JOURNAL OF ENGINEERING SCIENCES

Volume 11, Issue 1 (2024)

Mirmanto M., Nurpatria N., Hendra J. K. (2024). Effect of air intake temperatures on the air-water harvester performance. Journal of Engineering Sciences (Ukraine), Vol. 11(1), pp. G1–G8. https://doi.org/10.21272/jes.2024.11(1).g1

Effect of Air Intake Temperatures on the Air-Water Harvester Performance

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Article info:
Submitted: October 12, 2023
Received in revised form: February 20, 2024
Accepted for publication: March 6, 2024
Available online: March 15, 2024

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Abstract. During the dry season, some parts of Indonesia experience drought and a clean water crisis, resulting in scarcity and difficulty in drinking water. One of the solutions to solve this problem is to use an air-water harvester machine that produces water from the air. Since the intake air temperature affected the water yield, the article examined the relationship between the engine intake air temperature and the machine's performance. The study aimed to determine the performance of the air-water harvester machine at various air intake temperatures. The research was carried out experimentally for a refrigerant working fluid R134a. The rotary-type 1/4 PK compressor was used to realize the research. The air temperatures entering the condensing unit varied between 30, 35, and 40 °C. The results showed that the highest average water mass obtained was 0.34 kg at a temperature variation of 30 °C. The highest total heat absorbed by the condensing unit from the air of 184 W occurred at a temperature variation of 40 °C. Overall, an increase in the air intake temperatures allowed for a decrease in the performance of the air-water harvester machine by more than 5 %.

Keywords: energy efficiency, clean water and sanitation, process innovation, air intake temperature, heat transfer.

1 Introduction

Water is the source of life for all living things on earth. Life would not be possible without water. Clean water is a significant problem since water quality should always be maintained to meet human needs [1, 2]. If the dry season occurs too long, it causes drought in several regions of Indonesia [3].

The water scarcity problem must be resolved. One possible solution is to get water not from the ground but from another source [4]. As is known, air contains water vapor. Even when dry, water vapor remains, and the air still contains water vapor, even though the amount is minimal. The air volume is unlimited, which makes it possible to draw water from the air indefinitely [5].

There are many ways to harvest water from the air using membrane systems [6, 7], nanoporous materials [8, 9], and other materials [10, 11].

One of the devices that can produce water from the air is an air-water harvester machine. This machine uses cooling components such as an evaporator, condenser, compressor, and expansion valve or capillary tube [12]. However, freshwater production from this machine is still deficient. Hence, this machine needs to be developed.

Some previous researchers have been examining air-water harvester machines that produced water from the air [13, 14]. Many factors influenced the productivity of this machine, such as air intake temperature, air velocity, evaporator construction (evaporator shape), natural or forced system, and relative humidity [15].

Damanik [16] studied the effect of fan rotation speed on the performance of a water harvester machine from the air using a vapor compression cycle. R-22 refrigerant was used as the working fluid, and the independent variable was the rotation speed of two fans behind the evaporator (2100, 2400, and 2600 rpm). The results indicated that this water harvester machine could work optimally, producing water in the amount of 2.6 l/h. The results were enough; the refrigeration machine was a standard air conditioning machine without evaporator modification.

Monica [17] researched the effect of blowers and fans on the characteristics of water harvesting machines from the air using AC components and no modification of the AC machine. The fan rotation variation applied in this research was in a range of 50–150 rpm. The amount of water obtained by two fans with one blower was 2.7 l/h, one fan with 1 blower was 2.3 l/h, and 1 blower was 1.9 l/h.

In contrast, Prasetya [18] researched the effect of evaporator pressure on the mass of water produced. The evaporator pressure varied between 30, 40, and 50 psi. The refrigerant was R134a, and the compressor specification – 1/4 PK. The obtained results were the highest water mass of 0.44 kg at a pressure variation of 30 psi and the lowest water mass of 0.18 kg at 50 psi. However, the evaporator and condenser components were used without AC. As a result, the water yield was less; however, the power consumption was much lower.

