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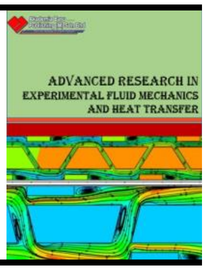

Evaluation of Indirect Evaporative Cooling Performance Integrated with Finned Heat Pipe and *Luffa Cylindrica* Fiber as Cooling /Wet Media

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ABSTRACT

Evaporative cooling is an air conditioning system in great demand by the public due to its low operating costs and easy maintenance. In countries with high humidity, direct evaporative cooling does not meet comfort requirements because the air to be conditioned is flowed directly to the cooling media. A decrease in temperature causes an increase in humidity. This is not the case with the indirect evaporative because the conditioned air does not directly contact, so an increase in humidity does not accompany the temperature decrease. This paper presents an experiment of indirect evaporative cooling integrated with finned heat pipes and luffa cylindrica fibers as a cooling media (wet media). This experiment aims to determine indirect evaporation cooling performance by utilizing the luffa cylindrica fiber's good wettability as a cooling media and the heat pipe's high thermal conductivity as a heat transfer. The system's performance is shown by wet-bulb effectiveness, dew point effectiveness, and cooling capacity. In this research, the finned heat pipe is arranged in a staggered manner in a module consisting of six rows and two columns where the finned heat pipe is divided into two parts; dry channel and wet channel. The test is carried out at conditioned intake air temperatures at 30, 35, 40, and 45 with a relative humidity of 25-54%. From the test results, the highest difference temperature is 16.6 C, the highest cooling capacity is 277 watts, the dew point effectiveness is 71%, and the wet-bulb effectiveness is 99%.

Keywords:
Heat pipe; luffa cylindrical; evaporative cooling; cooling pad

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1. Introduction

Thermal comfort indicates a person's satisfaction with the surrounding thermal environment. The factors that influence it are environmental factors, namely air temperature, humidity, air velocity, and radiant temperature, while individual factors include clothing and activities and personal conditions. This thermal comfort can only be achieved when environmental factors are within a certain range. Generally, thermal comfort is defined as a state of mind that expresses satisfaction with the thermal environment. According to the ASHRAE standard [1]. A country with a tropical climate, has two seasons, the dry season and the rainy season. During the dry season, the outside air temperature is very high and makes some areas to experience drought. This creates new problems when the dry season arrives. Hot air and dry environmental conditions cause human comfort to be

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disturbed and disrupt their activities. For this condition, the use of air conditioning equipment is undoubtedly necessary. In some circles, many use air conditioners; some people also use evaporative coolers, which are considered to be more environmentally friendly than air conditioners [2].

Camargo *et al*., [3] have carried out numerical and experimental investigations using rigid cellulose cooling media. His experiments obtain the fact that the efficiency of evaporative cooling increases when the air velocity is reduced. The study of cooling media with cellulose pad is carried out by Tung-Fu Hou *et al*., [4]. Beshkani and Houseini investigate parameters that affect saturation efficiency, indirect evaporative cooling, as well. His experiments are carried out using corrugated paper as a cooling media to increase the wet surface area [5]. Xiangjie *et al*., [6,7] conduct an experimental investigation of an evaporative cooling system integrated with hollow polymeric fibers as a humidifier and evaporative cooler. This system provides a comfortable indoor environment for hot and dry areas. Sonawan *et al*., [8] utilize banana midrib waste as a cooling media for direct evaporative cooling in 2020. An experimental study of eucalyptus fibers' potential as a cooling media in evaporative cooling is also investigated by Dodramaci *et al*., [9].

According to Al-Sulaiman *et al*., the fiber's performance to be selected as a cooling media must have three main criteria. The first criterion is initial cooling efficiency; the second criterion is material degradation, including salt deposition and bio-degradation (mold formation). The third criterion is a decrease in cooling efficiency over time. Al-Sulaiman *et al*., investigated cooling media such as jute fiber, *luffa* fiber, and palm fiber compared to commercial pad [10].

The investigation results by Y. M. Xuan et al., stated that most research on evaporative cooling in China only focuses on thermodynamic processes and performance optimization of some basic configurations, such as direct evaporative cooling (DEC) and tubular type or indirect evaporative cooling (IEC) plate.

Researches on the latest evaporative cooling technology, such as indirect evaporative cooling (IEC) heat pipes, indirect evaporative cooling (IEC) dew points, and semi indirect evaporative cooling, have not been widely carried out [2]. A heat pipe is a heat exchanger that does not require external power with a high heat exchanger capacity as a passive heat transfer device. In HVAC systems, heat pipes as heat exchangers are widely applied, especially as heat recovery in air conditioners [11-16].

The application of heat pipes in evaporative cooling is only made by a few researchers, including research from S.B. Riffat *et al*., [17] and R. Boukhanouf *et al*., [18], A Abdulrahman *et al*., [19] they developed heat pipes with porous ceramics in evaporative coolers by conducting simulated studies and validating them with experiments. The result mainly depicts that the ceramic wet area available was not sufficient for the airflow in the wet channel to reach saturation conditions. However, the idea of using heat pipes presents some advantages in that effective heat transfer between the two airflows has been achieved. A dry bulb temperature of the airflow in the dry channel dropped by 5 °C though the effectiveness was moderate.

