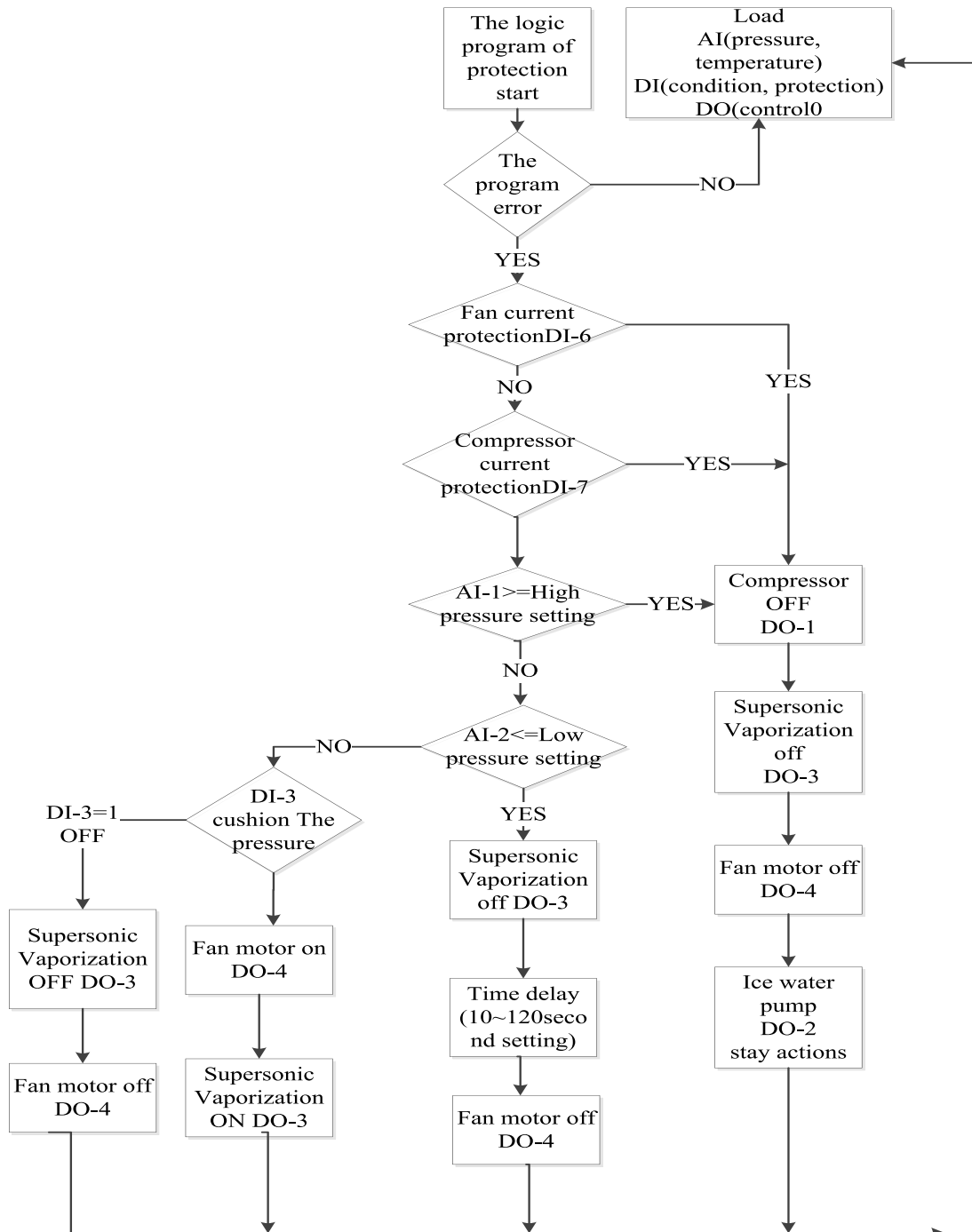


Fig. 3. Protection mechanism flow chart.