Due to those mentioned above, the study's main aim is to obtain a simple, cheap, portable, and productive air water machine that households can use to fulfill their demand for clean water when the dry season prevails.

The investigated parameters were air intake temperatures to know the relationships between incoming air temperatures and the mass of dew or water. The energy use ratio was used to determine whether the machine could be profitable.

2 Literature Review

Several studies investigating the air-water harvester using a refrigeration system have been conducted. Some factors can affect freshwater production, e.g., air velocity, RH, air intake temperature, evaporator type, condensation system, evaporator construction, and refrigerant pressure. Here are some previous studies with different investigated variables.

Gaol [19] researched a machine for producing water from air using a 3/4 PK vapor compression cycle machine. The research was carried out to produce the following findings: the energy use ratio W_{in} = 34.8 kJ/kg; the coefficient of performance (COP) – 3.06; the energy efficiency – 57 %; the volume of produced water – about 2.0 l/h.

Mirmanto et al. [20] experimentally studied an air-water harvester machine using a refrigeration machine they constructed. The free variables were the number of evaporators, namely 1, 2, and 3 evaporators. It was found that increasing the number of evaporators elevated the dew mass and the total heat transfer rate. However, the free convection condensation model was used. The maximum value of the obtained freshwater was about 0.5 kg/h for 7 h.

Recently, Mirmanto et al. [21] performed an experimental study of an air-water harvester using a custom refrigeration machine with different shapes of evaporators, i.e., coil evaporator, serpentine evaporator, and parallel evaporator. They concluded that the coil evaporator was the best for their experimental conditions. The freshwater mass and the total heat transfer rate obtained were 0.53 kg for 7 h and 75.5 W. However, a free convection condensation mode was also used.

Prasetya [18] studied the effect of condensing unit pressure on air-water harvester machines on the mass of the produced water. This research examined the effect of evaporator pressure on the mass of water. The evaporator pressure varied between 30, 40, and 50 psi. The refrigerant was R134a, which is environmentally friendly. The compressor specifications contained a compressor with 1/2 PK power.

The research showed that the highest water mass was obtained at a pressure variation of 30 psi with an average water mass of 0.44 kg for 7 h. Meanwhile, the lowest average water mass occurred at a pressure variation of 50 psi, amounting to 0.18 kg. The highest COP of 25.3 was obtained at a pressure variation of 30 psi; the lowest COP of 10.8 was at 40 psi. The highest increase in the energy efficiency of 4.8 % was obtained at 40 psi, and the lowest was 2.9 % – at 50 psi. The average inlet air temperature was 35.1 °C.

Atmoko [22] studied the characteristics of machines producing water from air using a vapor compression cycle machine with the addition of an air compressor fan with a fan rotation speed of 300 rpm and 350 rpm. The research results showed that the engine operates properly, and several characteristics were known (i.e., W_{in}, COP, and energy efficiency). The fan speed was 350 rpm, and the freshwater result was 4.2 l/h. Remarkably, a real AC without modification and the power was used by the compressor 1.5 PK.

Irawan [23] performed an experimental study on the effect of the number of fans on the characteristics of machines that capture water from the air. The study used a vapor compression cycle machine consisting of a 1.0 PK compressor, R410 refrigerant, capillary pipe, evaporator, condenser, evaporator fan, and condenser fan. The results showed that the machine for capturing water from the air could be designed and assembled and could work as expected. Also, the amount of water produced by the machine was 1.9 l/h (without the fan on), 2.0 l/h (with one fan on), and 2.1 l/h (with two fans on). The machine that produced the most significant volume of water resulted in the following parameters: W_{in} = 28.0 kJ/kg, the actual COP of 5.66, the ideal COP of 7.53, and the energy efficiency of 75.2 %.