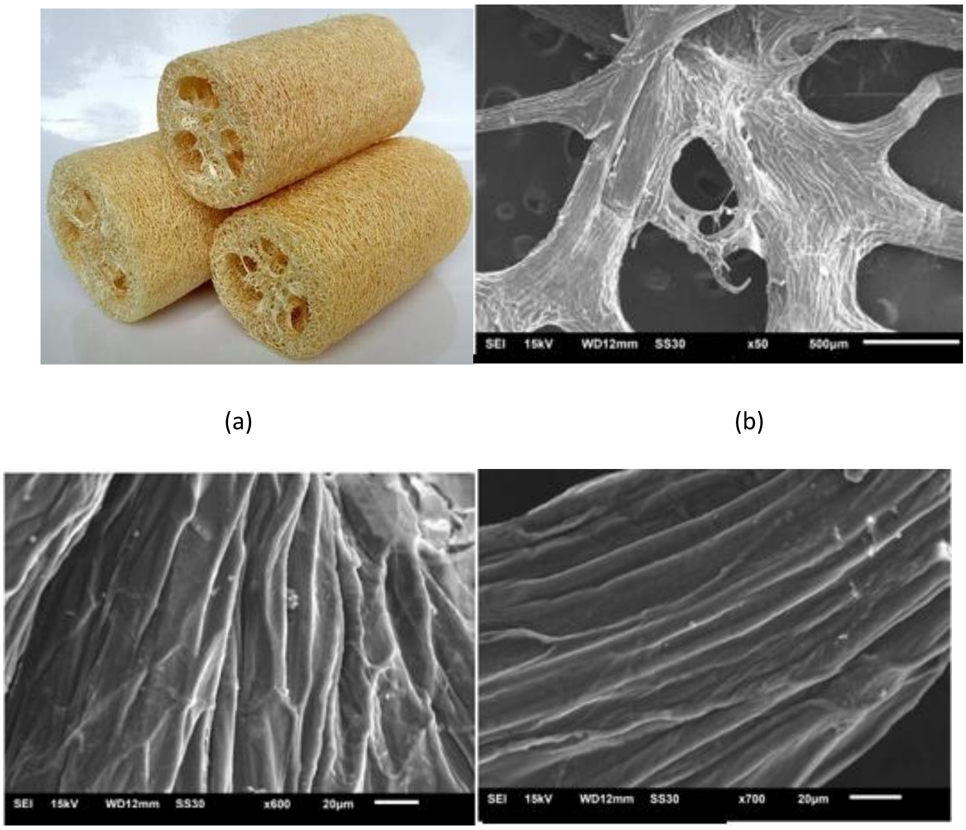
B Fikri *et al*., [20] developed a multi-stage direct-indirect evaporative cooler using straight heat pipes. His research shows that the heat pipe arrangement and evaporative cooler as a multi-stage direct evaporative cooler with a precooler can increase the efficiency of system saturation. The highest temperature reduction is achieved by the second setting (multi-stage direct evaporative cooler with a heat pipe as precooler) at an inlet temperature of 45°C and an air velocity of 0.8 m/s, with a value of 18.15°C.

Based on the literature reviewed above, this work attempts to determine the cooling performance of indirect evaporative cooling, with the *luffa cylindrica* fiber as the wet medium and the finned heat pipe as effective devices for heat and mass transfer. This experiment aims to determine indirect evaporation cooling performance by utilizing the *luffa cylindrica* fiber's good wettability as a cooling media and the heat pipe's high thermal conductivity as a heat transfer.

2. Methodology
2.1 Material and Methods

The cooling pad material to be used is *luffa cylindrica*, the advantage of *luffa cylindrica* fiber is its good wettability. Besides, the uniqueness of the *luffa cylindrica* is that each fiber binds to form cavities, so it is hoped that if it is used as a cooling medium these cavities will be able to increase the effectiveness of this evaporative cooling system.

Fig. 1 (a) shows the physical form of *luffa cylindrica*, where each fiber is bonded to each other and forms cavities. For a clearer shape, it can be seen from the results of Scanning Electron Microscopy (SEM) of *luffa cylindrica* with a magnification of 50 times in Figure 1 (b), it can be seen that the cavities formed from these fibers. Meanwhile, the magnification for each fiber section is at 600 x and 700 x magnifications (Figures 1 (c) and (d)).



(a) (b)

(c) (d)

Fig. 1. (a) *Luffa cylindrica* (b) Scanning Electron Microscopy (SEM) of *luffa cylindrica* 50 x magnification (b) 600 x magnification (c) 700 x magnification.

