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Effectiveness Measurement of a Cross-Flow Air Cooler Heat Exchanger in Steady State Condition

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Abstract - **Heat exchangers play a critical role in a wide range of industrial applications, including boilers, condensers, coolers, and cooling towers. This study focuses on evaluating the thermal performance, specifically the effectiveness and efficiency, of an air cooler heat exchanger operating under steady-state conditions with a constant hot water temperature. The aim is to examine how variations in water flow rate and fan air velocity influence the system's heat transfer behavior. An experimental setup was implemented, where the heat exchanger was tested at three water flow rates (0 L/min, 2.5 L/min, and 5 L/min) and three air velocities (1.8 m/s, 2.7 m/s, and 3.6 m/s). The results show that the highest effectiveness recorded was 60.87%, while the maximum thermal efficiency reached 96%. These values were obtained when the system operated with a water flow rate of 5 L/min and an air velocity of 1.8 m/s. This operating condition is identified as optimal due to the increased cooling capacity from the higher water flow and the improved heat transfer resulting from extended contact time between the airflow and the heat exchanger surface at lower air velocities.**

Keywords: air velocity, effectiveness, efficiency, heat exchanger, water flow rate.

I. INTRODUCTION

Heat exchangers are essential components in a wide range of industrial systems, including boilers, condensers, coolers, and cooling towers [1]. In automotive applications, the radiator functions as a type of heat exchanger, facilitating the transfer of thermal energy from the engine to the surrounding environment. The primary objective of heat transfer in industrial processes is to regulate fluid temperatures to meet specific operational requirements or to induce phase changes, such as in distillation, evaporation, or condensation, thereby enabling subsequent processing steps [2].

Common types of heat exchangers include shell-and-tube, plate, and finned heat exchangers. Finned heat exchangers offer high thermal efficiency and a compact design; however, they are prone to fin damage, which can significantly reduce performance [3]. Plate heat exchangers are valued for their compact size and ease of maintenance, but they are vulnerable to corrosion and are generally unsuitable for high-pressure environments. In contrast, shell-and-tube heat exchangers are capable of withstanding high pressures and large temperature differentials, making them suitable for heavy-duty industrial applications, although their fabrication and installation costs are relatively high [4].

The objective of ongoing research in this field is to enhance the efficiency and performance of heat exchangers by addressing these limitations and developing more effective, durable, and cost-efficient designs. Based on the flow type, heat exchangers have three flow patterns used in different construction types: parallel flow, counter flow, and cross flow. In parallel flow, both fluid streams flow in the same direction. In counter flow, the fluid streams flow in opposite directions, while in cross flow, the fluid streams flow perpendicular to each other [5].

An Air Cooler Heat Exchanger (ACHE) is composed of one or more groups of finned tubes, also referred to as tube bundles, through which a high-temperature fluid flows. Heat is transferred as air is forced across these finned tubes by one or more fans [6]. This study specifically examines compact and energy-efficient air coolers that require minimal installation space. It is important to note that the primary function of an air cooler is not to condition the air in the conventional sense but to reduce room temperature through evaporative cooling [7].

The application of modern cooling technologies is becoming increasingly prevalent in response to growing demands for improved living conditions. Common applications include food preservation and indoor air cooling [8]. Commercially available air coolers are typically priced between IDR 1.3 million and 1.7 million, operate at 220–240 V with power consumption around 100 W, and have dimensions of approximately 360 × 300 × 760 mm. However, many models are relatively bulky and non-portable, and their energy demands may be considered high for small-scale or mobile applications [9].

Moreover, conventional room cooling systems often rely on refrigerants that are potentially harmful to the environment,

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contributing to ozone depletion and posing challenges related to operational and maintenance costs. These issues highlight the need for more eco-friendly and cost-effective alternatives. Air coolers, which use water as the cooling medium, operate by evaporating water into cold vapor that is then distributed by a fan. Unlike traditional fans that merely recirculate warm air, air coolers actively reduce ambient temperature, making them an effective, energy-saving, and space-efficient solution for environmentally conscious room cooling [10].

This research contributes to the broader discourse on sustainable heat exchanger systems, with a focus on optimizing energy efficiency and resource utilization. By identifying the optimal operational parameters for temperature regulation in air cooler heat exchangers, this study aims to offer practical insights that can enhance system performance. Furthermore, a deeper understanding of the thermal and fluid dynamics involved will support future innovations in the development of efficient, compact, and environmentally sustainable cooling technologies for both domestic and industrial applications.