Wibowo [24] researched the effect of air temperature and humidity variations on the performance of LPG refrigerant cooling machines. In the research, a car with AC installation was used. The study aimed to determine the effect of air temperature and humidity before entering the evaporator on the performance of cooling machines with LPG refrigerant. The research was carried out by varying the air temperatures before entering the evaporator by 31, 33, 36, and 38 °C and the air humidity before entering the evaporator by 73, 77, and 81 %. The study showed that in tests with air temperature variations, the COP of 7.16–8.28 was most significant at 31 °C and the air humidity of 73 %. However, the study was not aimed at obtaining water from the air but only at studying the performance of cooling machines at various temperatures and air humidity.

Setiawan [25] conducted an experimental study on the effect of outlet fan rotation on the characteristics of machines with a vapor compression cycle. In this study, the compressor power used was 1.0 PK and refrigerant 32, and the water pouring circuit was made using two water pouring tanks with a volume of 0.034 m^3. The independent variables investigated were outlet fan rotation speeds of 0, 981, 1226, and 1664 rpm. The water-producing machine box had a volume of 2.5 m^3. The machine could produce distilled water with water of 1.9 l/h without the outlet fan rotation, 2.0 l/h at 981–1664 rpm. The vapor compression cycle machine that produced the most significant volume of distilled water per hour had an energy use ratio of 42.3 kJ/kg, an actual COP of 5.35, an ideal COP of 7.26, and an energy efficiency of 73.7 %.

3 Research Methodology

3.1 Experimental facilities

The method used in this research is experimental. This research method can be used to test a new treatment or design by comparing one or more test groups with and without treatment. The equipment and materials used in this research include compressors, condensers, condensing units, capillary tubes, thermocouples, digital thermometers, R-134a refrigerant, humidity control devices, data loggers, scales, water storage containers, fans, and air. The variables tested were water mass, air heat transfer flow rate to the evaporator, COP, and evaporator efficiency. All of these variables are dependent variables, while the independent variables are the incoming air temperatures of 30, 35, and 40 °C, while other parameters are room conditions.

The research equipment presented in Figure 1 consists of a compressor, condenser, evaporator, capillary tube, reservoir, and fan.

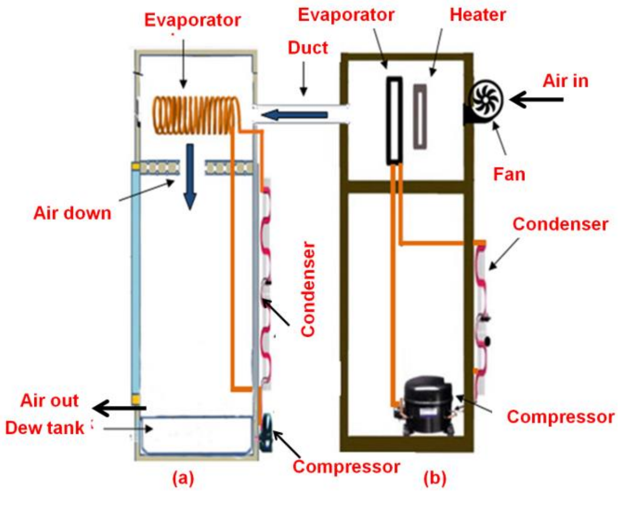


Figure 1 – Schematic diagram of the research tool and its components: a – air-water harvester unit; b – air temperature adjuster unit

Outside with room conditions, air entered the air temperature adjuster unit (ATAU) to increase its temperature. Then, it flowed to the air-water harvester unit (AWHU), as shown in Figure 2.

Air flowed in and came into contact with the evaporator coil walls in AWHU, where the temperature was very low, even lower than the dew point temperature of the water vapor.

