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Spray Angle on the Performance of Split-Type AC Condenser Installed on Concrete Rooftop in Tropical Climate

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ABSTRACT

This study investigated the influence of different water spray angles (0°, 15°, and 30°) on the thermal and energy performance of a split-type air-conditioning (AC) condenser installed on a concrete rooftop in a tropical climate. An experimental setup was designed to replicate actual concrete rooftop conditions, focusing on the condenser inlet temperature, compressor power consumption, and system coefficient of performance (COP). A 6-minute ON and 6-minute OFF intermittent spray cycle was employed to optimise water usage and minimise excessive humidity. Experimental measurements were conducted on a 9,000 Btu/h split-type unit equipped with a nozzle system connected to a 200 L water tank. The results demonstrated that the 0° spray angle achieved the most significant improvement, reducing the condenser inlet air temperature by up to 22.5% and decreasing the compressor power consumption by 7.7% compared with the baseline. This configuration also enhanced the COP from 2.77 to 2.93, representing a 5.8% improvement in performance. Wider spray angles (15° and 30°) yielded moderate improvements but were less effective because of droplet dispersion and reduced surface wetting. Thermal imaging confirmed that the 0° angle produced the most uniform cooling distribution on the condenser surface. These findings underscore that spray cooling with an optimised nozzle orientation is a cost-effective and sustainable retrofit solution for rooftop AC condensers in tropical environments, offering improved energy efficiency and reduced environmental impact.

Keywords: *Air-cooled condenser, COP, intermittent cooling, nozzle angle, spray cooling, tropical climate*

I. Introduction

Air conditioning (AC) systems are significant contributors to electricity consumption in tropical regions, where elevated ambient temperatures and intense solar radiation markedly increase cooling demands [1], [2]. Rooftop-mounted condensers, especially those situated on concrete surfaces, are particularly susceptible to urban heat island effects and direct solar radiation, which diminish their heat rejection efficiency and elevate the compressor workload [3]–[5]. Consequently, this leads to increased operating costs, reduced system efficiency, and increased greenhouse gas emissions [6]. The heat rejected from split A/C units can also degrade indoor–outdoor comfort in mixed-mode buildings, reinforcing the need to limit condenser discharge temperatures and mitigate plume heating [7].

Numerous strategies have been devised to enhance the efficiency of these rooftop condensers. Traditional techniques include the application of reflective coatings, insulation, and shading devices [8], [9]. Passive strategies such as natural ventilation and radiative-evaporative coupling have also been explored in recent literature as complementary methods

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[10]-[12]. Recently, evaporative spray cooling has gained prominence as a significant and cost-effective retrofitting method. This technique involves the atomization of water into fine droplets, which cools the ambient air through evaporation, thereby augmenting the heat rejection capabilities of the condenser and enhancing the overall system efficiency [7],[13],[14]. Empirical research has demonstrated that mist cooling can effectively reduce the condensing temperature, improve the coefficient of performance (COP), and decrease the energy consumption of split-type air conditioners operating in hot-humid climates [15]. Numerical simulations by Navarro *et al.* [16] demonstrated the effectiveness of ultrasonic spray systems in HVAC designs. Furthermore, advanced hybrid strategies—such as radiative-coupled evaporative cooling—have been proposed to address the limitations of conventional evaporative systems, offering improved thermal regulation in passive applications [11].

Despite these advancements, significant gaps persist within the literature. Most previous studies have concentrated on the general advantages of spray cooling, neglecting to examine the combined effects of nozzle orientation and cyclic operation. While continuous misting proves effective, it results in excessive water usage and uncontrolled humidity levels [12], [14]. Conversely, intermittent spraying has been suggested as a more sustainable alternative; however, experimental validation remains limited [7],[15]. Furthermore, research specifically pertaining to tropical regions, such as Indonesia, is scarce, despite the country's substantial reliance on rooftop AC systems [6].

This study aims to address existing research gaps by experimentally evaluating the combined effects of nozzle spray angles (0°, 15°, 30°) and intermittent operation cycles (6 minutes ON / 6 minutes OFF) on the performance of a split-type air conditioning condenser installed on a concrete rooftop in Palu, Indonesia. The primary objective is to identify an optimal configuration that enhances heat rejection, reduces compressor energy consumption, conserves water, and contributes to sustainable cooling strategies in tropical climates.

