SEMARAK ILMU PUBLISHING

Journal of Advanced Research in Fluid Mechanics and Thermal Sciences

Journal homepage:
https://semarakilmu.com.my/journals/index.php/fluid_mechanics_thermal_sciences/index
ISSN: 2289-7879

Effect of Inlet Air Humidity Control on a Novel Indirect Condensative Cooling Performances in Achieving Air Thermal Comfort

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ARTICLE INFO

Article history:
Received 25 January 2023
Received in revised form 8 May 2023
Accepted 14 May 2023
Available online 28 May 2023

Keywords:
Novel indirect condensative cooling system; air humidity control; air thermal comfort; cooling efficiency; condensation rate

ABSTRACT

The objective of this research is to investigate the effect of controlling inlet air relative humidity on the performance of solid dry pad based indirect condensative cooling (SDP-ICC) system, in an effort to have a better air thermal comfort. The main evaporative cooling parameter such as cooling efficiency, cooling capacity, and temperature drop, condensation rate and energy efficiency ratio would be observed, together with the final dry and wet bulb air temperature and relative humidity in respect to reach the standard air thermal comfort. During the experiment test, the inlet air would be heated respectively using 1.0 kW, 1.5 kW and 2.0 kW heater in a climate chamber before it passed through to the solid dry pad, to be cooled indirect condensatively. The air velocity would be set on 11.3 m^3/. The test results indicate that to achieve an air thermal comfort significantly in the evaporative and or condensative cooling system, the air should need to be treated with more than one thermal process, rather than cooling only. In this research, the SDP-ICC has only achieved the air thermal comfort in respect to its relative humidity of 67.3%, 55.65% and 44.3% respectively for heating capacity of 1.0 kW, 1.5 kW and 2.0 kW. The highest SDP-ICC cooling performance has been achieved on 1.5 kW heating capacity, in which it has reached 1.9 kW, 1.83, 3.4^{o}C and 0.237 m^3/hr respectively for cooling capacity, energy efficiency ratio, temperature drop and condensation rate. It can be concluded that by heating the inlet air relative humidity in evaporative and or condensative cooling system, it can be resulted the product air which has met the standard air thermal comfort.

1. Introduction

The distinctive climatic area in several country would provide a significantly fluctuative different on surrounding environmental air temperature and relatif humidity which would probably affect human thermal comfort. Indonesia has an average air temperature and relative humidity respectively around 33^{o}C and 80% in hot session. However other country like China, it has absolutely distinctively different climate condition, there was an area or city which has a hottest environment with quite high air temperature and low air relative humidity about 30% [1,2]. In contrast other city has quite

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https://doi.org/10.37934/arfmts.106.2.1421