2.2 Description of the System

This indirect evaporative cooling working principle is based on the modified Maisotsenko-cycle (M-cycle) of the indirect evaporative cooling (IEC) system. A fraction of the cooled supply air is diverted to the wet channel to become the working air [21,22]. The components which are the focus of this research are finned heat pipes and cooling media. Finned heat pipes are arranged in modules consisting of six rows and two columns where finned heat pipes are divided into two parts, namely dry channel, and wet channel.

Hot air will flow into the dry channel; there is a finned heat pipe in the dry channel, the finned heat pipe's evaporator side. On this side, the air will touch the finned heat pipe walls so that evaporation occurs on the wall. Air that has passed through the walls of finned heat pipes will decrease temperature but has almost the same relative humidity when air enters the dry side.

Part of the air passed through the finned heat pipe's evaporator side (dry channel) is partly discharged and utilized. Simultaneously, some of the air is deflected to the wet side and past the finned heat pipe's condenser side. The condenser part of the finned heat pipe is covered with a cooling medium made of *luffa cylindrica* / belustru / gambas. Water is sprayed on the condenser part of the finned heat pipe covered by *luffa cylindrica* / belustru / gambas. Water sprayed on this side produces the wet side in the process of heat transfer and mass transfer.

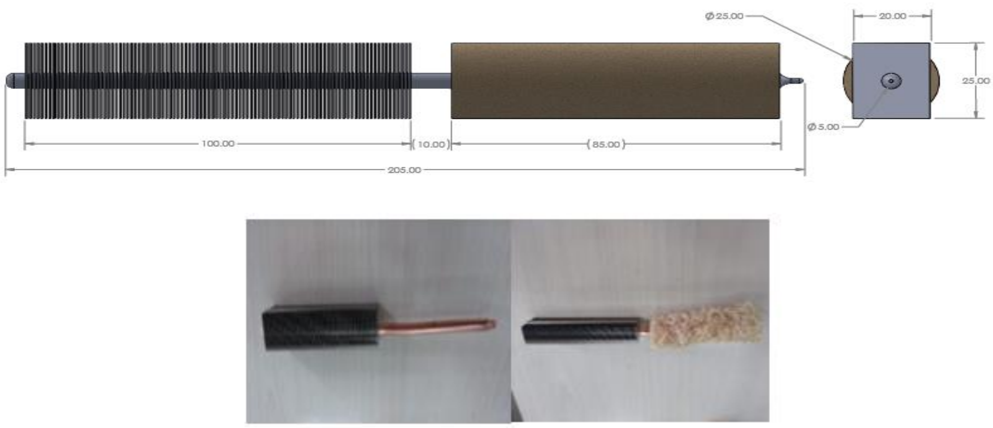


Fig. 2. Schematic figure of Finned heat pipe with *Luffa Cylindrica* / blustru

2.3 Performance Parameter

There are three parameters to be analyzed from this system; cooling capacity, wet bulb effectiveness, and dew point effectiveness.

Cooling Capacity

The cooling capacity of the system was calculated using the following equation:

$$Q_c = c_p \rho_f \dot{V}_{dc} \left(T_{dc,in} - T_{dc,out}\right) \tag{1}$$

where, Q_c: The cooling capacity of the system, W; ρ_f: Air density, kg/m^3; $\dot{V}_{dc}$: Supply air volume flow rate, m^3/s; C_p: Specific heat of air, J/(kg K); $T_{dc,in}$: Intake air dry-bulb temperature, °C; $T_{dc,out}$: outlet air dry-bulb temperature, °C.

Wet-bulb effectiveness

The literature states that an evaporated cooling system's performance is compared to the effectiveness of its wet bulb [19,23,24]. In this process, the intake wet-bulb air temperature is a parameter that limits the dry-bulb air supply temperature. This parameter also gives an idea of how close the outlet air dry bulb's temperature is to the intake air dry bulb's temperature. Typically, cooled air has a lower heat capacity rate than wet air. Therefore, the performance of the evaporative cooler is mainly determined by its effectiveness.

$$\varepsilon_{WB} = \frac{T_{dc,i} - T_{dc,o}}{T_{dc,i} - T_{dc,i(WB)}} \; x \; 100\% \tag{2}$$

Where, $T_{dc,in}$ and $T_{dc,out}$ is the air temperature to be cooled entering and leaving evaporative cooling, $T_{dc,in(WB)}$ is the wet-bulb temperature of the air entering indirect evaporative cooling (°C).

Dew-point effectiveness

In Indirect evaporative cooling, the inlet air is divided into two streams, and the supply air temperature is cooled as it passes through the heat exchanger module; in this case, it is the finned heat pipe. The limiting value of the outlet air temperature is the dew point of the intake air temperature, so it is better to compare the indirect evaporation performance based on dew point effectiveness. The dew point effectiveness can be defined as given in the below equation:

$$\varepsilon_{DP} = \frac{T_{dc,i} - T_{dc,out}}{T_{dc,i} - T_{dc,i(dew-point)}} \times 100 \tag{3}$$

where, $T_{dc,in}$ and $T_{dc,out}$ is the air temperature to be cooled entering and leaving indirect evaporative cooling, °C, $T_{dc,in(dew\text{-}point)}$ is the dew point temperature of the air entering indirect evaporative cooling, °C.