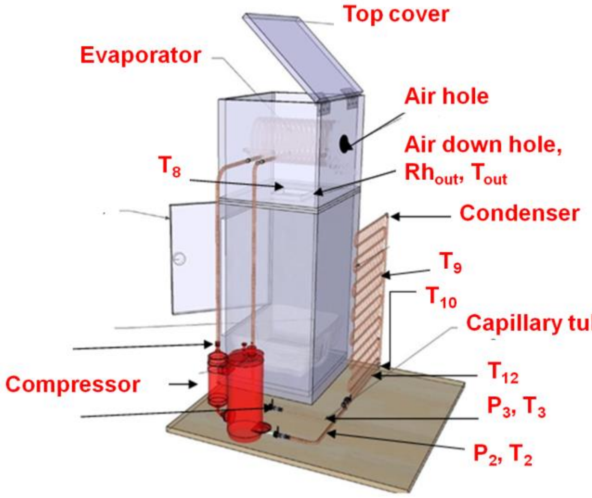


Figure 2 –3D sketch of the air-water harvester unit

Air contains water vapor, so when it comes into contact with the evaporator coil wall, some water vapor is condensed. This dew dripped continuously and was collected in the tank. Every hour, the collected dew was weighed. Finally, after 7 hours of experimentation, the total mass of dew or water could be determined. Cold air from inside the machine descended into the lower chamber and then exited through the hole above the dew tank.

This machine uses a vapor compression cycle with R134a working fluid. The refrigerant vapor in the accumulator, which comes from the evaporator, is sucked in by the compressor and then pressed to high pressure and high temperature. This high-pressure and temperature refrigerant then flows to the condenser. The refrigerant removes heat from the environment through the condenser walls. Then, the vapor refrigerant turns into liquid refrigerant. Refrigerant liquid flows into the capillary tube. After passing through the capillary pipe, the refrigerant turns into a mixture of vapor and liquid and enters the evaporator. In the refrigerant evaporator, this mixture turns completely into steam by taking heat from objects or the air around the walls of the evaporator. From the evaporator, refrigerant vapor flows into the accumulator, and so on, the working principle of the vapor compression cycle.

The air velocity was measured using a digital anemometer model SANFIX GM-8901 with a speed range of 0–45 m/s and a resolution of 0.1 m/s. All temperatures were measured using a type K thermocouple connected to data logger APPLENT AT45-24 with an uncertainty of ±0.5 °C from calibration.

The pressure was measured using a pressure gauge with psi units, while atmospheric pressure was measured using a barometer-hygrometer model TESTO 622 with an accuracy of 98 %.

The mass of water produced was weighed using a 5 kg Taffware Digital Scale with an accuracy of 1 g.

The experimental conditions and the measurement devices are listed in Table 1.

Table 1 – Experimental conditions and measurement devices

Device	Specification	Model	Uncertainty/resolution
Data logger	From –200 to 1 300 °C	AT45-24	±0.2 %
Thermocouple	From –60 to 300°C	K-type	±0.5 °C (calibration)
Pressure gauge	0–500 psi	Manifold gauge	5 psi
Hygro-barometer	5–95 % (RH); 0.50–1.03 bar (pressure)	TESTO 622	1 % (RH); 1 mbar (pressure)
Digital scale	0–5 kg	Taffware	Resolution 1 g
Digital anemometer	0-45 m/s	SANFIX GM-8901	±0.1 m/s
Digital thermometer-hygrometer	0–100 %	Digital	1 %
Ambient RH	65–70 %	Digital	1 %
Ambient temperature	27–30 °C	K-type	±0.5 °C

3.2 Calculation technique

To analyze the experimental results, several equations should be used to calculate the mass flow rate of condensation water, COP, heat flow rate from air to the evaporator, and evaporator efficiency.

$$\dot{m}_w = \frac{m}{t}, \quad (1)$$

where m – the mass of water produced, kg; $\dot{m}_w$ – the mass flow rate of water produced, kg/s; t – duration of the experiment, s.

The total air mass flow rate is calculated using the following equation:

$$\dot{m}_t = \rho AV, \quad (2)$$

where $\dot{m}_t$ – the total mass flow rate of air entering the engine, kg/s; ρ – the air density, kg/m³, obtained from the atmospheric pressure air table based on the air temperature when entering the engine; A – the frontal area of the air inlet, m²; V – the inlet air velocity, m/s.