high air relative humidity about 70%, as it located in hot summer and cold winter region [3-6]. In those different thermal environment, when people visit from low relative humidity area to high relative humidity area, they would feel uncomfortable with the high humidity environment [7]. On the other hand, in the case of building envelope maintenance and management, it is important and essential to improve occupant comfort and satisfaction, also reduce energy losses. The building should be provided with comfortable and healthy environment without any building defects [8]. It was a global concern that the demand for thermal comfort cooling in the building should meet the Sustainable Development Goals (SDGs), specifically SDG 7, encapsulated by Vivek and Balaji [9]. Regarding the climates influences on the use of such cooling system, Sprecher and Tillenkamp [10] analysed the suitability use of cooling tower integrated Thermally Activated Building System (TABS) for different climates in Zurich, Switzerland. It was found that the performance of TABS is not based on the behaviour and performance of coupling device, but highly depends on the climatic conditions, operating method and materials and its properties. Another research by Cholewa *et al.,* [11] which is experimentally analysed the transfer coefficient of radiant floor cooling using TABS system and under varying the surface heat emitted values in a climatic chamber. It was found that a range of 10% to 30% of the heat transfer coefficient value can be achieved on the radiant floor based on the occupant's position. It also concluded that the performance is related to the climatic conditions of local regions. Meanwhile, research in different climatic region in India by Samuel *et al.,* [12] has found that the TABS coupled with cooling tower (CT) has achieved a higher cooling performance in dry climates compared to humid zone, in which, floor and roof cooling could reduce operative temperature about 9.5°C in hot and dry region, while it would only reduce 4.4°C in humid area. Many researchs has been conducted to improve the TABS performance for humid climatic conditions. Teitelbaum *et al.,* [13] has investigated the indoor thermal comfort range and possibilities of condensation on the radiant panel in warm and humid region. It was achieved that the predicted main vote (PMV) in the daytime has maintained at 1.2 and 0.8 during night hour operation at constant water supply temperature of 25°C. It also can be concluded that no condensation has been occurred in radiant panel for 25°C water temperature. Zhao *et al.,* [14] has been investigated the response time of changing indoor conditions of the radiant embedded floor, such as concrete floor and low density floor. It found that the concrete core floor has give response time in about 1-3 hours, while the light floor only 10-20 min. On the other hand, Derakhtenjani and Athienitis [15] found that the panel embedded and low thermal mass radiant cooling system have a faster response time to changing indoor conditions, compared to high thermal mass radiant cooling system. Other researchs has investigated the thermal response characteristics of the radiant cooling system. Ning *et al.,* [16] investigated the radiant cooling system's thermal response characteristics by varying their configurations and boundary conditions. It concluded that the thermal response behaviour of the radiant cooling system has significantly influenced by its pipe spacing, properties of building material and panel thickness. Similarly, Wang *et al.,* [17] has conducted simulation investigation for the influence of pipe material conductivity and water supply inlet velocity to the effectiveness of a radiant cooling system. The simulation result shows that the radiant cooling system pipe's conductivity has a great impacts to its water supply inlet velocity. Radzai *et al.,* [18] experimentally investigated the effectiveness of the radiant ceiling panel cooling system in hot and humid climatic conditions. It recommended that the supply of chilled water flowrate ranged from 0.01 $m^3/h/m^2$ to 0.04 $m^3/h/m^2$ and water temperature ranging between 14°C and 20°C could prevent the condensation risk.