II. Material and Methods

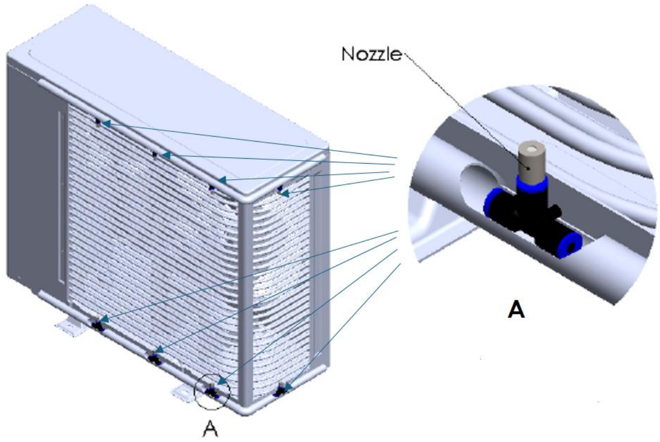
A. Experimental Setup

This study employed a quantitative experimental approach to investigate the impact of the water mist angle and spray cycle on the condenser performance. The experiment was conducted on the roof of the Integrated Laboratory Building at Tadulako University, Indonesia, to replicate a typical tropical-urban environment.

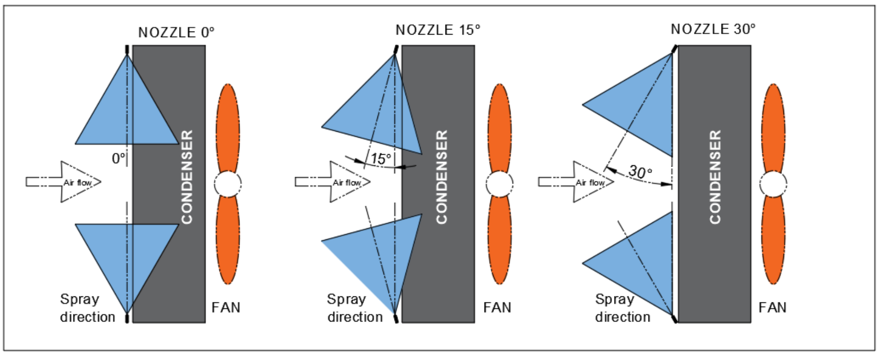
The experimental area was characterized by dimensions of 4.20 m in length, 1.80 m in width, and 2.80 m in height, with plastered brick walls and a concrete roof devoid of a ceiling. A split-type air-conditioning system, utilizing R-22 refrigerant and possessing a capacity of 9,000 Btu/h, was installed on the concrete roof. The condenser was oriented westward to optimize sunlight exposure. Throughout the experiment, temperatures frequently surpassed 30°C, with an average humidity level of 52% and wind speeds averaging approximately 5 kph. These environmental conditions highlight the substantial cooling requirements in tropical climates, which are essential for the efficiency of condensers in hot and humid regions [17]–[20].

As shown in Figure 1, the experimental setup included a misting system comprising a 200 L water tank, 12 V DC diaphragm pump, and eight brass mist nozzles with an orifice diameter of 0.3 mm. The application of auxiliary misting systems to enhance condensers has been examined in several studies [21], [22].

The nozzles were positioned 1 cm from the condenser fins to maximize droplet impingement, following the recommendations from earlier experimental and computational fluid dynamics (CFD) analyses [13],[14], [24]. Three angular orientations (0°, 15°, and 30°) were tested, and an intermittent spray cycle of 6 min ON / 6 min OFF was applied to optimize water usage and reduce humidity accumulation around the condenser (Figure 1(b)).



a) Horizontal distance (1 cm)



b) Angular nozzle variations (0°, 15°, 30°).

Fig. 1. Schematic diagram of nozzle installation on the condenser

2. Instrumentation and Data Acquisition

The system performance parameters were monitored using calibrated instruments, as recommended in previous condenser spray cooling experiments [18], [21]. Pressure gauges were installed at four points—suction, discharge, liquid, and expansion lines—to monitor the refrigerant pressure conditions. Digital thermocouples connected to to temperature data loggers (Elitech RC-4HC and Mastech MS6514) recorded the temperatures at multiple locations, including the condenser inlet/outlet, evaporator inlet/outlet, and ambient air, consistent with methods reported in previous studies [22], [23].

