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APPLICABILITY OF DIRECT EVAPORATIVE COOLING FOR LOW-RISE RESIDENTIAL BUILDING IN SURABAYA

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ABSTRACT

Direct evaporative cooling has been widely known as the passive design strategy for ameliorating the thermal conditions of building in hot-dry climates. In the recent past, the strategy has been extended to warm-humid climates. The scope varies from exploring the system to applying the method to buildings. Few studies have been conducted regarding its application to a multi-story residential building. In response to this gap, the present study will explore the strategy's applicability to the typical low-rise housing in Surabaya and analyze its environmental consequences. Simulation is used as the primary method for the analyses. Results of the study show that direct evaporative cooling is applicable in warm-humid tropics, but with some notes regarding the increase of air humidity. The dimensional properties of the cooling pad can be arranged to minimize the increased humidity.

Keywords: Direct evaporative cooling; residential building; thermal comfort; warm-humid tropic.

INTRODUCTION

The energy crisis has forced designer and scientist to come up with ideas for the building that should be able to provide comfort and at the same time consumes less energy. Many passive cooling strategies have been offered to meet the objective, one of which is evaporative cooling. The strategy is widely used in a hot and dry climate, as it can decrease air temperature and add some moisture to the air. This strategy particularly fits with the climate as it can restore thermal comfort by decreasing air temperature and at the same time also increasing air humidity and leaving the air less dry. Vernacular houses in the regions adopt this method and manifest it in the design of the wind tower ventilation system of the building and fountain in the middle of the courtyard house (Fernandes & Silva, 2007; Obeidat et al., 2021; Taleghani & Tenpierik, 1986). These two building components can lower internal air temperature and provide favorable outdoor air conditions. Besides, techniques such as desert cooler, passive downdraught, and roof surface evaporative cooling in hot-dry environments are also proven to reduce energy consumption and environmental damage (Kamal, 2012, 2013).

As distinct to those strategies found in the hot-dry climates, efforts of passively cooling a building in warm-humid tropics rely mainly on incorporating natural ventilation techniques. The strategy is believed to be suitable for combating heat and reducing air humidity in the building. Aside from providing fresh air for the building, natural ventilation is used to flush the warm air inside the building and replace it with cool external air. It is also used to encourage the physiological cooling effect on the body. Vernacular and some modern buildings have implemented this technique (Prianto et al., 2000; Wahab et al., 2019; Wahab & Ismail, 2012). Many studies have acknowledged its success in reducing heat gain (Aflaki et al., 2014; Soebarto & Handjarinto, 1998; Tantasavasdi et al., 2001).

Attempts have been made to explore the applicability of evaporative cooling techniques under warm-humid climates. The evaporative cooler package was developed using a physical model to decrease internal space temperature and restore thermal comfort (Mohammad et al., 2013; Suryana et al., 2014; Susila et al., 2019). Water spray was used to promote evaporative cooling over a metal roof surface and reduce indoor air temperature (Kindangen et al., 2015; Kindangen & Umboh, 2017). An indoor wall fountain using evaporative cooling principles is offered to reduce indoor air temperature (Seputra, 2018). The technique is also proposed for the room of a building (Yunianto, 2018), buildings that use passive downdraught evaporative cooler (Gokarakonda & Kokogiannakis, 2014), and building facades (Suwannapruk et al., 2020). These studies generally dealt with the physical model to investigate the evaporative cooler's performance, and some aimed to analyze its applicability to internal space and building elements. The finding suggests that the techniques can be applied to this climate as the strategy can reduce air temperature. However, it should be noted that care should be taken, primarily related to the increase of the air humidity resulting from the adoption of the technique (Gokarakonda & Kokogiannakis, 2014; Mohammad et al., 2013).