Some studies has indicate that the evaporative cooling system has been provided quite significant cooling performance within low energy consumption and low environmentally impact. This cooling system was meet to Indonesia's government policy to reduce the uses of fossil fuel energy, as this cooling system has only required low energy input. However, according to Indonesia's government policy in renewable energy, it is targeted that the application of renewable energy should be 23% out of total energy by 2025 [19]. Furthermore, for evaporative cooling studies, Peng *et al.,* [1] has been studied the application of evaporative cooling system on the clothing workshop which is located in hyperthermia and humidity conditions with outdoor temperature 35^{o}C. It results that the direct evaporative cooling system could provide a better cooling performance compare to traditional mechanical refrigeration system [1]. Al-Sulaiman [2] has conducted a special test to investigated the cooling performance of date palm fiber, jute and luffa as a wet cooling medium in evaporative cooling system. It results that jute has the highest cooling efficiency of 62.1%, then 55.1% for luffa fiber, and 38.9% for date palm fiber, compare to the reference commercial pad with cooling efficiency of 49.9% [2]. The LDCS has been equipped with nanofluid fed pipe implant in desiccant pad in shell and tube configuration. The results showed that for 0.01-0.04 volume concentration of Al_2O_3-W, Fe_3O_4-W and ZnO-W nanofluids respectively, there would be improvement for convective heat transfer coefficient of 7.20-14.40%, 6.20-12.30%, and 5.50-9.10%. On the other hand, the energy effectiveness has been increased to 27.50-50.10%, 25.01-40.10% and 24.00-32.02% for volume fractions for 0.01-0.04 of ZnO, Fe_3O_4, Al_2O_3 respectively [4]. Kulkarni and Rajput [5] has developed a study to investigate the performance of three different cooling pad shapes and material. It has been used rectangular, cylindrical and hexagonal pad shapes with rigid cellulose and corrugated paper, high density polythene packing and aspen fiber for evaporative cooling system, within air velocities of 0.75 to 2.25 m/s and inlet air temperature of 39.9^{o}C, relative humidity of 32.8%. It revealed that the hexagonal shaped pad with aspen material has achieved the highest saturation efficiency of 91%, followed by cylindrical and rectangular shape pads with saturation efficiency of 90% and 89% respectively [5]. However, evaporative cooling system which has a public great demand, as it required low operating cost and easy maintenance, does not meet when it use in the country with high humidity. It decreased the air temperature and at the same time the air humidity increase [20]. Furthermore for indirect evaporative cooling (IEC), many studies has been reported. Heidarinejad *et al.,* [6] studied the performance of two-stage indirect/direct evaporative cooling within the various simulated climate condition. Results show that the IEC stage effectiveness has varies 55-61% and for the IEC/DEC system has achieved effectiveness range of 108-111% and provided 60% power consumption compare to vapor compression cooling system [6]. Xu *et al.,* [7] has investigated the performance of indirect evaporative cooling using various fabrics weaved within various fiber as an irregular fiber and compared to Kraft paper. It resulted that the higher moisture wicking ability of 171-182%, higher diffusion ability of 298-396%, and higher evaporation ability of 77-93% has been obtained by most of textile fabrics compare to the Kraft paper. Sofia *et al.,* [20] has studied indirect evaporative cooling performance by utilizing a better wettability of the luffa cylindrica fiber as a cooling media and high thermal conductivity heat pipe as a heat transfer media. It result the highest air temperature drop of 16.6^{o}C, the highest cooling capacity of 277 watts, the dew point effectiveness of 71% and wet-bulb effectiveness of 99%. Fikri *et al.,* [21] has investigated the performance of a multistage direct-indirect evaporative cooler using a heat pipe. It was found that the largest temperature decrease has been achieved when evaporation occurred during the first stage heat pipe with 0.8 m/s air flow rate and 45^{o}C of inlet air temperature. Another research regarding multistage evaporative cooler has been carried out with evaporative cooling system consists of two-stage indirect-direct evaporative cooling system (IDECS) that integrated with a solid desiccant dehumidification system (SDDS). The experiment result shows that the indirect ECS and direct ECS can provided the sensible heat and adiabatic cooling, and when it integrated with SDDS, it can reduce energy requirement for energy saving about 54-82% compared to conventional cooling system [22,23]. Pandelidis *et al.,* [24] conducted experimentally analysis the performance of a cross-flow dew point evaporative cooler. The result shows that when air moisture content is taking about 25g/kg, it obtained the cooler wet bulb efficiency of 90%-110% and the dew point efficiency of 63%-68%. Furthermore, Zhan *et al.,* [25,26] has compared cross-flow heat exchangers and counter-flow heat exchanger within the same geometric dimension and operating condition. It found that the cross-flow dew point indirect evaporative cooler has obtained the wet bulb efficiency of 116%, while the counter-flow dew point indirect evaporative cooler has achieved dew point efficiency about 80%-90%. Duan [27] and Duan *et al.,* [28] has designed and developed a counter-flow dew point indirect evaporative cooler. It examined the inlet, outlet and outlet air temperature, and also humidity and flow rate of the cooler system. The result showed that the dew point indirect evaporative cooler has obtained the wet bulb efficiency of 55%-106% within the energy efficiency ratio of 2.8-15.5. Xu *et al.,* [29-31] has developed an ultrahigh-efficiency counter-flow dew point indirect evaporative cooler and it examined under standard dry test conditions. The test under the dry bulb temperature of 37.8^{o}C and wet bulb temperature of 21.1^{o}C has reached the cooler wet-bulb efficiency of 114% and dew point cooling efficiency of 75%. When the test is conducted with working air and total air ratio of 0.364, the dew point indirect evaporative cooler has obtained the highest COP of 52.5. Most of those study above has been done without controlling the inlet air humidity yet. When using the direct evaporative cooling, the outlet air humidity would be increased, meanwhile it would be constant in indirect evaporative cooling. So then, in this research, the inlet air would be controlled by pre-heating the inlet air using 1.0 kW, 1.5 kW and 2.0 kW heater. It expected could decrease the inlet air humidity, before it condensed by indirect condensative cooler at the second stage and provide the product air that meet the standard air thermal comfort.

