Controlling The Comfort of Large Heat Load Rooms in The Tropical Region at Low Cost

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Abstract. Staff productivity becomes main concern in modern business. There are many requirements to maximise staff productivity in a company. Working in a comfortable room will result in not only good productivity, but also good quality of product. Among of criteria of room comfort are temperature, humidity, oxygen content and air flow. People commonly use air conditioner (AC) to make a room as a convenient place to work. However, it is not rare the room is very big and heat load is very high, such as a production building in industries in which may have many machineries installed and an open space office. Using an AC system to make a room comfortable may not a good option, because it will require high capital cost and very costly operational cost. In this report, other approaches, such as well-arranged fans, direct evaporative cooler device, underground evaporative cooler chamber, and ground cooling heat exchanger are explained. The techniques have been simulated, developed, and tested for open space offices and plant production buildings to make the rooms more convenient with minimum capital cost and operational cost. These approaches to some extend even also provide better comfort index as compared to AC, because they are not only able to lower down the temperature, but also supply fresh air and air flow. The main different between the technologies reported here and AC system, they need a room with well ventilated, and do not require chemical, such as refrigerant.

Keywords: Evaporative Cooler, Down Hole Heat Exchanger, Temperature, Humidity, Air Flow, Oxygen Content

1 Introduction

Productivity and quality are two main concerns that can't negate one another to maximise revenue and profit in modern industries [1]. Lack of productivity means what is produced is less than supposed to be. Hence, it is a kind of loss in the view of business. Low quality products may lead many products are rejected or downgraded by the consumers and it can also cause loss of revenue and profits [2][3]. Therefore, these two concerns must be accomplished concurrently. In Indonesia and other developing countries, most of factories are still labour intensive [4]. As a result, the productivity and product quality highly depend on the workers.

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There are many factors that affect human productivity and product quality in the workplaces. A comfortable environment is one of them [5]. Many studies show that people work in a comfortable environment, such as a convenient room, will have better performance, as compared to people working in an inconvenient room. People tend easily to be tired and loss concentration if the room is uncomfortable to them. There are many factors that cause a workplace becomes an inconvenient place to work. Comfort of a room is closely related to air quality, such as temperature and oxygen content [6][7]. In the tropical region, such as Indonesia, air conditioner (AC) system is commonly used to better the condition of air of a room [8][9]. However, in labour intensive factories, like shoe and textile factories, a workplace, particularly the production rooms, is a huge open space room. It is not rare that a floor of one big production building is an open working space in which lot of workers, machines, and equipment. AC may not be suitable to maintain air quality in this type of working room, because it will be costly.

Human bodies, machineries, and equipment release heat to environment. The released heat will contribute to the air temperature [10]. The more heat released by human body, machineries, and equipment is, the higher heat load of the room is. If an AC system is used to maintain the temperature of such a room, the operational cost will be very costly. Hence, non-AC techniques to maintain room comfort are reported here to replace an AC system. In general, the techniques reported here are well arranged fans [11][12], evaporative cooler devices [13][14], underground evaporative chamber [15], and ground-cooling heat exchanger [16][17].

An example to improve room comfort by rearranging existing fans are explained here. The objective of this project was to better room comfort, and at the same time lower down the operational cost (not increasing energy consumption). A fan just blows air, not lowering temperature of air. However, with proper air flow direction, it can lower sensation temperature on human skin [18][19].

Vaporizing water needs energy. The energy needed to vaporize water was also used in other studies reported here to lower down air temperature and to improve room comfort. Two types of evaporative cooler are reported here. They are direct evaporative cooler device [13][14] and underground evaporative cooler chamber [15].

Soil can be viewed as a huge heat sink. Hence, with proper down hole heat exchanger design, heat from room air can be transferred to underground soil [16][17]. The other study reported here utilized this potential.

2 Methodology

The researches started from the problems faced by various types/uses of room spaces. In order to solve the problems properly, data, constraints, limitations and objectives were gathered in detail, and they were used to calculate, model and design. Some designs were simulated before being constructed. The final one was the performance tests of constructed units or systems. These steps are described by the flowchart shown in **Figure 1**.

3 Result and Discussion

It is commonly misunderstood that the comfort air for a room is solely determined by temperature. In fact, many factors that affect the air quality, such as temperature, humidity, oxygen content, odor, and air flow. At least there are five factors that determine the comfort index of a room. They are temperature, oxygen content, relative humidity, air pressure and air flow [20][21], which are shortened by the equation (1) to calculate air comfort index (ssd) [18]. The methods to improve the convenience of a room in the researches reported here are based on these criteria.

$$\text{Comfort index} = (1.818T+18.18)(0.88+0.002\,F) + (T-32)/(45-T) - 3.2V + 18.2 \qquad (1)$$

Where T = temperature; F = relative humidity and V = velocity of fresh air flow.