Figure 2 provides a comprehensive overview of the experimental setup, detailing the placement of the instrumentation, including the locations of the thermocouples, pressure sensor points, flow path, and orientation of the mist nozzle. The surface temperature of the condenser was validated using a surface infrared thermometer, and the electricity consumption of the compressor was recorded using a digital power meter [24]. To visualize the distribution of surface cooling, a thermal imaging camera (HTI–HT02, 0.3 MP infrared resolution, 2.4-inch full-color display) was employed, a method widely applied for diagnosing condenser performance under evaporative cooling Econditions [13], [18], [25].

The water spray rate was continuously monitored using a flowmeter in accordance with the instrumentation practices established in recent mist cooling studies [18], [19].

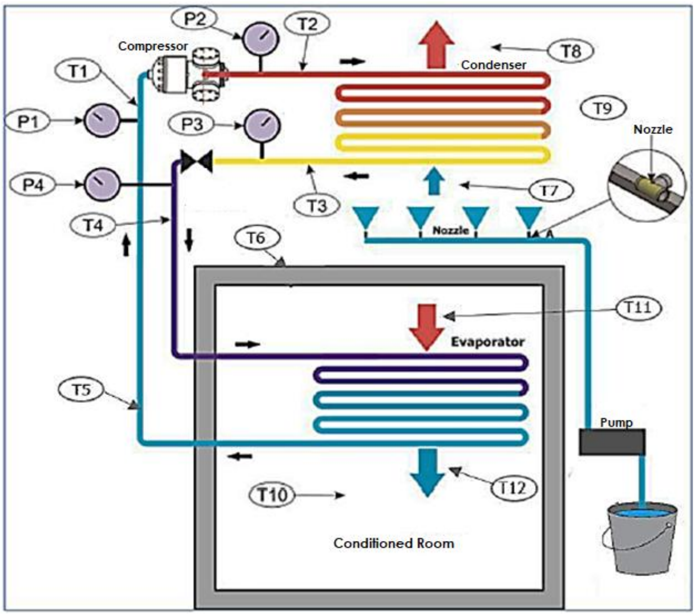


Fig. 2. Experimental setup and equipment layout on rooftop test site.

3. Data Processing

The thermal performance of the system was assessed using standard thermodynamic relationships [14], [25]. Specifically, the cooling capacity (Qe), condenser heat rejection (Qc), and compressor work (Wc) were calculated based on the refrigerant enthalpy differences derived from property tables. This methodology is consistent with that of previous studies that examined mist-assisted air-conditioning systems [15], [22]. The coefficient of performance (COP) was calculated as the ratio of Qe to Wc.

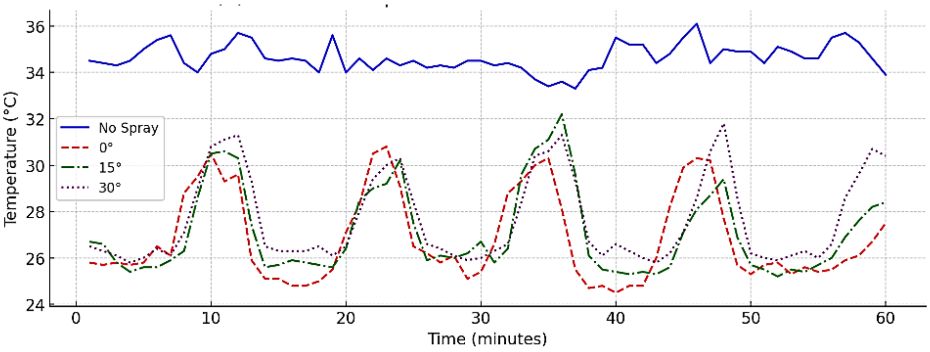
4. Statistical Analysis

Each experimental condition was replicated three times ($n = 3$), and the results were expressed as the mean ± standard deviation (SD). Error bars are included in the graphical representations to depict data variability, which is a standard practice in experimental heat transfer research [23], [28]. Statistical significance was assessed using one-way analysis of variance (ANOVA) at a 95% confidence level ($p < 0.05$). Similar statistical methodologies have been documented in recent experimental evaluations of air-conditioning system performance [7], [26]. Data processing and statistical analyses were performed using OriginPro 2022 and SPSS Statistics v25, consistent with the tools employed in comparable studies [22], [25].