Next, to calculate the dry air flow rate, the following equation is used:

$$\dot{m}_{da} = \frac{\dot{m}_t}{1 + w_1}, \quad (3)$$

where $\dot{m}_{da}$ – the mass flow rate of dry air, kg/s, and w_1 is the portion of water vapor in the air when it enters the engine, kg/kg; w_1 – the parameter obtained using the psychrometric analysis [26] for temperature and *RH*.

The mass flow rate $\dot{m}_v$ of water vapor, kg/s:

$$\dot{m}_v = \dot{m}_t - \dot{m}_{da}. \quad (4)$$

Once all the mass flow rates are known, the heat flow rate from the air to the evaporator walls can be predicted. The heat flow rate $\dot{Q}_d$ due to condensation, W:

$$\dot{Q}_d = \dot{m}_d h_{fg}, \quad (5)$$

Furthermore, the heat flow rate of dry air can be predicted by the equation:

$$\dot{Q}_{da} = \dot{m}_{da} c_{pda} (T_i - T_o), \quad (6)$$

where c_{pda} – the specific heat of the air, J/(kg·K), obtained from the atmospheric pressure air for T_i; T_o – the temperature of the air entering and leaving the condensing chamber, °C.

Lastly, the heat flow rate of steam in the cooled air can be estimated using the equations [20, 21]:

$$\dot{Q}_v = \dot{m}_v c_{pv} (T_i - T_o); \quad (7)$$

$$\dot{Q}_t = \dot{Q}_d + \dot{Q}_{da} + \dot{Q}_v, \quad (8)$$

where $\dot{Q}_t$ – the total heat transfer from the air to the walls of the evaporator, W.

Next, the following equations must be used to analyze the refrigerant flow section and can be retrieved in Cengel and Boles [27]. The cooling load Q_{in}, J/kg, can be calculated with the equation:

$$Q_{in} = h_1 - h_4 \quad (9)$$

where h_1 and h_4 are enthalpies on the inlet and outlet of the evaporator, respectively, J/kg.

Also, the compressor work, J/kg:

$$W_{in} = h_2 - h_1, \quad (10)$$

where h_2 – the enthalpy at the compressor outlet, J/kg.

Then COP can be defined as follows:

$$COP = \frac{Q_{in}}{W_{in}}. \quad (11)$$

P-h and T-s diagrams for the ideal refrigeration cycle are presented in Figure 3.

The state 1–2 is the isentropic compression process conducted by a compressor with the work of W_{in}. The state 2–3 is the heat rejection process; Q_{out} is the symbol of heat rejection. The process occurs at the condenser. The state 3–4 is the isenthalpic process prevailing at the capillary tube. The liquid refrigerant is expanded, becoming a mixing vapour-liquid refrigerant entering the evaporator. The state 4–1 is the heat input process occurring in the evaporator. The heat comes from the air flowing over the evaporator.

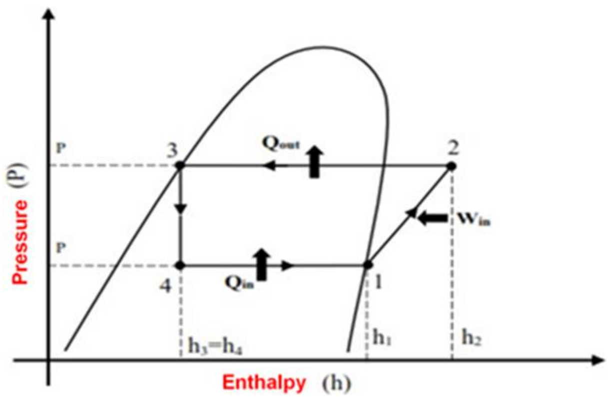
The mass flow rate of refrigerant $\dot{m}_{ref}$, kg/s:

$$\dot{m}_{ref} = \frac{P_c}{W_{in}}, \quad (12)$$

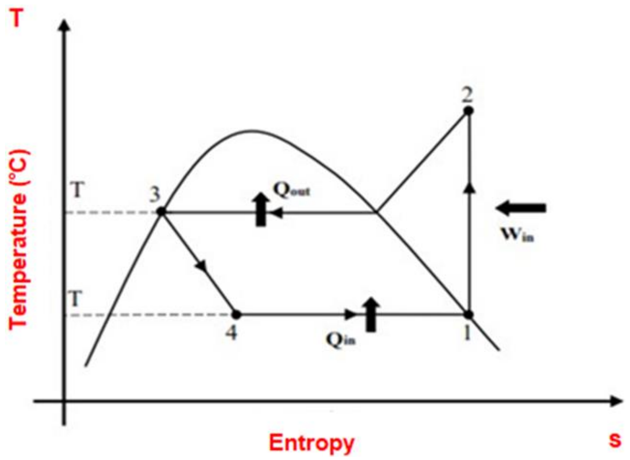
where P_c is the electrical power supplied to the compressor, W.

The evaporator efficiency is as follows:

$$\eta = \frac{\dot{Q}_t}{\dot{m}_{ref} Q_{in}}. \quad (13)$$



a



b

Figure 3 – “P–h” (a) and “T–s” (b) diagrams
for the ideal refrigeration cycle

4 Results

An experimental investigation examined the relationship between the air intake temperatures and the machine performances. The machine’s performance in this study is in terms of freshwater mass, COP, total heat transfer rate, efficiency, and the energy used ratio EUR. The results of the experiments are presented in the form of figures. The experiments were conducted for 7 hours at the Mechanical Engineering Department, Faculty of Engineering, the University of Mataram, Indonesia.

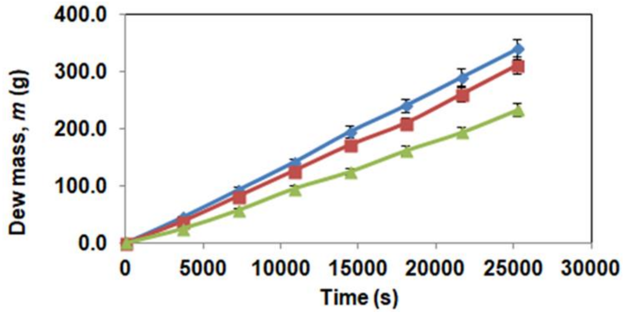
Data described in Figure 4 were obtained by weighing the dew collected in a bucket. The dew dropped from the evaporator continuously.

Figure 4a is the accumulated dew mass, while Figure 4b is the total dew mass. The total dew mass obtained at 30, 35, and 40 °C is 0.34, 0.31, and 0.23 kg, respectively, for a running machine of 7 h.

Data presented in Figure 5 were calculated using equation (11), comparing cooling load to COP. The cooling load was calculated using equation (9), while the COP was determined using equation (10).

Figure 6 presents the total heat transfer rate, calculated using equation (8).

Figure 7 presents evaporator efficiency at different air intake temperatures.



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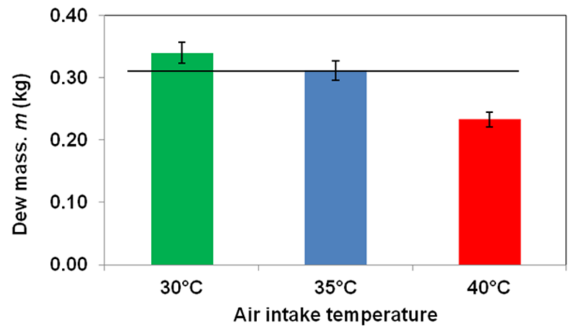

b

Figure 4 – Mass of dew obtained in the experiments concerning the air intake temperature: a – accumulated; b – total