The present study explores the applicability of DEC in low-rise residential housing in a warm-humid environment. As the above review shows, it aims to extend its applicability to this building type, which is relatively limited. It is also directed to analyze the influence of the increase of air humidity on thermal comfort, which was rarely discussed in the previous studies. The low-rise residential housing in Surabaya is chosen as the subject of the application. The underlying consideration is that the technique can offer an affordable passive cooling system for the occupant, who generally belongs to the middle-income group. A previous study stated that the technique is relatively low cost and highly efficient (Mehere et al., 2014). Moreover, the proposed strategy is intended to support the building energy efficiency agenda of the city.

DIRECT EVAPORATIVE COOLING FOR BUILDING

Evaporative cooling is categorized as one of the passive cooling techniques (Chetan et al., 2020; Kamal, 2012; Santamouris & Asimakopoulos, 2013). It is designed to provide cooling for buildings without energy-based equipment, mechanization, or minimum energy utilization. It can also be seen as natural cooling because the technique uses a natural heat sink to contain excess heat released from internal spaces (Santamouris & Asimakopoulos, 2013). This technique allows hot outdoor air to come into contact with water droplets or wetted porous materials, resulting in evaporation. Two types of evaporative cooling techniques are generally utilized in buildings (Santamouris & Asimakopoulos, 2013). The first is DEC, which produces cooled air by extracting outdoor hot air and channeling it through a cooling pad. The process will decrease the air temperature and, at the same time, increase the relative humidity. The second is indirect evaporative cooling (IEC), which changes hot outdoor air into cool air involving two processes. It first mixes hot outdoor air with the resulting cooled air from the direct evaporative process in a heat exchanger and then blows it into internal space. This technique can reduce moisture content in the air, which is intrinsic in the case of DEC.

As previously mentioned, DEC is commonly used to cool buildings in hot-dry climates and has been tried in warm-humid climates. Many studies have been conducted on various topics (Mehere et al., 2014). Some explored the materials used for the cooling pad (Suryana et al., 2014; Susila et al., 2019). Some investigated its application to buildings (Kindangen et al., 2015; Kindangen & Umboh, 2017; Mohammad et al., 2013; Seputra, 2018; Yunianto, 2018). The studies that focus on exploring cooling pad materials found that different properties of the cooling pad, i.e., materials, area, and thickness, could result in different performances (Suryana et al., 2014; Susila et al., 2019). Most of the studies agreed that cellulose pad is the most effective material. High system performances were also noted if the cooling pad's area is large and thick. Incorporating an evaporative cooling system on a metal roof resulted in decreasing roof surface temperature, but no notable reduction in indoor air temperature was observed (Kindangen & Umboh, 2017). The indoor wall fountain only has a negligible impact on air temperature reduction and increases air humidity substantially (Seputra, 2018).

In the case of buildings located in the warm-humid regions, the technique is also required to limit the increased relative humidity. In this regard, previous studies recommend the use of other complementary techniques. The most basic proposal combines DEC with natural ventilation (Yunianto, 2018). This recommendation can improve comfort and is relatively affordable. Other proposals are a desiccant-dehumidifier (Mujahid Rafique et al., 2015; Suwannapruk et al., 2020) and solar assisted dryer (Abaranji et al., 2020; Hussain et al., 2020). A combination of direct and indirect evaporative cooling was also put forward to tackle the humidity problem (Darmawan et al., 2021). The last three efforts are not simple, require more resources, and can be expensive.

METHODOLOGY

The thermal condition of the building in the present study is simulated using Design Builder software. The tool enables DEC to be simulated, and a wide range of outputs such as air temperature, relative humidity, and ventilation rate can be analyzed. The typical five-floor residential building developed by the local government of Surabaya is used as a model where DEC is applied (Figure 1a). The residential block consists of two rows of housing units connected by corridors that form two inner courtyards (Figure 1c). For the simulation, a unit located on the fifth floor of the building is considered. This decision allows the model to have more surfaces exposed to the heat, including the roof. It, therefore, can represent the criticality of the unit from the thermal design standpoint. The study uses a studio unit to represent the housing unit (Figure 1b).

The simulation is set on two critical months, i.e., January represents the coolest month and October the warmest month. Scenario for the simulation is organized in Table 1. below.