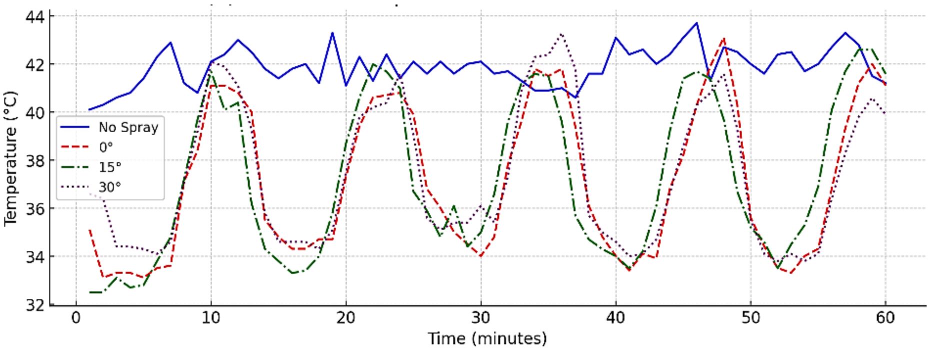
III. Results and Discussions

1. Effect of Spray Angle on Condenser Air Temperature

Figure 3 illustrates the temporal variation in the air temperatures at the condenser inlet and outlet during the intermittent misting cycles. A distinct cyclic pattern was evident, characterized by rapid temperature decreases during the ON phase and gradual recovery during the OFF phase. Notably, a 0° spray angle resulted in the most significant temperature reduction, decreasing the condenser inlet air temperature by up to 7 °C (22.5%) compared with the baseline condition.



a) Inlet air temperature at Condenser Vs Time



b) Outlet air temperature at Condenser Vs Time

Fig. 3. (a) Inlet air temperature at the condenser over time; (b) outlet air temperature over time

Yang *et al.* [3] and Larpruenrudee *et al.* [13] have observed comparable outcomes, illustrating that mist-assisted cooling is effective in lowering condensing temperatures in tropical environments. However, wider spray angles of 15° and 30° proved to be less efficient, which is consistent with CFD studies that suggest diminished impingement and surface wetting with increased dispersion [17], [21].

2. Thermal Performance

The thermal performance results are presented in Table 1. In the 0° configuration, the condenser heat rejection was 245.40 ± 1.31 kJ/kg, whereas the evaporator heat absorption was 182.97 ± 1.21 kJ/kg, indicating the most favorable overall performance among the tested conditions. This improvement can be attributed to enhanced droplet impingement and surface wetting, which is consistent with the findings of previous studies [18], [20]. Similar enhancements in cooling capacity with direct spray application were also reported by Roy and Dubey [27] and Wiratmaja *et al.* [6].

Table 1. Thermal performance with standard deviation (Mean ± SD)

Parameter	No Spray	0°	15°	30°
Inlet air temp (°C)	34.66 ± 0.21	26.85 ± 0.22	27.09 ± 0.18	27.65 ± 0.24
Outlet air temp (°C)	41.88 ± 0.25	37.10 ± 0.23	37.16 ± 0.20	37.32 ± 0.26
ΔT Air across condenser (°C)	7.22 ± 0.12	10.25 ± 0.14	10.07 ± 0.11	9.67 ± 0.13
Qcond (kJ/kg)	241.90 ± 1.14	245.40 ± 1.31	245.09 ± 1.27	244.89 ± 1.19

These results demonstrate a key thermodynamic principle: a cooler condenser environment facilitates refrigerant phase transition, thereby improving the latent heat absorption in the evaporator. Similar behavior has been reported in studies on evaporative cooling-assisted condensers, which emphasize the direct link between condenser air temperature reduction and system efficiency [13], [28], [29]

As illustrated in Figure 4, cyclic misting influenced the refrigerant pressure at the expansion valve. Both the inlet and outlet pressures exhibited fluctuations corresponding to the ON/OFF spray cycle. Among the tested configurations, the 0° orientation resulted in more stable pressure behavior, whereas wider spray angles (15° and 30°) produced greater variability. Stable refrigerant pressures indicate smooth expansion and evaporation processes, which are essential for efficient thermodynamic performance.