2.4. Measurements and Instrumentation.

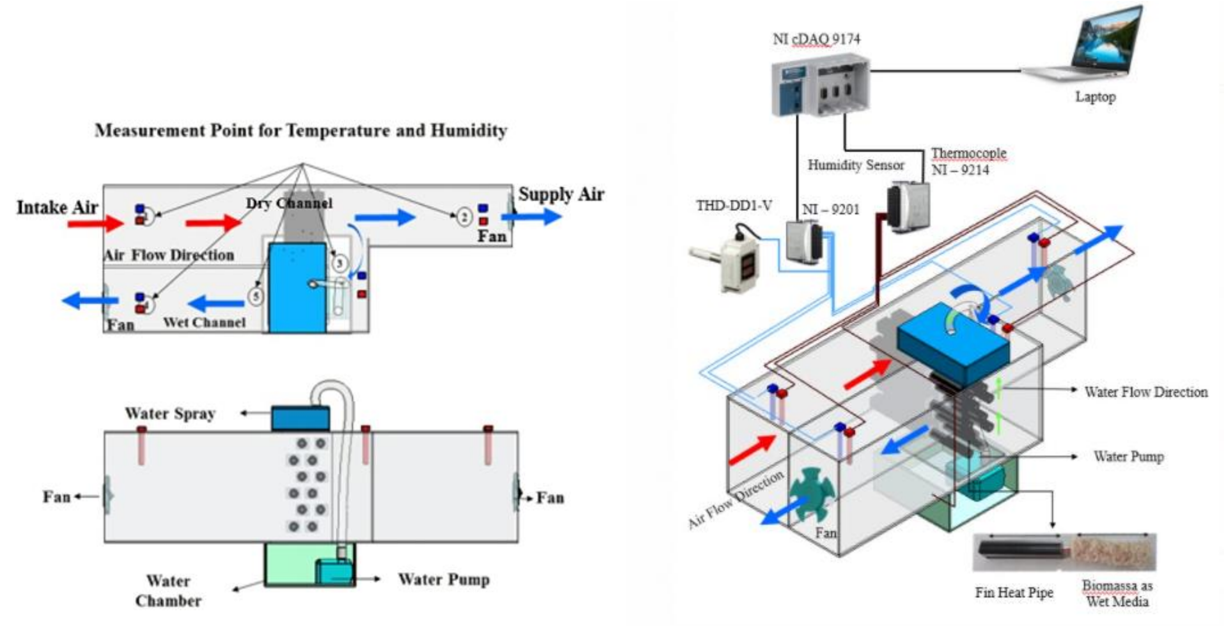


Fig. 3. Measurement point

Air temperature sensors that are placed on the inlet and outlet of the system, measured using four K-type thermocouples with an accuracy of ± 0.1 ° C and a test temperature range of -10-110°C, are connected to the NI-DAQ 9214 module. The relative humidity is measured using the Autonic type The THD-DD1-V humidity sensor with an accuracy of ± 3% RH and a measurement range of 10-90% is connected to the NI DAQ 9219 module. Both modules are connected to a data acquisition device (NI cDAQ-9174).

The test point is placed in the airflow before entering the finned heat pipe and after passing the finned heat pipe, before and after the cooling pad.

The air velocity was measured using an AMI-300 hotwire anemometer with an accuracy of ± 5% and a measurement range of 0.2-20.0 m / s. The measuring point is located on the inside of the air duct, and the airflow speed is regulated using an inverter fan motor.

Calibration of all measuring instruments was performed during the experimental set-up. The selected fan speed is high and low air velocity. The intake air temperature is the ambient temperature that is flowed through the dry side through the finned heat pipe, which is also the heat pipe's condenser part. The fins are attached to the heat pipe evaporation section to increase heat transfer from the dry air duct through the heat pipe to the wet duct. After passing through the condenser, part of the air to be utilized is flown out, and part of it flows to the wet side to flow to the cooling pad or the evaporator part of the heat pipe.

Several test conditions were selected to investigate the thermal performance of the laboratory prototype. The test is carried out at a range of temperatures, humidity, and airflow rates representing the climate of hot and dry areas in Indonesia.

This experiment evaluates the prototype unit's performance by measuring the effect of one or more of the following variables: intake air temperature, air velocity in and out of the channel, and water temperature in the reservoir.

For this set of tests, four different temperatures (30,35,40, and 45°C) were selected for the intake air. Each inlet temperature, e.g., 30°C, was tested at three different water temperature values, i.e., 15,20, and 25^{o}C. Then, for each temperature inlet and water temperature, e.g., 30°C and 20°C, the fan operated at two different speeds, low speed at 0.9 m/s and high speed at 1.2 m/s.