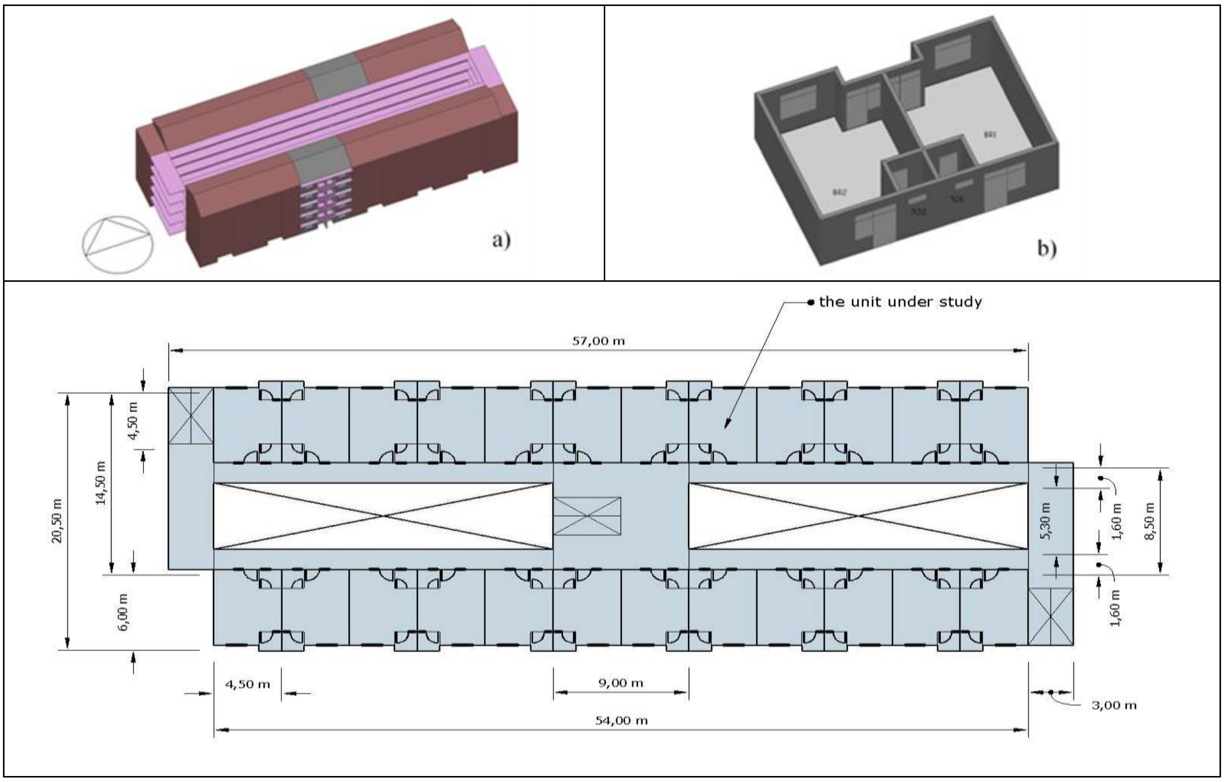

Fig. 1 Model of typical residential housing used for the simulation: a) housing block; b) housing unit; c) housing layout

Table 1. Schedule of the simulation

No.	Applied Techniques	Code of the Unit
1.	Natural ventilation only	NV5U
2.	Direct evaporative cooling, with different cooling pad properties:	
	a. Area = 0.6 m2; thickness =0.2 m	D625U
	b. Area = 0.6 m2; thickness =0.1 m	D615U
	c. Area = 0.4 m2; thickness =0.2 m	D425U
	d. Area = 0.4 m2; thickness =0.1 m	D415U

Analysis of environmental parameters includes air temperature dan relative humidity. The extent to which these two environmental parameters contribute to thermal comfort is analyzed using a bioclimatic chart. Olgyay initially developed the chart (Olgyay, 1972) and Koenigsberger et al. adapted it for tropical climate (Koenigsberger et al., 1973). The area on the chart in which the simulated thermal conditions are scattered relative to the comfort zone will determine the technique's applicability and how other means of cooling, such as that air velocity, can be included to restore indoor comfort. The required number of air velocities can be indicated on the chart, and the value is calculated using a formula proposed by Aynsley (Cowan, 1991). The formula is given below:

$$WSc = 0.15\,[DBT - 27.2 + (0{,}56 \times (RH-60)/10)]\ \text{m/s} \qquad (1)$$

Where:

WSc = wind speed for restoring thermal comfort (m/s)
DBT = dry-bulb temperature (^oC)
RH = relative humidity (%)

RESULTS AND DISCUSSIONS

The results of the study are presented in two parts. The first is thermal conditions in the housing unit, and the second is the contribution of DEC to comfort.

Thermal Condition in the Housing Unit

Thermal conditions of the housing unit, which were simulated for two sets of scenarios defined above, are illustrated in Figures 2 and 3. Under a naturally ventilated setting, indoor air temperatures inside the housing unit are generally lower during the day and higher during the night than the outside air temperature. The condition can be observed both in January's coolest month and October's warmest month. The results indicate that natural ventilation can be adopted to cool the building in warm-humid conditions because it can reduce heat inside the building, especially during the day. The increase in air temperature during the night is thermally tolerable.

Figure 2 also shows that introducing DEC in the building can even lower the air temperature during the two critical months. It can be seen from the figure that the air temperature can reduce up to 3 K during the day as compared to the outdoors. This reduction is around 2.5 K lower than applying the natural ventilation technique. In the case of natural ventilation, the minimum air temperature is 27.3 °C, and the maximum is 32.7 °C in the coolest month. The minimum and maximum values in the warmest month are 28.9 °C and 33.6 °C (Table 2). In the case of DEC, the range of air temperatures is between 27.3 °C and 30.6 °C in the coolest month and 28.1 °C and 31 °C in the warmest month.

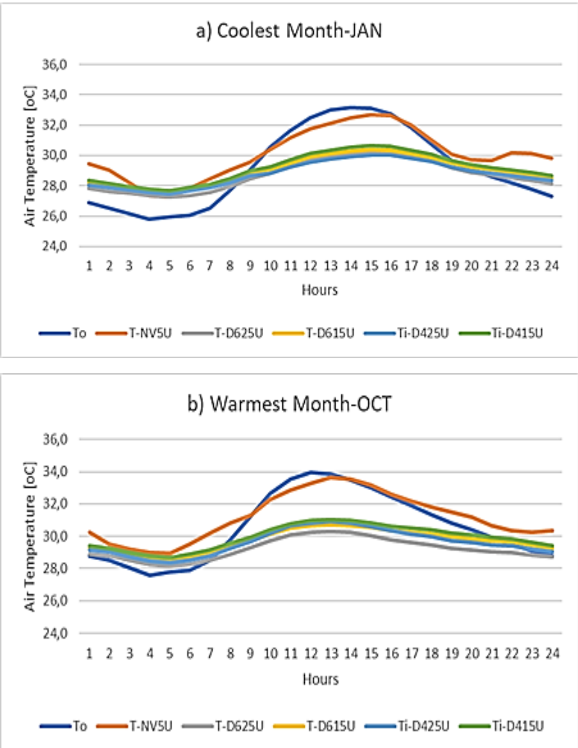

Fig. 2. Profile of air temperature inside the housing unit

The influence of the different sizes of evaporative cooling pads on the indoor air temperature is observed in the figure, but the differences are slight. The range of the differences is less than 1 K in both the coolest and warmest months (Table 2). It is also found that the higher the area and the thicker the cooling pads, the larger the temperature reduction tends to be attained. The highest reduction is observed on D625U (0,6 m2 pad's area and 0.2 m thick), and the lowest is on D415U (0,4 m^2 and 0.1 m). Similar performance is found in D615U (0.6 m^2 and 0.1 m) and D425U (0.4 m^2 and 0.2 m), in which D615U is the highest and D425U the lowest. The techniques' ability to lower the air temperature inside the building is also found in the previous studies (Mohammad et al., 2013).