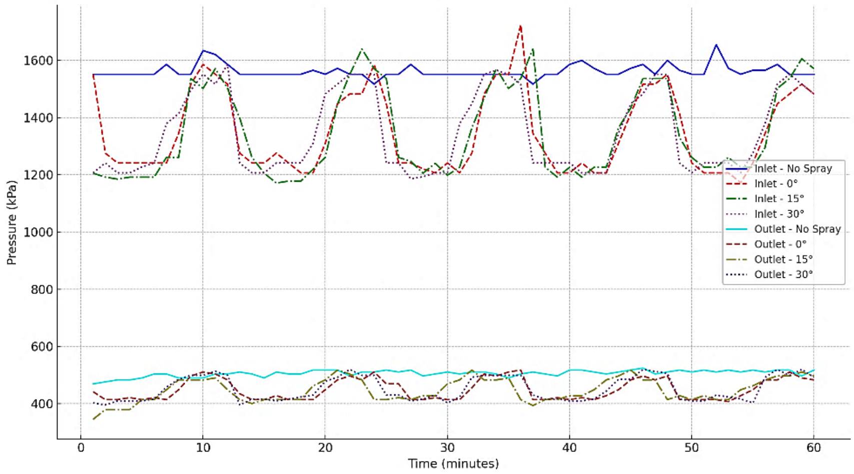


Fig. 4. Comparison of inlet and outlet pressure at the expansion valve over time

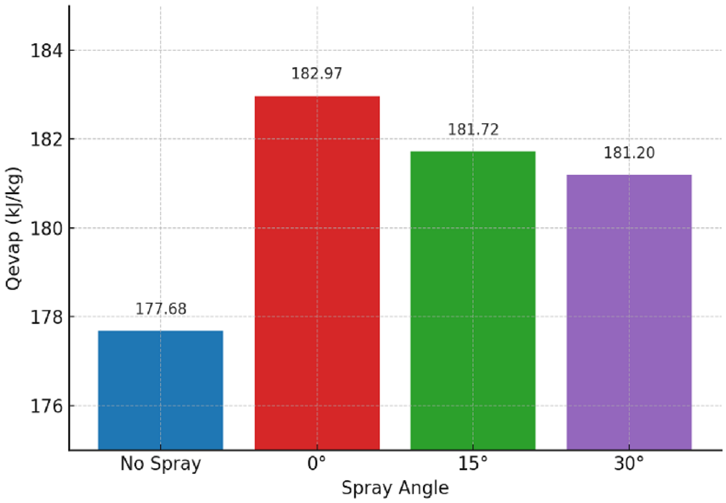


Fig. 5. Average heat absorbed by the evaporator (Qe)

Additional evidence is presented in Figure 5, which illustrates the average heat absorbed by the evaporator (Qe). The 0° spray configuration attained the highest value of 182.97 kJ/kg, compared to 177.68 kJ/kg for the baseline, with marginally lower values observed for the 15° and 30° orientations. This finding corroborates the assertion that enhancing condenser cooling directly augments the downstream latent heat absorption, thereby amplifying the overall cooling efficacy of the cycle.

The direct impact of these enhancements on the room cooling performance is illustrated in Figure 6. In the absence of spray, the cooling curve revealed that the room required nearly 60 min to reach approximately 26 °C. In contrast, with the 0° spray configuration, the cooling rate was significantly accelerated. This finding indicates that the thermodynamic benefits observed at the condenser and evaporator levels effectively translated into a more rapid reduction in the indoor temperature, thereby validating the overall efficacy of the spray cooling retrofit.