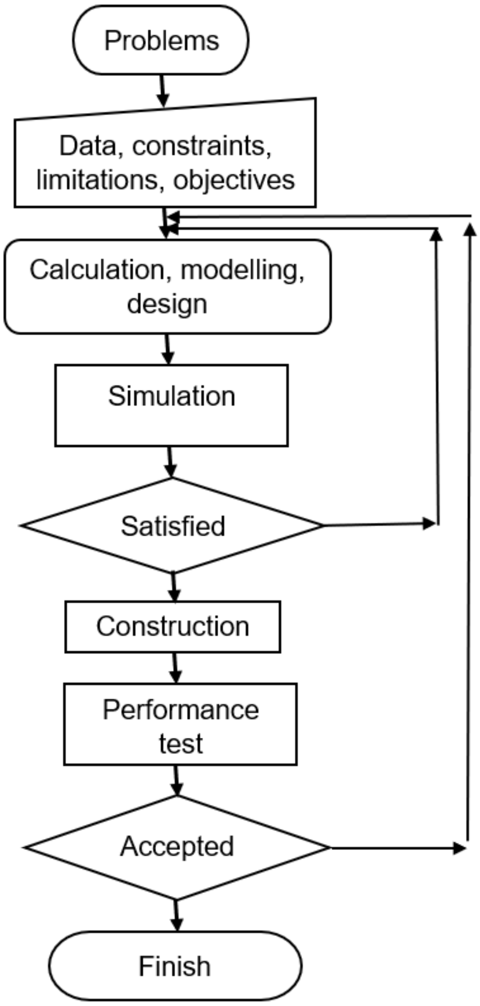


Fig. 1. Flowchart of the studies.

Following discusses some results obtained from the techniques previously explained.

Proper arrangement of fans technique

Many big workplaces, such as production rooms, use fans to make the space become convenient place for people to work. Inside the production building, it commonly consists of not only human, but also machineries and equipment. The machines usually release significant heat. Even, some of the machines work based on heat. Meanwhile, a fan is not an air cooler. It does not lower down the temperature of air. It only lets the air move. However, air movement on the skin can help to lower the temperature sensation on the human skin. Hence, people will feel as if the air temperature is lower few degrees as compared to without air movement. How many degrees lower depends on the speed of air flow [18][20][21]. For example, if the speed of wind is about 10 m/s, the temperature sensation on the human skin will be lower about 3 ^oC than that of without air movement. It means a fan can be used to improve room comfort. However, it is often that a fan system fails to do the job due to improper fan arrangement.

Table 1. Temperature sensation on the human skin due to air movement [18].

Air velocity m/s	**Supply air temperature ^oC**			
	25	**27**	**29**	**31**
	Equivalent temperature sensation on human skin			
8	22.1	24.7	27.8	29.8
9	22.1	24.7	27.8	29.8
10	22.0	24.5	27.4	29.6
12	21.9	24.3	27.2	29.4

In the case study here, the arrangement of a big production room of a labor-intensive factory in Banten Province, Indonesia was initially as illustrated in **Figure 2.** There were also plenty of small fans around the workers which are not shown in **Figure 2.** The ambient temperature around the factory was between 25 ^oC – 35 ^oC with the relative humidity was in between 60-80%. Although, plenty of 2 kW wall mounted fans were installed, the workers in the room still felt the air was hot and humid. They felt it was inconvenient to work. To obtain the data, the wind speed at several locations in the room was measured and it was found that many locations had no air movement (zero wind speed).

Based on the data obtained from observation and measurement, the air circulation and movement inside the room was simulated using computational fluid dynamics (CFD). The simulation result in **Figure 3** shows that the wind direction was irregular and chaotic. It was very unfortunate that the simulation found that the room did not have a clear flow air outlet. Similar to the measurement result, some areas inside the room had almost zero wind speed. It may be due to that the wind forces canceled each other at those areas. The air inside the room was trapped inside and it meant the heat, humidity, and pollutant were also trapped. They were just circulated inside the building. The heat generated by the machineries inside the room could be also just recirculated inside the room. It was the reason why the workers inside the room felt the room hot and humid.

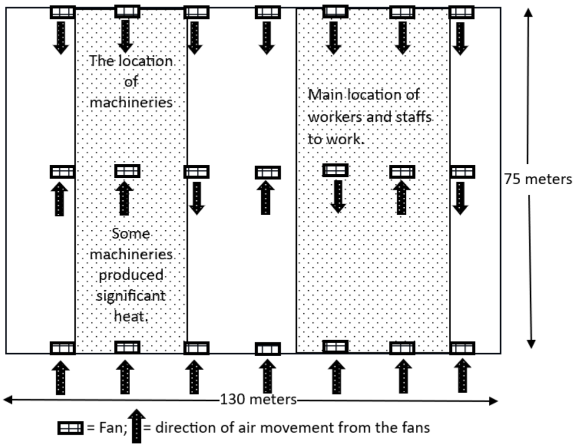


Fig. 2. Illustration of the studied production room initially: size, positions of main fans, directions of main fans, and space allocation.