Figure 3 shows that ventilation and evaporative cooling strategies can reduce relative humidity from midnight to the morning compared to outdoors. However, the opposite is valid during the day. Compared with external conditions, average relative humidity due to natural ventilation may decrease by about 3.8%. Conversely, the condition increases to 5.9% due to DEC during the coolest month (Figure 3a and Table 2). However, the profile of the natural ventilation technique (60.7-84.6%) is relatively close to the external relative humidity (57.9-93.6%). The minimum and maximum values of DEC, by contrast, tend to space apart when compared with those of outdoors, i.e., 14.6% and 7.4% deviations in terms of minimum and maximum values, respectively. Looking at the simulation results in the warmest month of October (Figure 3b and Table 1), the profile and values of DEC are different. Most of the time, relative humidity resulting from the DEC is generally higher (65.2-84.5%) than the results of the natural ventilation (50.6-78.4%) and the outdoor (49.5-84.7%). They almost coincide with the outdoor from midnight to the morning, and the remaining times are generally higher. The differences in terms of minimum and maximum values between the outdoor and DEC are 15.7% and 0.2%, respectively, and the average value is 11%. From the standpoint of relative humidity, the influence of DEC is more pronounced in the warmest month, especially during the daytime. The high air temperature that generally occurs during the day and predominates thermal conditions in the warmest month accelerates the evaporation process and thus increases the presence of moisture in the air.

Table 2. Indoor thermal conditions in the housing unit

		Indoor Thermal Conditions			
		Coolest Month		Warmest Month	
		RH	T	RH	T
Outdoors	Avg.	74,8	29,2	65,4	30,5
	Min.	57,9	25,8	49,5	27,6
	Max.	93,6	33,2	84,7	33,9
NV5U	Avg.	71,0	30,1	64,5	31,2
	Min.	60,7	27,3	50,6	28,9
	Max.	84,9	32,7	78,4	33,6
D625U	Avg.	80,7	28,7	76,4	29,2
	Min.	76,1	27,3	68,6	28,1
	Max.	86,2	30,2	84,5	30,3
D615U	Avg.	78,6	29,0	74,0	29,7
	Min.	73,7	27,6	65,3	28,6
	Max.	84,3	30,4	82,6	30,7
D425U	Avg.	80,2	28,8	73,8	29,6
	Min.	76,2	27,5	65,2	28,4
	Max.	85,0	30,0	82,8	30,9
D415U	Avg.	77,6	29,2	72,7	29,9
	Min.	72,1	27,7	63,7	28,7
	Max.	83,8	30,6	81,7	31,0