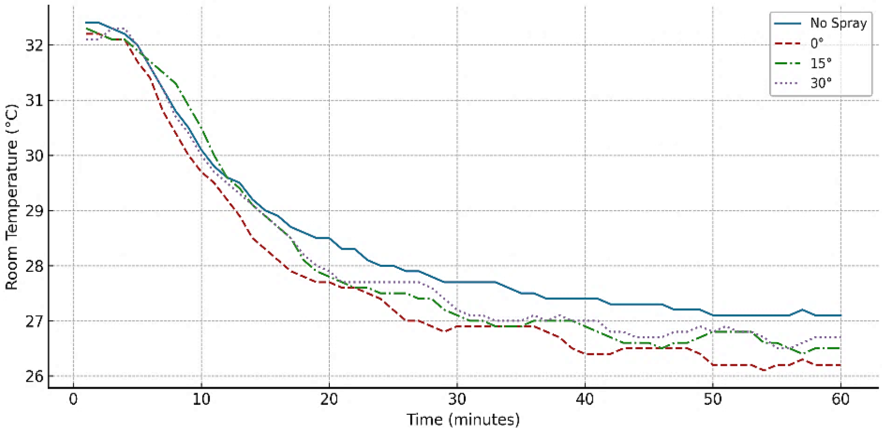


Fig. 6. Room temperature variation over time under different spray angles (0°, 15°, 30°) and no-spray conditions.

3. Compressor Power Consumption

The compressor works under various spray configurations, as shown in Figure 7. The baseline condition, characterized by the absence of spray, required the highest work, averaging 64.23 kJ/kg. Conversely, the 0° spray orientation reduced the compressor work to 62.43 kJ/kg, whereas the 15° and 30° orientations resulted in intermediate values of 63.37 kJ/kg and 63.69 kJ/kg, respectively.

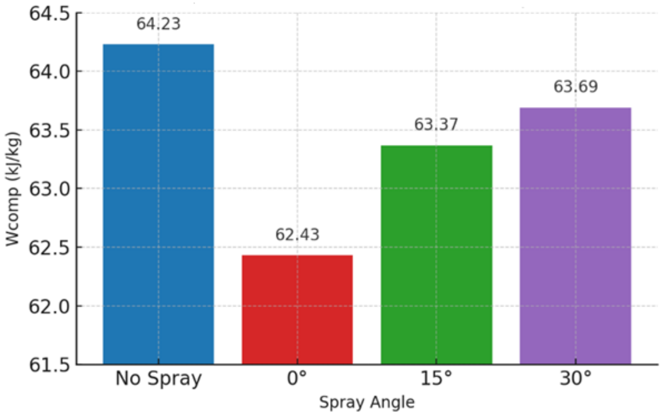


Fig. 7. Average compressor work

The observed reduction in compressor work at the 0° configuration demonstrates the thermodynamic advantage of lowering the condensing temperature, which subsequently decreases the pressure ratio across the compressor and reduces the mechanical energy requirement. Similar reductions in compressor power have been documented in evaporative cooling-assisted air-conditioning systems, corroborating that enhanced condenser performance alleviates the workload on the compressor [19], [23], [24].

4. Coefficient of Performance and Environmental Implications

Table 2 provides a summary of the coefficient of performance (COP) results for all tested configurations. Under the baseline condition, which involved no spray, the average COP was 2.77. The configuration with a 0° spray orientation achieved the highest COP of 2.93. Meanwhile, the 15° and 30° spray orientations resulted in moderate improvements, with COP values of 2.88 and 2.86, respectively. These results underscore that the direct 0° spray orientation significantly enhanced efficiency. The improvements in the cycle efficiency can be attributed to the increased evaporator heat absorption and decreased compressor work, which were facilitated by lower condenser air temperatures and stabilized refrigerant pressures. These findings align with similar COP enhancements reported in experimental studies [13], [15] and are supported by thermodynamic analyses of evaporative retrofits [5], [29].

Recent advancements in deep reinforcement learning have demonstrated its ability to dynamically adjust HVAC loads, thereby facilitating the optimization of mist activation schedules in response to fluctuating rooftop microclimates [30]. Furthermore, contemporary systematic reviews indicate that AI-driven supervisory control can enhance both energy efficiency and indoor environmental quality in buildings, thereby underscoring the potential of intelligent spray-assisted retrofits [10].