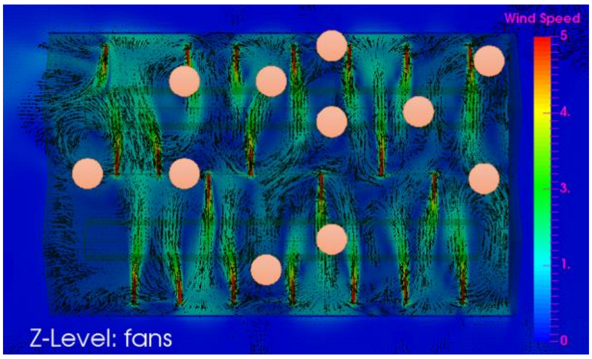


Fig. 3. Simulated air movement with original fan arrangement.

In order to solve the chaotic wind direction as shown in **Figure 3**, the main fans in **Figure 2** were rearranged as illustrated in **Figure 4.** It was expected that the arrangement in **Figure 4** would result in the air was pushed from one end of the building to the other end because the direction of the fans was the same. To achieve more efficient wind force, the fans were not installed in one line. Hence, it would result in not only good air movement, but also good air exchange. This fan arrangement would also remove quickly heat generated by machineries in the room without passing through the location where most people worked.

The wind direction from the fans arranged as in **Figure 4** was simulated also using CFD and it resulted in shown in **Figure 5. Figure 5** shows that the air movement due to the fans became one direction only, from one end to the other end. The direction of air movement is well defined. The consecutive fans resulted in the following fans amplified the blowing wind from previous fans. It is similar to constructive force vectors. The simulation result in **Figure 5** clearly indicated that the new fan arrangement shown in **Figure 4** resulted in more comfortable thermal working condition as compared to the initial fan configuration. The air movement direction let the heat inside the building, including heat generated by the machineries, escape the building quickly. This new configuration also let the wind blow over the skin of workers about 3 – 5 m/s, so that the temperature sensation on the workers dropped about 2 – 3 ºC. Moreover, likely due to the heat generated was taken away from the room immediately, the real air temperature also dropped about 3 ºC. Definitely, the new fan arrangement improved air changes per hour (ACH) a lot which means more fresh air in the room and higher oxygen content [22]. It helped relaxing workers and reduced sick building syndrome (ABS) [23][24]. The air humidity inside the room is similar to that of outside the room.

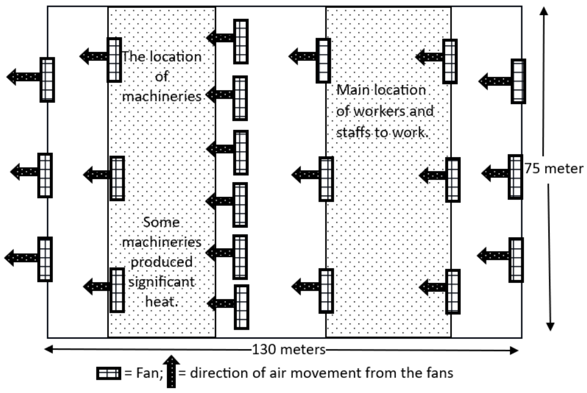


Fig. 4. Sketch of the room with new fan arrangement: size, positions of main fans, directions of main fans, and space allocation.

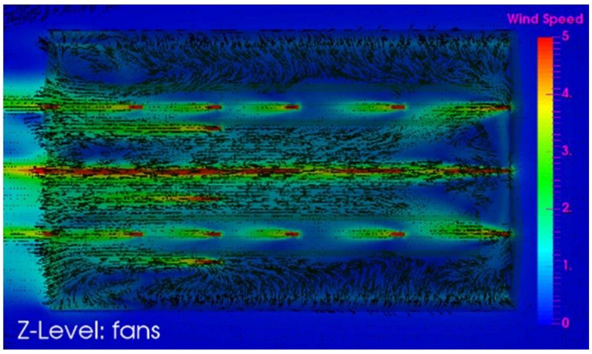


Fig. 5. Simulated air movement with fan arrangement shown in Figure 4.