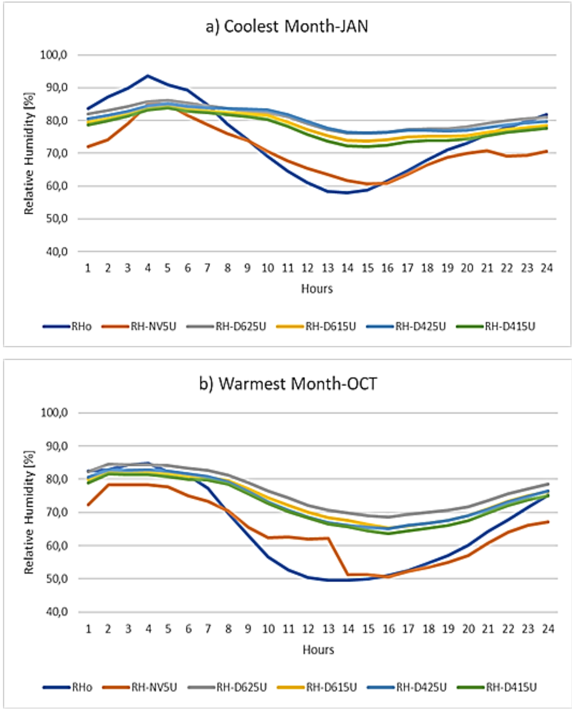

Fig. 3. Profile of relative humidity inside the housing unit

Contribution of the Strategy to Comfort

Applicability of DEC to residential housing under warm-humid conditions is evaluated based on its contribution to comfort and explored concerning other strategies. The first is natural ventilation (Figure 4), and the second is variations of DEC property, i.e., area and thickness of the cooling pad (Figures 5 and 6). From the bioclimatic chart, it can be seen that the indoor air conditions are all outside of the comfort zone (Figure 4). It scattered within a temperature range between 27.3 and 33.6 ºC, and relative humidity between 50.6 and 84.9%. However, if air velocity is introduced between 0.2-1 m/s (see Figure 7 below), thermal comfort in the housing unit can be restored. This introduction will enlarge the comfort zone to cover indoor air conditions. Previous studies emphasizing air velocity analysis inside a housing unit in a warm-humid climate found that 0.2 m/s of air velocity is rarely detected in the housing unit under standard ventilation settings (Aflaki et al., 2014). In the light of this study, it can be said that the opportunity to provide comfort using natural ventilation will be significantly reduced in the housing unit under study. Only a tiny portion of the time will be comfortable with low air velocity assistance, which is in the warmest month.

The contribution of DEC cooling to comfort is illustrated in Figures 5, 6, and 7. A direct evaporative cooler with a 0.6 m^2 cooling pad area can reduce air temperature, as previously stated, yet the relative humidity can still be considered high (Fig. 5). The internal air conditions are all scattered outside the comfort zone. In the case of the cooling pad of 20 cm thick (DEC-625U), the air temperature range is between 27.3-30.3 ºC, and relative humidity is between 68.6-86.2%. In the case of a pad with 10 cm thickness (DEC-615U), the values range from 27.6-30.7 ºC and 65.3-84.3% for air temperature and relative humidity, respectively. An aid of air velocity is required to induce physiological cooling. Like that applied for the natural ventilation strategy, at least an air velocity of 0.2 to 0.6 m/s is needed (Fig.7). During the coolest month, most of the time, the unit requires an air velocity of 0.2-0.5 m/s and 0.3-0.5 m/s during the warmest month. A low thermal condition during the coolest month and high thermal conditions in the warmest month contribute to the requirements.

Reducing the thickness of the cooling pad does not significantly affect the air temperature and only slightly reduces the relative humidity. However, the introduction of the thinner cooling pad can still be considered better than the thick one, especially from the comfort provision point of view.

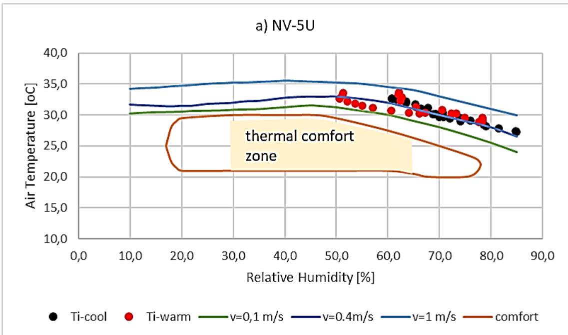

Fig. 4. Comfort analysis for natural ventilation strategy

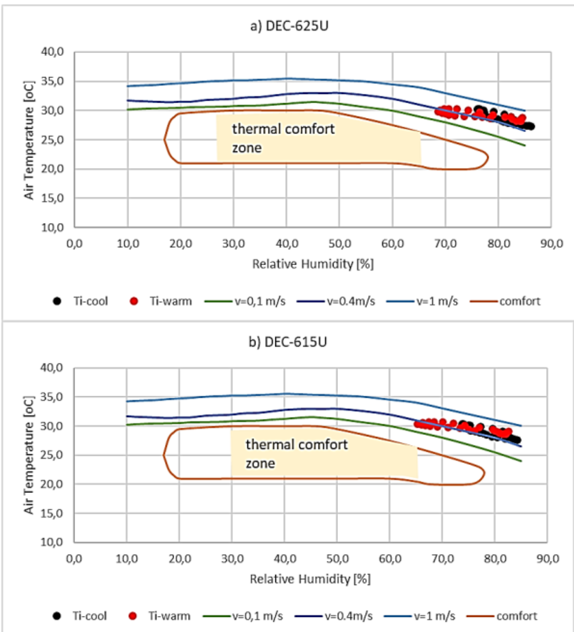

Fig. 5. Comfort analysis for DEC strategy with 0.6 m^2 cooling pad area: a) 20 cm and b) 10 cm thickness