Table 2. Average energy performance with standard deviation

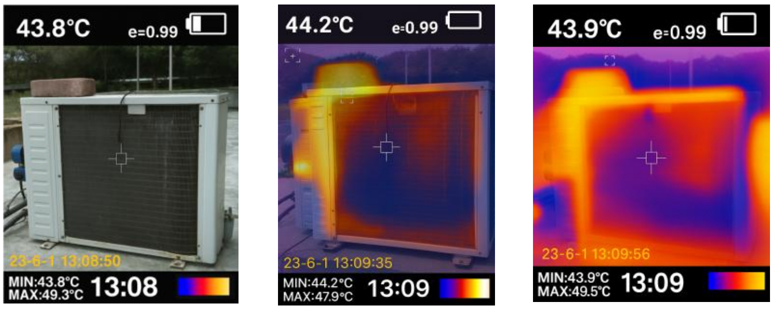
Spray angle	Power consumption (kW)	COP	EER	CO_2 emission (kg/h)	CO_2 reduction (kg/h)
No Spray	0.843 ± 0.007	2.77 ± 0.02	9.46 ± 0.03	0.692	0.000
0°	0.778 ± 0.005	2.93 ± 0.03	10.01 ± 0.04	0.638	0.054 ± 0.002
15°	0.780 ± 0.006	2.87 ± 0.02	9.80 ± 0.03	0.640	0.052 ± 0.001
30°	0.791 ± 0.004	2.84 ± 0.03	9.69 ± 0.02	0.649	0.043 ± 0.001

From a thermodynamic standpoint, the coefficient of performance (COP) is considerably sensitive to the condensing temperature. The recorded 5.8% enhancement at the 0° orientation indicates that even slight reductions in the condenser air temperature can lead to substantial improvements in system efficiency. This finding is consistent with the research of Yang et al. [3] and R. Charoensin-O-larn et al. [4], who highlighted the importance of an optimized spray orientation in tropical operating conditions. Similar experimental results were reported by Ahmed et al. [31], who demonstrated that the adiabatic precooling of air-cooled condensers in hot-humid environments can significantly enhance efficiency while decreasing the compressor workload. In addition to enhancing system performance, improvements in the coefficient of performance (COP) also result in notable environmental advantages. As detailed in Table 2, the 0° spray configuration led to a reduction in CO_2 emissions of 0.054 ± 0.002 kg/h when compared to the baseline. This decrease was attributed to the synergistic effects of the increased condenser efficiency, reduced compressor workload, and reduced electricity consumption. These outcomes align with the findings of previous studies on evaporative retrofits [23], [24].

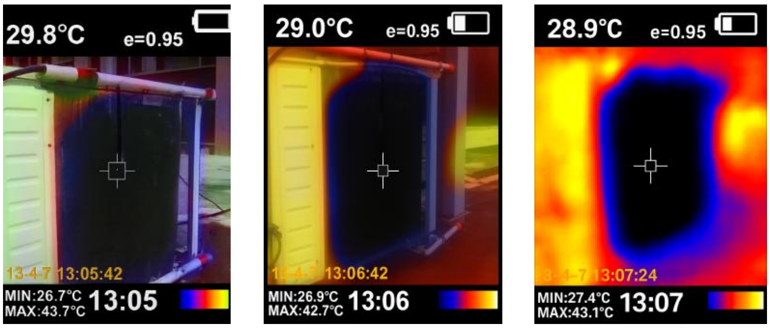
Local studies in Indonesia [2], [6] further emphasize that optimizing water use is critical for sustainable implementation, suggesting that intermittent misting offers a practical balance between energy savings and resource conservation. Moreover, recent studies have highlighted that combining spray-assisted cooling with hybrid systems [32] and intelligent control strategies [27], [30] could enhance sustainability by optimizing spray timing, minimizing water use, and maximizing efficiency.