2. Methodology

2.1 Material

The dew point indirect evaporative cooling is constructed by dry ice based solid dry pad, mechanical fan which produces three air velocity level of 4.8 m/s, 9.5 m/s, and 11.3 m/s and a 100 cm length air channel. Solid dry pad is made of 20 cube pipes in a staggered arrangement which is fed with dry ice. The solid dry pad construction can be seen as following Figure 1.

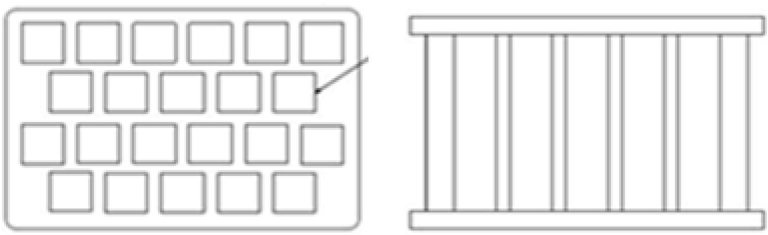

Fig. 1. Solid dry pad

2.2 Method

The solid dry pad is fed by dry ice and placed in the middle of isolated air channel. Mechanical fan is regulated to produce air velocity of 4.8 m/s (V1), 9.5 m/s (V2) and 11.3 m/s (V3). The ambient air would be flowing to the solid dry pad within pad surface temperature of 7^{o}C. The temperature would be recorded as ambient air (TdB1,TwB1), heater inlet air temperature (TdB2, TwB2), pad inlet air temperature (TdB3,TwB3) and pad outlet air temperature (TdB4,TwB4) as shown in Figure 2. There would be twice repetition for every air velocity. When the ambient air (T2) have contact with the heater surface, the air would be heated and dehumidified (T3). The heated and dehumidified air would be passed through the solid dry pad. The air then would be cooled and dehumidified (T4). On the other hand, the ambient air moisture would be condensed as pad surface temperature has a far lower temperature than wet bulb temperature of the ambient air, this would significantly reduce ambient air moisture content. The more the ambient air moisture condensed, the lower the moisture content of the outlet air dry bulb temperature. This would enlarge the temperature different between the inlet and outlet dry bulb air temperature, and then would improve cooling efficiency and cooling capacity of the evaporative system. The experiment set-up could be showed in Figure 3.