II. RESEARCH OBJECTS

2.1 Heat Exchanger

A heat exchanger is a device used for the process of transferring heat between fluids with different temperatures, or for transferring heat from a hot fluid to a cold fluid. The heat transfer occurring within the heat exchanger happens through convection and conduction without mixing the two fluids, due to the presence of a separator.

2.2 Air Cooler Heat exchanger

An Air Cooler Heat Exchanger (ACHE) is a type of pressurized vessel designed to lower the temperature of a working fluid flowing through finned tubes by directing ambient air across the external surface of the tubes. This air flow is typically generated by one or more fans. The fins increase the surface area available for heat transfer, thereby enhancing the cooling efficiency. A common example of this system is the automotive radiator, which functions as a compact air-cooled heat exchanger [7]. In industrial applications, an ACHE generally consists of one or more tube bundles, each composed of arrays of finned tubes, over which forced air is circulated to achieve the desired cooling effect [6]. In an air cooler heat exchanger, several components are assembled into a single unit. The components are listed in Table 1.

Figure 1: Air Cooler Heat Exchanger

Table 1: Components of an Air Cooler Heat Exchanger

No	Components of an air cooler heat exchanger
1.	Part water storage tank on
2.	Part water storage tank lower
3.	Fan
4.	Pump
5.	*Inline Pipe*
6.	Switch*on / off*

2.3 Effectiveness (ε)

The effectiveness of a heat exchanger represents the ratio between the actual heat transfer rate (QQQ) and the maximum possible heat transfer rate (QmaxQ_{\text{max}}Qmax) under ideal conditions. This relationship is expressed mathematically in Equation (1), which is used to calculate the effectiveness of the heat exchanger.

$$\varepsilon = \frac{Q}{Qmax} \quad \text{........ (1)}$$

Where,

ε = Effectiveness

Q = Heat transfer rate (W)

$Qmax$ = Maximum heat transfer rate (W)

2.3.1 Calculation of Heat Transfer Rate (Q)

The heat transfer in the fluid can be calculated using Equation (2) as follows.

$$Q = \dot{m} \times Cp \times \Delta T \quad \text{..... (2)}$$

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Where:

Q = Heat transfer rate (Watts)
C_p = Heat capacity of the fluid (W/kg.K)
ΔT = Temperature between the fluid and the environment

2.3.2 Calculation rate displacement hot actual ($Qact$)

The actual heat transfer rate refers to the amount of thermal energy either released by the hot fluid or absorbed by the cold fluid. This quantity can be determined using the heat transfer equations provided in Equations (3) and (4) as follows:

$$Q_{act} = C_h.(T_{h1} - T_{h2}) \;\ldots\ldots.. \;(3)$$

$$Q_{act} = C_c.(T_{c2} - T_{c1}) \;\ldots\ldots\ldots (4)$$

Where:

Q_{act}= Actual heat transfer (W)
C_h = Heat capacity of the hot fluid (W/K)
C_c = Heat capacity of the cold fluid (W/K)

2.3.3 Calculation of Maximum Heat Transfer Rate (Qmax)

Maximum heat transfer rate can be calculated using Equation (5) as following:

$$Q_{max} = C_{min}\,(T_{hi} - T_{ci}) \quad \ldots..\,(5)$$

Where:

Q_{max} = Maximum heat transfer rate (W)
C_{min} = The smallest value of C_h and C_c (W/K)
$T_{h,i}$ = Temperature of the hot fluid entering the heat exchanger (K)
$T_{h,o}$ = Temperature of the cold fluid leavinh the heat exchanger (K)

2.4 Efficiency (η)

The thermal efficiency (η) of a heat exchanger is defined as the ratio between the actual amount of heat transferred and the total energy input required to drive the heat transfer process. This efficiency is closely related to the term *effectiveness* (ε), which is defined as the ratio of the actual heat transferred to the maximum possible heat transfer under ideal conditions (Moran, 2018). The efficiency can be calculated using Equation (6), as shown below:

$$\eta = \frac{Qact}{P} \qquad \ldots\ldots. (6)$$

Where:

η = Efficiency of heat exchanger (%)
Q_{act} = Actual heat transfer (Joule)
P = Power (Watts)

III. DATA COLLECTION

Data collection was carried out manually and in real time for 40 minutes under steady-state conditions, with the water temperature maintained at a constant level. The set up of experiment is shown in Figure 2. The experimental procedure involved systematically varying the air velocity produced by the fan and the water flow rate supplied by the pump. The fan speed was adjusted to three levels: 100% (3.37 m/s), 75% (2.5 m/s), and 50% (1.67 m/s). Similarly, the water flow rate was varied at 100% (5 L/min), 50% (2.5 L/min), and 0% (0 L/min, indicating no flow). Upon completion of data collection, the recorded values were analyzed to determine the thermal effectiveness of the heat exchanger as a function of time.