5. Surface Temperature Distribution

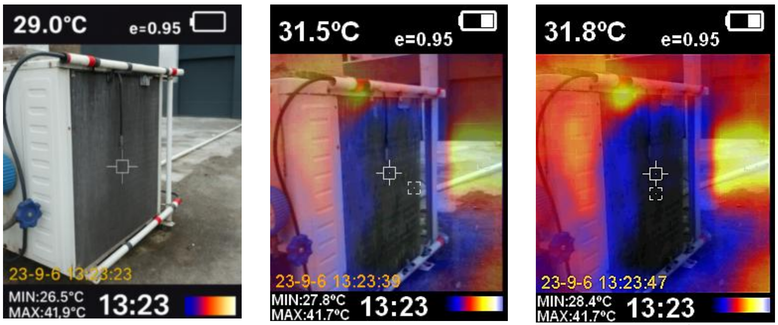
The effectiveness of the spray orientation on condenser surface cooling was further validated using infrared thermal imaging, as shown in Figure 8.



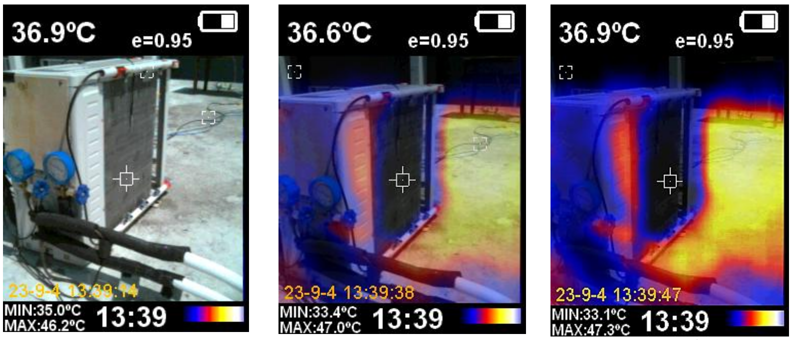
a) Surface temperature distribution of the condenser without mist spray



b) Surface temperature distribution of the condenser with 0^{O} mist spray



c) Surface temperature distribution of the condenser with 15^{O} mist spray



d) Surface temperature distribution of the condenser with 30^{O} mist spray

Fig. 8. Surface temperature distribution of the condenser

Without the spray (Figure 8a), hotspots exceeding 43.8 °C were observed across the condenser surface, indicating inefficient heat rejection. In contrast, the 0° orientation (Figure 8b) produced a uniform cooling pattern, with surface temperatures ranging from 26.7–29.0 °C. At the 15° spray angle (Figure 8c), partial uniformity was achieved, with surface temperatures between 29.0–31.8 °C, whereas the 30° configuration (Figure 8d) showed less effective coverage, leaving dry patches with localized temperatures reaching 36.9 °C. These patterns confirm that direct impingement improves heat dissipation, whereas wider spray angles result in droplet dispersion and incomplete surface wetting.

Similar cooling distributions have been reported in prior experimental studies employing infrared thermography [18],[25], while CFD simulations have predicted the same behavior, highlighting the difficulty of achieving uniform coverage at wider orientations [14], [20]. The present findings reinforce the importance of nozzle orientation in ensuring effective evaporative heat transfer across the condenser surface. Additional simulation-based studies have shown the complexity of achieving uniform surface wetting at wider angles, especially under wind-induced evaporative conditions [33].

IV. Conclusions

The results showed that the 0° spray direction was the most effective. This lowered the air temperature at the condenser inlet by up to 7 °C. It also increased the heat absorption in the evaporator, reduced the compressor work by 2.8%, and improved the coefficient of performance (COP) by 5.8% compared with the baseline. Wider spray angles (15° and 30°) offered moderate improvements but were less effective because of droplet dispersion and incomplete surface wetting. Thermal imaging confirmed that the 0° spray orientation achieved the most uniform condenser cooling, whereas wider spray angles resulted in hotspots and uneven coverage. The intermittent spray cycle effectively balanced the cooling performance and water conservation, validating its suitability for tropical applications. Environmental assessment indicated that the optimized configuration reduced CO_2 emissions by 0.054 kg/h, demonstrating the dual benefits of enhanced energy efficiency and reduced environmental impact of the proposed method.

In summary, this study highlights the importance of nozzle orientation as a critical factor in designing evaporative cooling retrofits. The integration of direct spray (0°) with intermittent operation offers a cost-effective and sustainable approach for improving the efficiency of rooftop air-conditioning systems in hot-humid climates. Future research should focus on long-term field evaluations, adaptive control strategies, and integration with hybrid cooling systems to optimize water usage and energy performance.

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