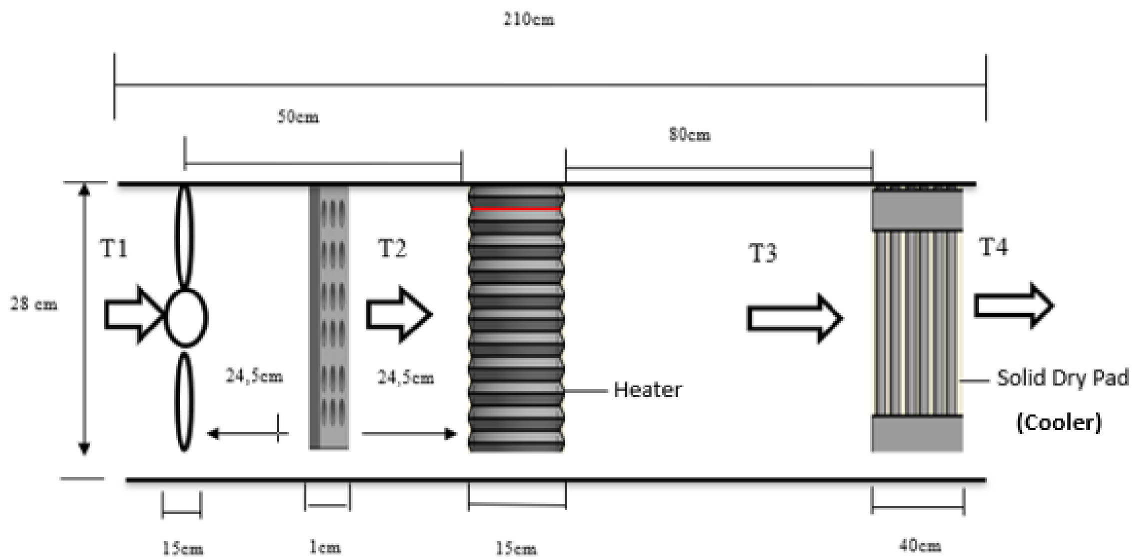

Fig. 2. Experimental arrangement

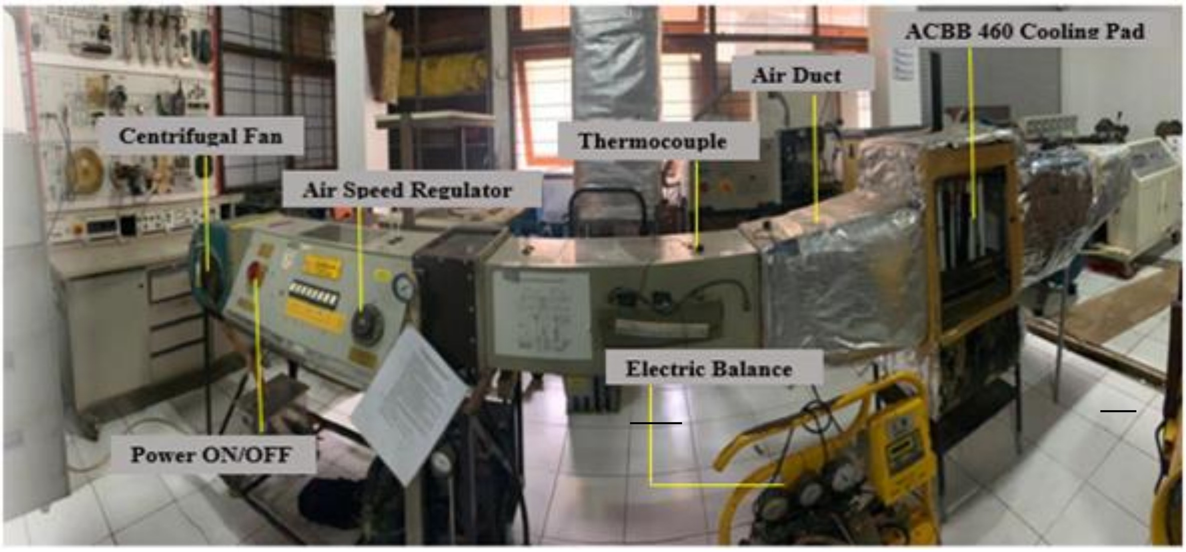

Fig. 3. Experimental set-up

2.3 Experiment Formulas

In this study, it would be assessed the performance of dew point indirect evaporative cooling, included cooling efficiency (ϵ), cooling capacity (qs) and condensation rate (Er) which can be determined within the formulas as follow

$$\mathcal{E} = \frac{TdB1 - TdB3}{TdB1 - TwB1} \quad (1)$$

where ϵ denote cooling efficiency; TdB_1 is inlet air dry bulb temperature (°C); TdB_3 denote outlet air dry bulb temperature (°C); TwB_1 is inlet air wet bulb temperature (°C).

$$qs = Q.\rho.Cp\ (T_{dB,i} - T_{dB,o}) \tag{2}$$

where qs denote cooling capacity (kW); Q denote air volume flowrate (m^3/s); ρ is air density (kg/m^3); Cp denote air specific heat (kJ/kg.K); $T_{dB,i}$ is inlet air dry bulb temperature (°C); $T_{dB,o}$ denote outlet air dry bulb temperature (°C)

$$Er = \frac{(mf - mi)/\rho w}{t} \tag{3}$$

where Er is condensation rate (m^3/hr); mf is final condensate mass (kg); mi denote initial condensate mass (kg), ρ water is water density (kg/m^3); t is time required (hr).