### 3.4. Dual-effect fuzzy control system

As an alternating voltage is applied to the supersonic atomizer that will generate alternate compression into water, generating mist. It is an object of this study to provide an electronic oscillator which is suitable as a driving means to couple the supersonic atomizer having a relatively high resonant quality factor. Besides, this oscillator also can cause the best mechanical activity of the atomizer over a range of resonant frequencies. For this object, a dual-effect fuzzy controller having the described capability and including a frequency-tunable circuit whereby oscillations are sustained at a selected mechanical harmonic frequency of the atomizer which is dictated by the frequency-tunable circuit.

#### a. System design

Fig. 4 is a diagram of the closed-loop system. Its main controls are a supersonic oscillation driving circuit (SOD), a pulse-width modulation (PWM) control circuit, and a dual-effect fuzzy control (DEFC). The main functions of the controls are as follows:

1. SOD: producing the frequency of the supersonic atomizer.
2. PWM: adjusting the volume of water misting by controlling the frequency of the supersonic vibrator.
3. DEFC: determining the size of the PWM control signal.

The dual-effect fuzzy control system is used to cover the entire system. The atomization volume output control used the PWM to adjust the supersonic frequency in response to actual demand,



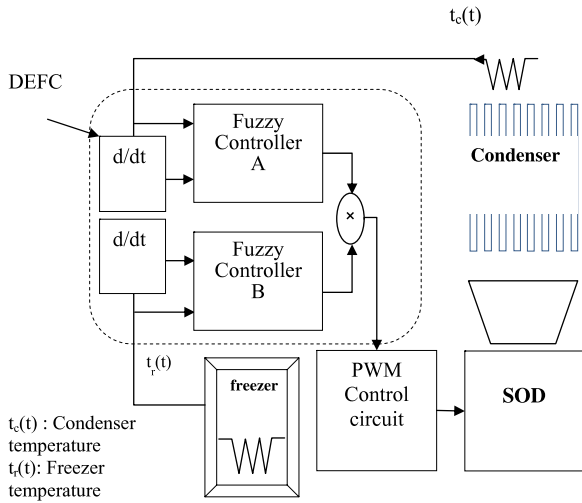


Fig. 4. Closed loop system.

automatically adjusting the volume of atomization so that it can save power and improve efficiency.

3.5. COP calculation

In this study, the chiller COP was calculated from the measured variables but directly measured. First, the chiller load  $E_L$  can be obtained by (6), then the chiller COP, using the chiller load divided by the measured variables, including the chiller power and supersonic atomizer power. Besides, chiller power includes the compressor power and condenser fan power, can be found and shown in (7).

$$E_L = m_W \cdot C_p(T_{chwr} - T_{chws}) \tag{6}$$

$$COP = \frac{E_L}{(E_{ch} + E_{sa})} = m_W \cdot C_{WP}(T_{chwr} - T_{chws}) / (E_{cc} + E_{cf} + E_{sa}) \tag{7}$$

where,  $m_w$  is chilled water flow rate ( $m^3/s$ ),  $C_{WP}$  is the specific heat capacity of water ( $4186 J/kg \text{ } ^\circ C$ ),  $T_{chws}$  and  $T_{chwr}$  are temperatures of supply and return chilled water ( $^\circ C$ ),  $E_{ch}$  is chiller power (kW),  $E_{sa}$  is supersonic atomizer power (kW),  $E_{cc}$  is compressor power (kW), and  $E_{cf}$  is condenser fan power (kW).

4. Results and discussion

4.1. Experimental conditions

Based on head pressure control, the air-cooled chiller is operated and studied. In order to examine the performance of the air-cooled chiller with or without water-mist cooling system, experiments under a representative range of ambient temperature ( $T_{db}$ :  $22.8\text{--}36.5 \text{ } ^\circ C$ ), relative humidity (RH:  $33.4\%\text{--}91.1\%$ ) and part load ratios (PLRs:  $0.1\text{--}1.2$ ) in the local climate of Tainan, Taiwan were conducted over a period of 3 months from July to September 2014.