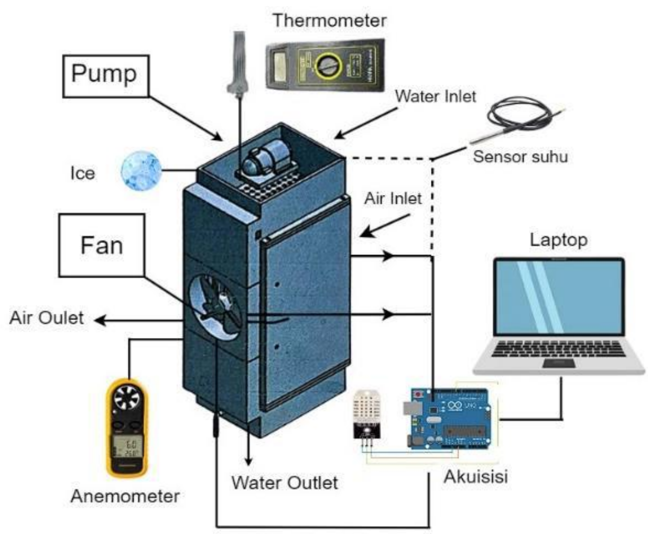

Figure 2: Data Collection Scheme

IV. RESULTS AND DISCUSSION

4.1 Effectiveness (ε)

The influence of water flow rate on heat exchanger effectiveness is clearly observed in the experimental results. At a flow rate of 5 liters/min, the effectiveness is higher than that at 2.5 liters/min. Interestingly, the condition with zero water flow (0 liters/min) yields the highest effectiveness among all tests, suggesting a significant relationship between water flow rate and thermal performance. Furthermore, the effectiveness is not solely dependent on water flow; variations in fan air speed also play a crucial role. In all test scenarios, an air velocity of 1.67 m/s consistently produces higher and more stable effectiveness values compared to the maximum speed of 3.37 m/s, indicating that lower air speeds may enhance heat transfer stability under specific conditions.

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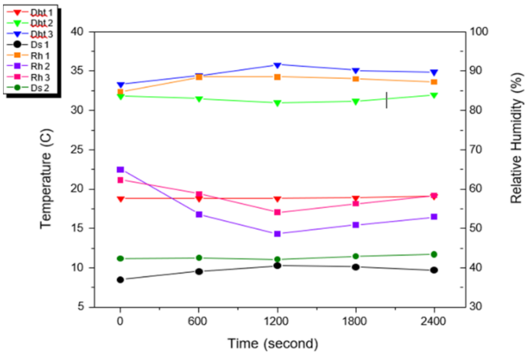

Figure 3: Effectiveness (ε)variations in water flow of 5 liters/minute

4.2 Calculation of Effectiveness (ε)

The effectiveness of the air cooler heat exchanger is determined by calculating the average temperature of the cold fluid under steady-state operating conditions. This effectiveness reflects the amount of heat transferred between the circulating water and the surrounding air. The calculated values, based on the average temperature measurements, are presented in Table 1 below.