3. Results

Pre-heating the ambient air with heater capacity vary before it enters the solid dry pad cooler, could provide higher cooling performance results. As it shown in Figure 4, heating the ambient air with 1.5 kW heater before enters the pad cooler has provided higher cooling capacity, energy efficiency ratio and dry bulb temperature drop of 1.9 kW, 1.83 and 3.4°C respectively. It can be seen that the higher cooling capacity has been achieved as it produces higher dry bulb temperature drop. Then the higher cooling capacity would increase energy efficiency ratio. The higher cooling capacity has been resulted as the higher dry bulb temperature drop occurred. When the inlet air to be heated, the air temperature and humidity would be increased and then sharply drop to a lower temperature when it passed through to the condensative cooler. On the other hand, lower cooling efficiency has been achieved as a result of a higher wet bulb temperatur inlet produced by heating the ambient air using 1.5 kW heater, inwich even higher when using 2.0 kW heater.

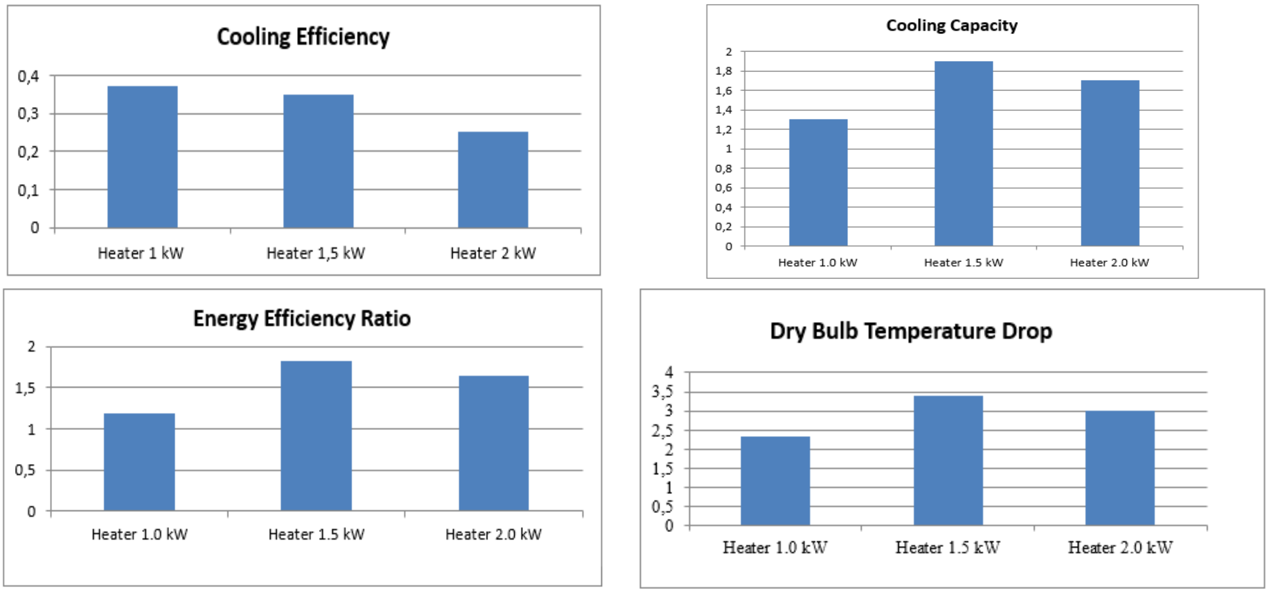

Fig. 4. Experiment results

On the other hand, the lowest cooling performance has been achieved by pre-heating the ambient air using the lowest heater capacity. This has been caused as this pre-heating process could only produced the lowest dry bulb temperature drop. Consequently, it would decrease the cooling capacity and the energy efficiency ratio as well. However, this pre-heating has been provided the highest cooling efficiency as it produced the lowest inlet wet bulb air temperature before it cooled and produced the lowest dry bulb product air temperature at the cooler outlet.

4. Conclusion

This study has been revealed cooling performance characteristic of pre-heated the ambient air before it cooled to the solid dry pad cooler. As a result, it can be concluded that by pre-heating the ambient air using a proper heater capacity before it cooled, has been produced higher cooling performance of solid dry pad based - indirect condensative cooling system. It achieved a lower temperature and relative humidity product air which is met the standard air thermal comfort.

Acknowledgement
The authors are grateful to Lembaga Penelitian dan Pengabdian Kepada Masyarakat Universitas Udayana (UNUD) for their financial support in the completion of this research.

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