4.2. Results

The temperature distribution was observed using an infrared photo-detector after the air-cooled water chiller was run for 2 h. The condenser temperature was approximately  $45.6 \text{ } ^\circ C$  without supersonic atomization, as displayed in Fig. 5(a). The condenser temperature was approximately  $40.2 \text{ } ^\circ C$  with supersonic atomization, as displayed in Fig. 5(b). The difference was approximately  $5.4 \text{ } ^\circ C$ . The experiment indicated that the studied fixed-frequency air-cooled water chiller consumes  $4.249 \text{ kW}$  on average, whereas the chiller, equipped with a variable-frequency mist-cooled system, consumes  $3.716 \text{ kW}$  on average. In addition, through (6) and (7) and using the experimental variables which were measured and logged in every 20-min intervals over the experimental period, the COP values of with/without water-mist cooling system were found. Here, as the studied chiller with mist-cooled system a COP value of  $4.34$  was obtained. Concluding above results knows that the variable-frequency air-cooled water chiller was 25% more energy efficient.

5. Conclusion

The green industry is becoming increasingly mainstream and people are searching for methods that save power, are energy efficient, and do not pollute the environment.

This study established an experimental platform for conducting tests, observing cooling efficiencies, and calculating power saving statuses. Regarding the application’s cooling efficiency, a temperature difference of  $5.4 \text{ } ^\circ C$  was observed before and after the application, which is substantial regarding efficiency. The method

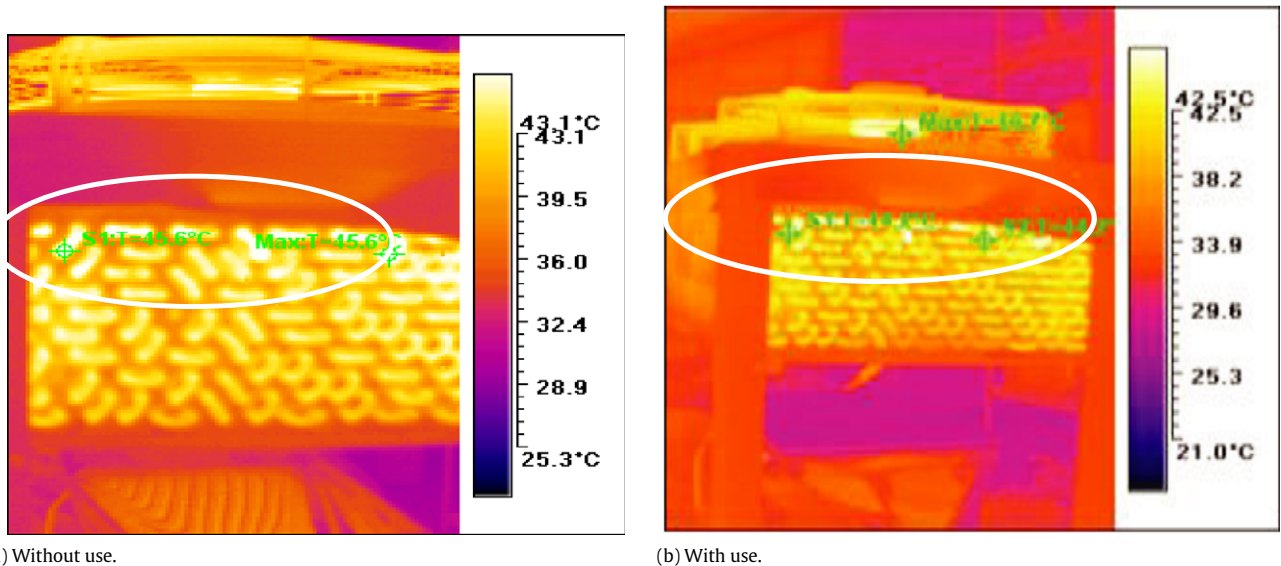


Fig. 5. Temperature distribution.

caused no environmental pollution or water accumulation in its surroundings. When compared with fixed frequency air-cooled water chillers, a 25% energy saving was observed, which is exceptional regarding power saving. The newly developed supersonic mist-cooled water chiller is an effective solution to the problem of rising water and electricity fees.

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