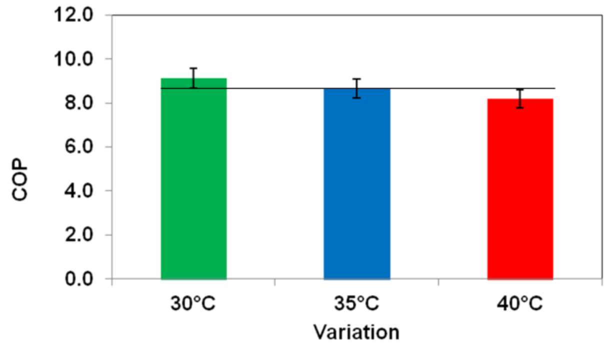

Figure 5 – COP of the machine at different temperatures

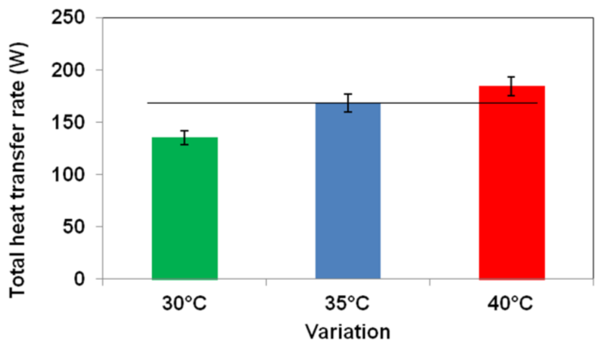

Figure 6 – Total heat transfer rates vs. air intake temperature

The total heat transfer rate from the air to the evaporator walls $\dot{Q}_t$ contains heat transfer due to the cooling of the dry air and water vapor and the condensation or latent heat (phase change from vapor into water).

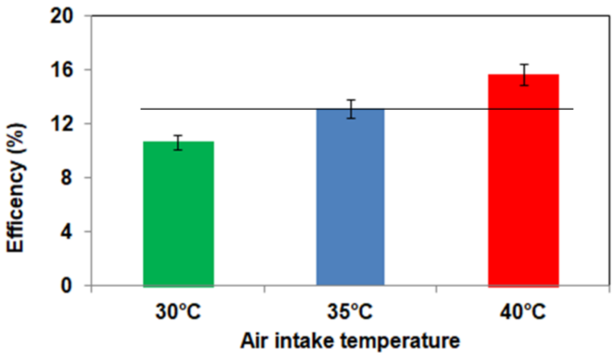

Figure 7 – Evaporator efficiency at the different air intake temperatures

Currently, the machine should be checked using the parameter EUR [28], which should be lower than 1.0. The EUR data are presented in Figure 8.

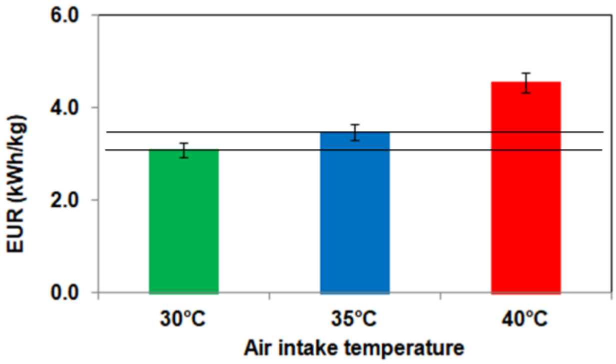

Figure 8 – EUR at the three different air intake temperatures

5 Discussion

The experimental results are presented in figures that are easy to analyze. The results of this study were data of the used compressor power (P_c), RH of the evaporator inlet air (RH_{in}), RH of the evaporator outlet air (RH_{out}), RH of the environmental air, pressure and temperature of the refrigerant entering the condenser (P_1, T_1), pressure and temperature of the refrigerant leaving the condenser (P_2, T_2), pressure and temperature of the refrigerant entering the capillary pipe (P_3, T_3), pressure and temperature of the refrigerant entering the evaporator (P_4, T_4), environmental temperature, incoming air velocity, and the mass of water produced.

Testing was carried out with three repetitions for each variation during 7 h, starting from 08.30 to 15.30 of the local time every day. The ambient temperatures and RH were ranged from 27–30 °C to 65–70 % during the experiments.