2.5. Uncertainty Analysis

The performance of evaporative cooling such as wet-bulb effectiveness, dew point effectiveness, and cooling capacity depends on the measuring instrument's accuracy. Moreover, the accuracy of calculating the thermal performance of evaporative cooling is subject to the reading uncertainty associated with the individual instrument and sensor precision. After calibrating the temperature measuring device (the K-type thermocouple connected to the NI-9214 module and the NI cDAQ-9174 data acquisition device), the error associated with ($T_{dc,in}$-$T_{dc,out}$) was ± 0.13, the associated error ($T_{dc,in}$-$Twb_{dc,in}$) is ± 0.13, and the associated error (Tdc, in-$Tdew_{dc, in}$) is ± 0.13.

The effectiveness of evaporative cooling can be estimated in equations (1) and (2). The uncertainties the effectiveness ($S\varepsilon_{WB}/\varepsilon_{WB}$) and ($S\varepsilon_{DP}/\varepsilon_{DP}$) can be determined as in equation (4) and (5).

$$\frac{S\varepsilon_{wb}}{\varepsilon_{wb}} = \sqrt{\left(\frac{S(T_{dc,i}-T_{dc,o}}{(T_{dc,i}-T_{dc,o})}\right)^2 + \left(\frac{s(T_{dc,i}-T_{dc,wb}}{(T_{dc,i}-T_{dc,wb})}\right)^2} \quad (4)$$

$$\frac{S\varepsilon_{dp}}{\varepsilon_{dp}} = \sqrt{\left(\frac{S(T_{dc,i}-T_{dc,o}}{(T_{dc,i}-T_{dc,o})}\right)^2 + \left(\frac{s(T_{dc,i}-T_{dc,dp}}{(T_{dc,i}-T_{dc,dp})}\right)^2} \quad (5)$$

Cooling capacity (Qc) obtained from the evaporative cooling can be estimated in equation (1). With the assumption that air density (ρ) and specific heat (Cp) are constant and there is no change in the ducting area (A), the uncertainties of the energy recovery (SQ_c/Q_c) can be estimated as equation (7).

$$\frac{SQ_c}{Q_c} = \sqrt{\left(\frac{S_V}{V}\right)^2 + \left(\frac{S_T}{T}\right)^2} \quad (6)$$

From the results of calculations using equations (4), (5), and (6) and based on some literature [2, 19], it is found that the uncertainty value for dew point effectiveness ($S\varepsilon_{WB}/\varepsilon_{WB}$) is 7%, wet bulb effectiveness ($S\varepsilon_{DP}/\varepsilon_{DP}$) is 7%, and cooling capacity (SQ_c/Q_c) is 13%.

3. Results and Discussions

Indirect Evaporative cooling integrated with finned heat pipe was tested for different environmental conditions. The tests were carried out at four different temperatures, three different water temperatures, and two different air velocity. **Error! Reference source not found.Error! Reference source not found.** shows some temperature differences at several variations in the inlet air temperature, the water temperature in the reservoir, and the air velocity on the dry channel.