Similar to the results described in the previous analysis, the application of DEC with a smaller cooling pad area shows the same tendency in indoor air conditions and comfort. As illustrated in figure 6, indoor air temperatures are between 27.5-30.9 °C, and relative humidity is between 65.2-85% when a cooling pad area of 0.4 m^2 and 20 cm thick (DEC-425U) is applied. Reducing the thickness to 10 cm (DEC-415U) will result in air temperature ranging between 27.7-31 °C and relative humidity between 63.7-83.8%. The study found that reducing the cooling pad's thickness does not significantly affect temperature reduction but slightly influences relative humidity. As shown in figure 7, to extend the comfort zone, the housing unit requires an indoor air velocity of 0.2-0.6 m/s. Air velocity of 0.2-0.6 m/s should be provided during the coolest month, and 3.5-0.6 m/s is needed for the warmest month. In the coolest month, the housing unit requires low air velocity (0.3-0.4 m/s) most of the time and, conversely, high air velocity (0.4-0.6 m/s) in the warmest month. As mentioned before, the outdoor thermal conditions contribute to this different requirement.

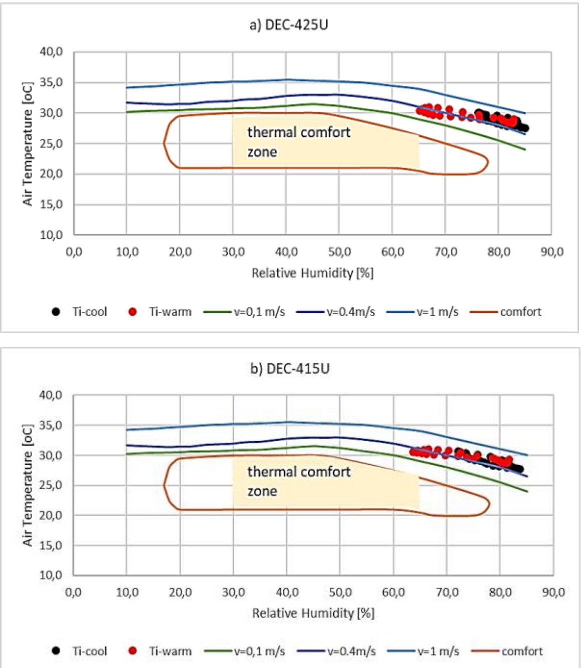

Fig. 6. Comfort analysis for DEC strategy with 0.4 m^2 cooling pad area: a) 20 cm and b) 10 cm thickness

The above analysis showed that the application of DEC in residential housing poses an obstacle in providing comfort due to the increased air humidity. Compared with the utilization of natural ventilation, DEC does reduce indoor air temperature. However, it has a consequence of having high relative humidity due to the nature of the evaporative process. Under warm-humid conditions, this consequence has a significant impact on comfort.

Change in the DEC property will influence the effectiveness of the evaporative process, as mentioned by the previous studies. An increase in cooling pad area and thickness can elevate the saturation efficiency of the system. It, therefore, will increase the ability to reduce air temperature, but at the same time, it will increase air humidity substantially. As the study shows, however, the change of the system property does not make significant differences. The change in indoor environmental parameters due to variation in cooling pad area and thickness is marginal.