The mass of dew or water collected following the air velocity is given in Figure 4. The mass of dew was measured directly using a digital scale, as described in section 3 of Table 1.

The accumulated dew mass increases with time (Figure 4a). This finding corresponds to the research work [20]. The effect of air intake temperature on dew mass is significant based on the error bars. No error bar is overlapping; it indicates that the difference in dew mass at the three temperatures is more than 5 %. Increasing the air intake temperature decreases the dew mass. At higher temperatures, the water vapor gets difficult to condense because just less the water vapor reaches its dew point; consequently, the dew mass obtained is less.

Another parameter that should be presented is the COP concerning the air intake temperature. This calculated parameter is presented in Figure 5. COP was calculated using equation (11). Figure 5 depicts that increasing the air intake temperature decreases the COP. At higher temperatures, the Q_{in} increases, but the compressor work elevates. The increase in compressor work is higher than the increase in Q_{in}. Therefore, the COP decreases according to the equation (11). The difference in COP at the three air intake temperatures is significant because the error bar does not overlap. The COP difference between each other is more than 5%. For example, since COP = 9.12 at 30 °C and COP = 8.65 at 35 °C, then the difference is 0.47. Therefore, 0.47/9.12·100 % = 5.2 %.

The total heat transfer rate is calculated using equation (8). The calculated total heat transfer rate is given in Figure 6. Figure 6 indicates that increasing the air intake temperature elevates the total heat transfer rate. This was due to $\Delta T = T_i - T_o$. Raising ΔT causes the heat transfer rate to elevate according to equations (6) and (7). Therefore, the total heat transfer rate is higher at the higher air intake temperature. This also corresponds to the theory of heat transfer [29].

The difference in heat transfer rate at the three air intake temperatures is significant because it is more than 5 %, indicating no error bar overlapping in Figure 6. Hence, the effect of air intake temperature on the total heat transfer rate is apparent. The total heat transfer rates at 30, 35, and 40 °C are 135.6, 168.7, and 184.6 W, respectively.

The efficiency of the evaporator given in Figure 7 increases with an increase in the air intake temperature. This is due to the total heat transfer rate increase, as depicted in Figure 6. According to equation (13), increasing the total heat transfer rate elevates the efficiency. The efficiencies at 30, 35, and 40 °C are 10.7 %, 13.1 %, and 15.7 %, respectively.

The last parameter that should be checked is the kWh/kg. Figure 8 indicates the experimental EUR, however, the value of EUR is higher than 1.0. This finding was also found by Mirmanto et al. [21]. However, Ahmad et al. [28] found lower than 1.0. Therefore, the machine used in this study is not effective and then a further intensive study should be conducted to decrease the EUR parameter. Increasing the air intake temperatures raises the EUR parameter or decreases the performance of the machine.

Unfortunately, there is no study on this subject yet, so the results cannot be checked using other results worldwide. This indicates that the novelty of this study is new. In Indonesia, 1 kWh for a standard household is 1444 IDR. The total kWh consumed during the experiments was an average of 1.07 kWh. This means the machine spends 1444·1.07 = 1547.59 (IDR) for 1.6 kg water.

Since the price of bottled water (0.6 l) is 1750 IDR, the machine resulted in a lower price of water, although the machine is not effective according to the EUR parameter.

6 Conclusions

An experimental study to determine the effect of air inlet temperatures on the air-water harvester was conducted, and some findings are found as follows. The effect of air intake temperatures on water mass production, total heat transfer rate, and efficiency is significant, while the COP is almost neglected. Increasing the air intake temperatures decreases the performance of the air-water harvester machine by more than 5 %.

Based on the water price, the machine can result in a lower water price than the bottled water sold in the mini market. The study needs to be extended with a better machine design, and further research will be aimed at a comparative analysis of new and prospective refrigerants.

7 Acknowledgments

The authors acknowledge the Mechanical Engineering Department, Faculty of Engineering, University of Mataram, for the provided research facilities.

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