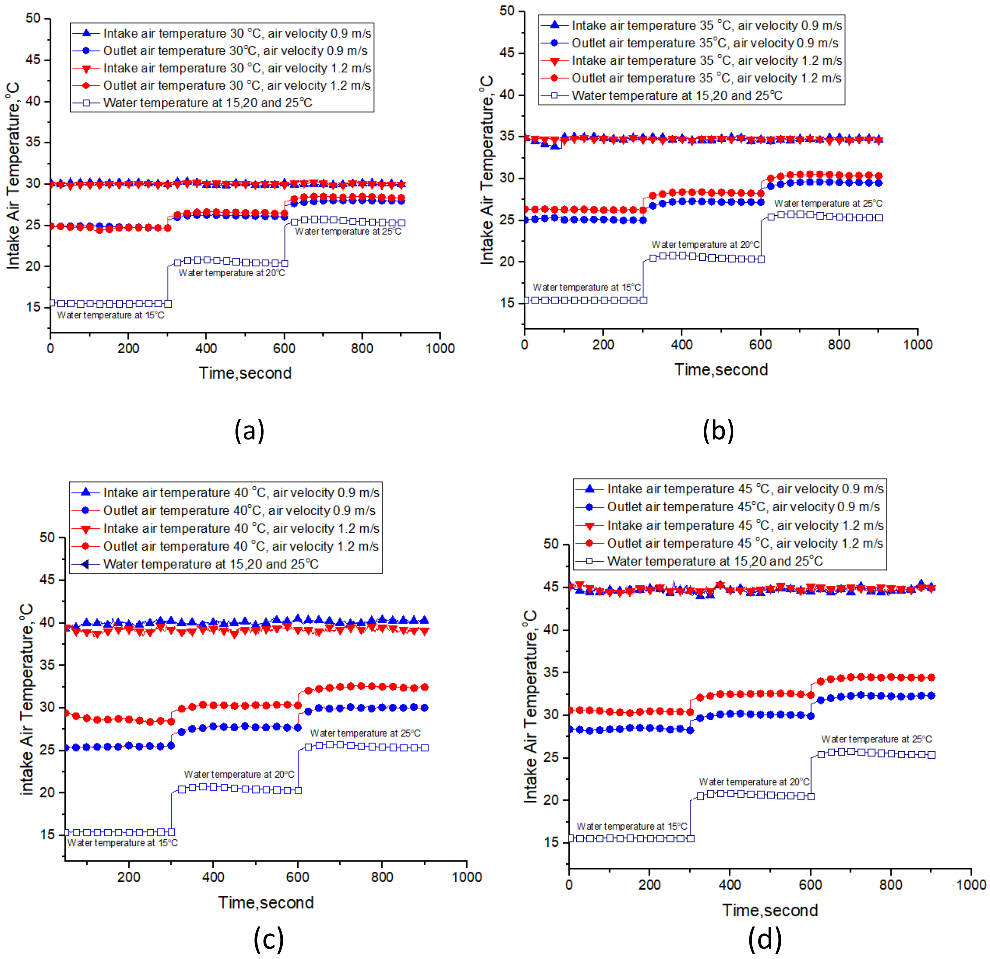


Fig 4. Temperature profile at an intake air temperature of 30 °C, with an airflow rate of 1.2 m/s and 0.9 m/s (a) Temperature profile at an intake air temperature of 35 °C, with an airflow rate of 1.2 m/s and 0.9 m/s (b) Temperature profile at an intake air temperature of 40 °C, with an airflow rate of 1.2 m/s and 0.9 m/s (c) Temperature profile at an intake air temperature of 45 °C, with an airflow rate of 1.2 m/s and 0.9 m/s (d). Scematic figure of Finned heat pipe with *Luffa Cylindrica* / blustru

Figure 4 shows a graph of the temperature profile for several conditions. Figures 4 (a), (b), (c), and (d) show the intake air temperature conditions 30,35,40 and 45°C, respectively. The triangle symbol shows the intake air temperature, and the circle symbol shows the temperature of the outlet air temperature. Whereas the symbol in red indicates a high air velocity of 1.2 m/s, and the blue symbol for low velocity is 0.9 m/s. Each test was carried out at different water temperatures, 15.20 and 25°C.

Error! Reference source not found. is the temperature profile, and the temperature profile has the same tendency. The highest temperature difference occurs when the water temperature is low at 15°C, and the air velocity is low at 0.9°C. This is the same as research conducted in previous studies and several other researchers [8, 19, 20, 25].

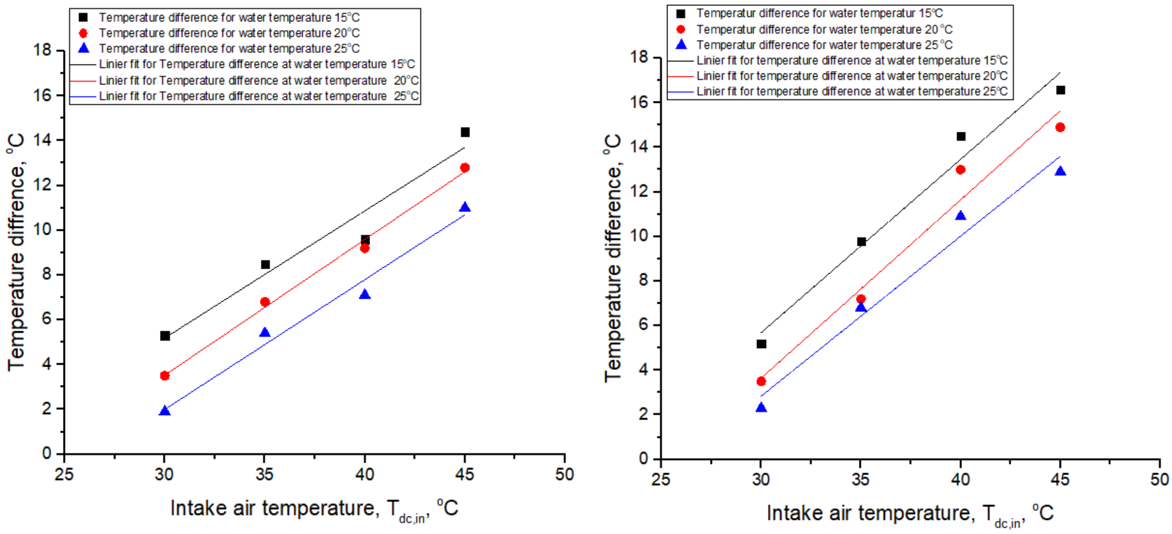


Fig.5. Temperature difference for air velocity at 1.2 m/s (a) Temperature difference for air velocity at 0.9 m/s.

Figure 5 shows the relationship between temperature difference and intake temperature for three different air temperatures, 15, 20, and 25 ° C, indicated by different points. Figure 5 (a) for air velocity 1.2 m/s and figure 5 (b) for air velocity 0.9 m/s.

The temperature difference will increase with increasing intake air temperature and decreasing air velocity from the trend lines shown in Figures 5 (a) and 5 (b). Also, the temperature difference is greatly influenced by the water's temperature dripping on the cooling pad.