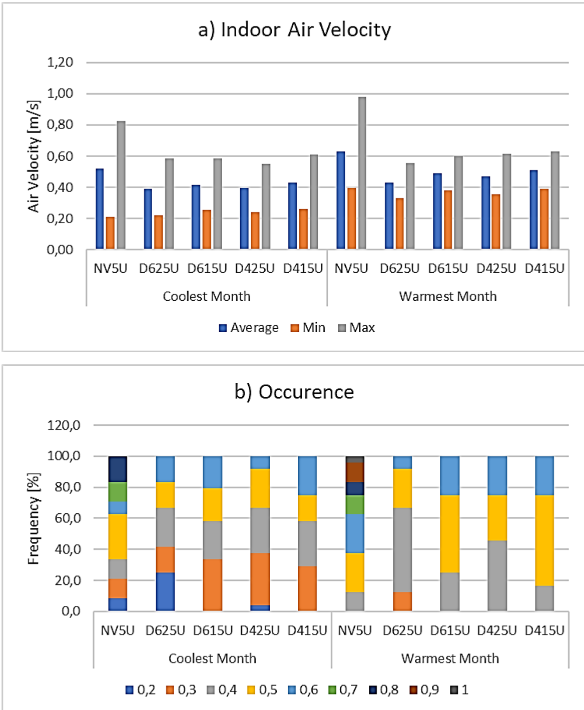

Fig. 7. Calculated wind support comfort by passive cooling strategies

In order to offset the discomfort in a warm-humid environment, higher air velocity should be introduced, and this can range, as the study shows, between 0.2-0.6 m/s. The condition is difficult to be attained in a standard building design as the average air velocity generally does not exceed 0.2 m/s (Aflaki et al., 2016; Alfata et al., 2015; Sujatmiko et al., 2015). Nevertheless, previous studies indicated several strategies could be employed to meet the objective. For example, the correct window orientation relative to wind direction may increase air velocity up to 0.4 m/s (Sujatmiko et al., 2015). Wing walls or fins can also be incorporated into the design and elevate the air velocity 0,3 m/s above the standard design (Mozaffari Ghadikolaei et al., 2020). Increasing the inlet by opening the external door can also have an impact, and in this case, the average air velocity can step up to 0.4 m/s (Arifah, 2017). A more advanced strategy is utilizing a ventilation shaft at the back of the housing unit. However, this strategy can only increase air velocity up to 0.5 m/s (Fahmi et al., 2018). These efforts show that the passively proposed strategies can still not achieve the required air velocity. It follows that another means of cooling should be introduced. Low-energy equipment, such as a ceiling fan, can be the nearest solution. The ceiling fan is a common practice in warm-humid climates as it helps improve comfort without air movement. The fan can increase air velocity by more than one m/s (Jain & Shorey, 2015; Zhai et al., 2015) and reduce thermal discomfort.

Other techniques are to be directed to reduce the increased relative humidity. As mentioned above, several techniques may be adopted. These techniques may vary from desiccant-dehumidification, solar-assisted dryers, and a combination of direct and indirect evaporative cooling. Since the objective of applying DEC in low-rise residential housing of Surabaya is to find a low-cost technique that can approach the comfort level, all techniques dedicated to lowering the relative humidity may be considered more complicated and costly. Therefore, using a ceiling fan might be regarded as the optimum solution.

CONCLUSION

Aside from adopting natural ventilation as a passive cooling strategy, DEC can be applied in low-rise residential buildings under warm-humid conditions like Surabaya. However, it is not a straightforward application, but it can be used under several conditions. As found in the study, DEC can reduce air temperature by 3 K compared with natural ventilation utilization, but it elevates the relative humidity by 10%. This condition poses a problem in terms of thermal comfort. In order to restore comfort, it requires indoor air velocity between 0.2-0.6 m/s. As previously highlighted, many studies suggested using passive techniques to fulfill the objectives. Several options are also available if comfortable conditions are to be achieved by reducing air humidity. As raised in the above discussion, among all these probable techniques, the ceiling fan can be employed in conjunction with DEC because it is low cost, low energy, and easily operated.

The study recommends that the DEC system be applied in a studio housing unit in which a ceiling fan is added. Since the present study only concentrates on investigating DEC application on studio units, further research is required to explore its applicability to other types such as one- or two-bedroom units. Investigation of the effectiveness of the ceiling fan is also needed to ensure the feasibility of the proposal.

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