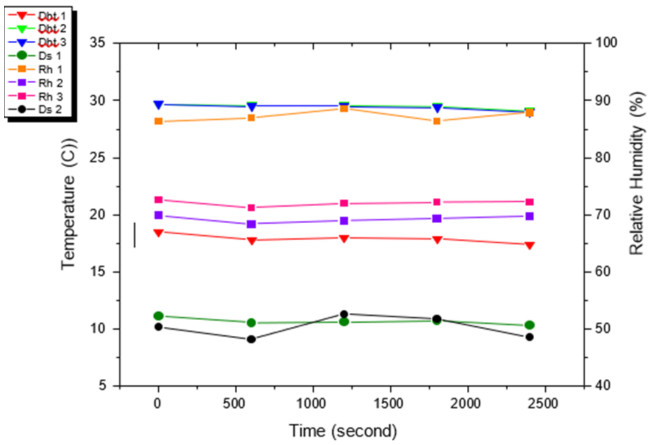

Figure 4: Effectiveness (ε)variations in water discharge of 2.5 liters/ minute

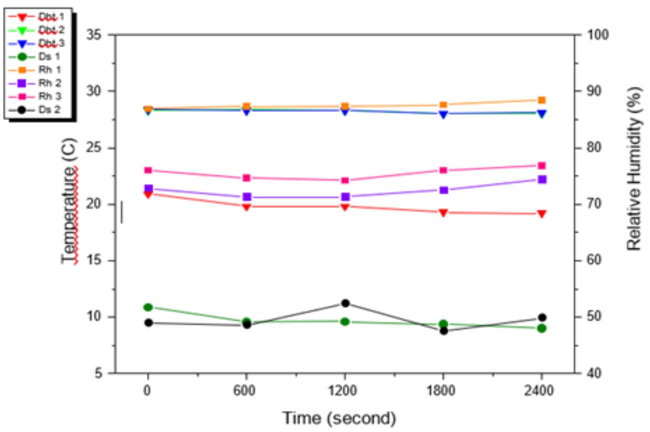

Figure 5: Effectiveness (ε)variations in water flow of 0 liters

Table 2: Results of Effectiveness Calculations

Speed Flow		Q	Qmax	ε
Water	Air			
1 L/12 S	100 (3,37 m/s)	831,197	2307,87	0,36
	75 (2,5 m/s)	1643,484	2826,793	0,58
	50 (1,67 m/s)	1836,92	3017,798	0,608
1 L/24 s	100 (3,37 m/s)	1211,528	2449,111	0,49
	75 (2,5 m/s)	1400,097	2512,323	0,557
	50 (1,67 m/s)	1541,474	2542,774	0,606
0%	100 (3,37 m/s)	1083,466	2226,981	0,486
	75 (2,5 m/s)	1353,447	2576,755	0,52
	50 (1,67 m/s)	1126,08	2396,195	0,469

Based on the data presented in Table 2, the highest effectiveness value achieved by the air cooler heat exchanger is 0.608. This optimum performance is observed under operating conditions with a water flow rate of 5 liters per minute and an air velocity of 1.67 m/s.

4.3 Calculation of Efficiency(η)

The calculation of thermal efficiency (η) involves determining the ratio of the actual heat transfer rate to the total electrical power consumed by the pump, fan, and cooling unit within the air cooler heat exchanger system. The results of the efficiency calculations for each operating condition are summarized and presented in Table 3.

Table 3: Calculation Results of Efficiency

Speed Flow		Q_{act} (watt)	Power(watt)	Efficiency (%)
Water	Air			
1 L/12 S	100 (3,37 m/s)	831,2	1.906,17	43
	75 (2,5 m/s)	1.643,5	1.899,98	86
	50 (1,67 m/s)	1.836,921	1.893,71	96
1 L/24 S	100 (3,37 m/s)	1.211,529	1.870,17	64
	75 (2,5 m/s)	1.400,097	1.870,17	75
	50 (1,67 m/s)	1.541,475	1.857,71	83
0	100 (3,37 m/s)	1.083,467	1.834,17	59
	75 (2.5 m/s)	1.353,448	1.827,98	74
	50 (1,67 m/s)	1.126,081	1.821,71	62

According to the efficiency data presented in Table 3, the air cooler heat exchanger achieves its highest thermal efficiency of 96% under operating conditions with a water flow rate of 5 liters per minute and an air velocity of 1.67 m/s.

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V. CONCLUSION

The following key findings were derived from the steady-state measurements and subsequent analysis of the air cooler.

1. The highest effectiveness value achieved by the air cooler heat exchanger is 0.608, which occurs under operating conditions of a water flow rate of 5 liters per minute and an air velocity of 1.67 m/s. Under the same conditions, the system also attains its highest thermal efficiency of 96%, indicating optimal performance both in terms of heat transfer and energy utilization.
2. This particular operating condition is considered optimal because the higher water flow rate enhances the heat exchanger's cooling capacity by increasing the volume of fluid available for heat absorption. Simultaneously, the lower air velocity allows for extended contact time between the air and the finned surfaces of the heat exchanger, thereby improving the overall heat transfer effectiveness.

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