Error! Reference source not found. shows the data of indirect evaporative cooling's performance integrated with finned heat pipes using *luffa cylindrica* as cooling media, have ranged from 23-99%. The evaporative cooling performance decreases with increasing water temperature. It is understood that when the water temperature is low, the temperature on the condenser side of the finned heat pipe is also low. If the temperature on the condenser side is low, then the heat absorbed on the finned heat pipe's evaporator side in the dry channel becomes large.

The intake air temperature affects the effectiveness value and cooling capacity. Likewise, with the water temperature (feed water), low water temperature increases the cooling capacity, but it takes a lot of energy to lower the water temperature (feed water). So it is necessary to observe the system performance at a water temperature of 25°C. The results of this study indicate that at 25°C the best system performance occurs at an intake air temperature of 40°C and low air velocity (0.9 m / s), with a wet bulb effectiveness value of 73% and a dew point effectiveness of 53%.

Theoretically, the supply air can be cooled to 100% saturation, but the wet bulb's effectiveness is often limited to 70-80%. This is mainly influenced by the air supply's wet-bulb temperature, the short contact time between the water surface and the air (insufficient wetting of the evaporation pad) [26].

Table 1
Performance result of the system

	High Velocity											
Intake air Temperature, °C		30			35			40			45	
Water Temperature, °C	15	20	25	15	20	25	15	20	25	15	20	25
Wet Bulb Effectivenes,%	71	47	23	77	64	51	67	65	49	80	71	63
Dew Point Effectiveness,%	50	33	17	56	46	37	48	46	35	60	53	46
Cooling capacity, W	105	70	37	167	134	107	186	179	139	277	245	211
Temperature difference, °C	5,3	3,5	1,9	8,5	6,8	5,4	9,6	9,2	7,1	14,4	12,8	11,0

	Low Velocity											
Intake air Temperature, °C		30			35			40			45	
Water Temperature,°C	15	20	25	15	20	25	15	20	25	15	20	25
Low Velocity												
Wet Bulb Effectiveness, %	40	28	18	89	66	62	99	94	73	89	82	70
Dew Point Effectiveness, %	24	17	11	65	48	45	71	70	53	66	60	51
Cooling capacity, W	78	52	34	146	106	100	211	189	155	240	215	185
Temperature difference, °C	5,2	3,5	2,3	9,8	7,2	6,8	14,5	13,0	10,6	16,6	14,9	12,9

4. Conclusion

This study aimed to determine Indirect cooling performance integrated with finned heat pipes and *luffa cylindrica* fibers as a cooling / wet medium.

With the cellulose content found in plants, fiber will quickly absorb water and have good wettability to improve the system's performance. In this study, *luffa cylindrica* fiber was used as a cooling medium. Besides, by taking advantage of the high thermal conductivity properties, heat pipes are used as heat and mass transfer.

From the experimental results with water intake temperature of 30,35,40 45°C and relative humidity of 25-54%, the highest temperature difference is 16.6 °C, the highest cooling capacity is 277 watts, the dew point effectiveness is 71%, and the wet-bulb effectiveness is 99%. From these results, it can be concluded that this system functions well, especially at the intake air temperature of 45°C

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References
[1] Standard, A. S. H. R. A. E. "Standard 55-2013: Thermal Environmental Conditions for Human Occupancy." *ASHRAE, Atlanta, GA* 30329 (2013).
[2] Xuan, Y. M., Fu Xiao, X. F. Niu, X. Huang, and S. W. Wang. "Research and applications of evaporative cooling in China: A review (II)—Systems and equipment." *Renewable and Sustainable Energy Reviews* 16, no. 5 (2012): 3523-3534.
[3] Camargo, Jose Rui, Carlos Daniel Ebinuma, and Jose Luz Silveira. "Experimental performance of a direct evaporative cooler operating during summer in a Brazilian city." *International journal of Refrigeration* 28, no. 7 (2005): 1124-1132.
[4] Hou, Tung-Fu, Yu-Yuan Hsieh, Ting-Le Lin, Yi-Hung Chuang, and Bin-Juine Huang. "Cellulose-pad water cooling system with cold storage." *international journal of refrigeration* 69 (2016): 383-393.
[5] Beshkani, A., and R. E. Z. A. Hosseini. "Numerical modeling of rigid media evaporative cooler." *Applied thermal engineering* 26, no. 5-6 (2006): 636-643.
[6] Chen, Xiangjie, Yuehong Su, Devrim Aydin, Xingxing Zhang, Yate Ding, David Reay, Richard Law, and Saffa Riffat. "Experimental investigations of polymer hollow fibre integrated evaporative cooling system with the fibre bundles in a spindle shape." *Energy and Buildings* 154 (2017): 166-174.

[7] Chen, Xiangjie, Yuehong Su, Devrim Aydin, Yate Ding, Shihao Zhang, David Reay, and Saffa Riffat. "A novel evaporative cooling system with a polymer hollow fibre spindle." *Applied Thermal Engineering* 132 (2018): 665-675.

[8] Sonawan, Hery, Evi Sofia, and Arief Ramadhan. "Assessment of direct evaporative cooler performance with a cooling pad made from banana midrib and ramie fiber." *Smart and Sustainable Built Environment* (2020).

[9] Doğramacı, Pervin Abohorlu, Saffa Riffat, Guohui Gan, and Devrim Aydın. "Experimental study of the potential of eucalyptus fibres for evaporative cooling." *Renewable Energy* 131 (2019): 250-260.

[10] Al-Sulaiman, Faleh. "Evaluation of the performance of local fibers in evaporative cooling." *Energy conversion and management* 43, no. 16 (2002): 2267-2273.

[11] Ghani, Saud, Seifelislam Mahmoud Ahmad Gamaledin, Mohammed Mohammed Rashwan, and Muataz Ali Atieh. "Experimental investigation of double-pipe heat exchangers in air conditioning applications." *Energy and Buildings* 158 (2018): 801-811.

[12] Wang, Haitao, Shunbao Zhou, Zhongshi Wei, and Ren Wang. "A study of secondary heat recovery efficiency of a heat pipe heat exchanger air conditioning system." *Energy and buildings* 133 (2016): 206-216.

[13] Abd El-Baky, Mostafa A., and Mousa M. Mohamed. "Heat pipe heat exchanger for heat recovery in air conditioning." *Applied thermal engineering* 27, no. 4 (2007): 795-801.

[14] Noie-Baghban, Seyed Hossein, and G. R. Majideian. "Waste heat recovery using heat pipe heat exchanger (HPHE) for surgery rooms in hospitals." *Applied thermal engineering* 20, no. 14 (2000): 1271-1282.

[15] Kusumah, A., I. Hakim, Ragil Sukarno, F. Rachman, and Nandy Putra. "The application of U-shape heat pipe heat exchanger to reduce relative humidity for energy conservation in heating, ventilation, and air conditioning (HVAC) systems." *Int J Technol* 10 (2019): 1202.

[16] Sukarno, Ragil, Nandy Putra, Imansyah Ibnu Hakim, Fadhil Fuad Rachman, and Teuku Meurah Indra Mahlia. "Multi-stage heat-pipe heat exchanger for improving energy efficiency of the HVAC system in a hospital operating room." *International Journal of Low-Carbon Technologies* (2020).

[17] Riffat, S. B., and Jie Zhu. "Mathematical model of indirect evaporative cooler using porous ceramic and heat pipe." *Applied Thermal Engineering* 24, no. 4 (2004): 457-470.

[18] Boukhanouf, R., A. Alharbi, O. Amer, and H. G. Ibrahim. "Experimental and numerical study of a heat pipe based indirect porous ceramic evaporative cooler." *International Journal of Environmental Science and Development* 6, no. 2 (2015): 104.

[19] Alharbi, Abdulrahman, Abdulmajeed Almaneea, and Rabah Boukhanouf. "Integrated hollow porous ceramic cuboids-finned heat pipes evaporative cooling system: Numerical modelling and experimental validation." *Energy and Buildings* 196 (2019): 61-70.

[20] Fikri, Bintang, Evi Sofia, and Nandy Putra. "Experimental analysis of a multistage direct-indirect evaporative cooler using a straight heat pipe." *Applied Thermal Engineering* 171 (2020): 115133.

[21] Anisimov, Sergey, Demis Pandelidis, Andrzej Jedlikowski, and Vitaliy Polushkin. "Performance investigation of a M (Maisotsenko)-cycle cross-flow heat exchanger used for indirect evaporative cooling." *Energy* 76 (2014): 593-606.

[22] Wani, Chandrakant, Satyashree Ghodke, and Chaitanya Shrivastava. "A review on potential of Maisotsenko cycle in energy saving applications using evaporative cooling." *Int. J. Adv. Res. Sci. Eng. Technol* 1, no. 1 (2012): 15-20.

[23] Ahmad, Aftab, Shafiqur Rehman, and Luai M. Al-Hadhrami. "Performance evaluation of an indirect evaporative cooler under controlled environmental conditions." *Energy and Buildings* 62 (2013): 278-285.

[24] Duan, Zhiyin, Changhong Zhan, Xingxing Zhang, Mahmud Mustafa, Xudong Zhao, Behrang Alimohammadisagvand, and Ala Hasan. "Indirect evaporative cooling: Past, present and future potentials." *Renewable and Sustainable Energy Reviews* 16, no. 9 (2012): 6823-6850.

[25] Wu, J. M., X. Huang, and H. Zhang. "Theoretical analysis on heat and mass transfer in a direct evaporative cooler." *Applied Thermal Engineering* 29, no. 5-6 (2009): 980-984.

[26] Xuan, Y. M., Fu Xiao, X. F. Niu, X. Huang, and S. W. Wang. "Research and application of evaporative cooling in China: A review (I)–Research." *Renewable and Sustainable Energy Reviews* 16, no. 5 (2012): 3535-3546.