Direct Evapotive Cooler Device

A direct evaporative cooler also uses a fan or blower, not a compressor like an AC. In a direct evaporative cooler device, a fan sucks warm ambient air and blows it into the room through wet cooling pads as shown in **Figure 6**. A cooling pad is made from cellulose fibers, such as from wood fibers and coconut fibers. They absorb water when wetted. When the wind blows through the wet cooling pads, it vaporizes the water in the cooling pads [25]. Vaporizing the water needs energy and this energy is taken from the air. As a result, the temperature of air drops few degrees and become cooler as illustrated in **Figure 7**, and water temperature rises. The water will be recycled and reused.

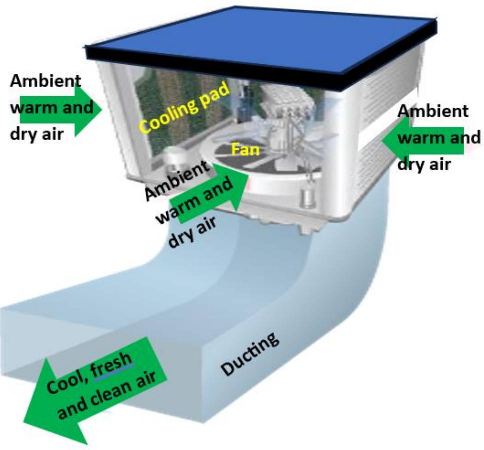


Fig. 6. Illustration of direct evaporative cooler device.

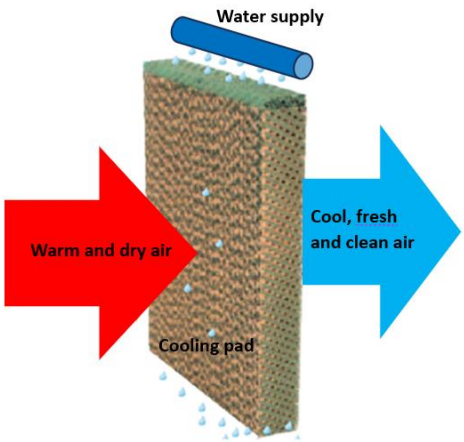


Fig. 7. Wet cooling pad drops air temperature.

The research problem for this technique was taken from a fast-food restaurant in Jakarta. This restaurant had mainly kitchen area, dining areas, playland, cashier area, and party room. The volume of the room was 331 m^3. This restaurant had a problem that the visitors experienced that the dining area next to the kitchen area was hot. Actually, the amount of AC installed was more than enough for the size of the room. However, due to heat transfer from the kitchen area, this dining area was still hot. To solve the problem, direct evaporative cooler machines and exhaust fans were installed. The total flow rate of direct evaporative cooler machines was designed 2.76 m^3/s which resulted in ACH 30. ACH 30 provides enough wind speed to remove warm air from the room. How low the temperature drop due to evaporative cooler depends on humidity of air, because it depends on how much water can be vaporized. Hence, the lower the ambient air humidity is, the bigger the temperature drop is. It is confirmed by the data shown in Table 2. Similar to fan system, direct evaporative cooler also creates air movement, so it also results in lower temperature sensation on the human skin as shown in Table 1 [18].

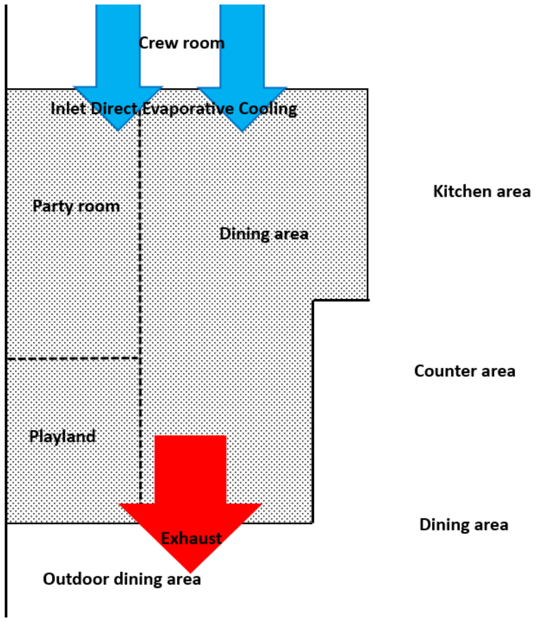


Fig. 8. The sketch of room utilisation

Table 2. Temperature drop due to direct evaporative cooler machine

Intake relatif Air humidity	**Supply air temperature °C**			
	30	**31**	**32**	**33**
	Output air temperature of Direct Evaporative Cooler			
80	-	28.5	-	30.5
70		27.5	28	29
60	25	26	27	28
50	23.5	-	25.5	-

Evaporative Underground Chamber

Almost similar to a direct evaporative cooler, an evaporative underground chamber uses fan and blower, not compressor like AC. In an evaporative underground chamber, a blower blows the warm ambient air through mist of water or water showers inside an underground chamber and fans suck cooled air from the chamber and blow it into the room as illustrated in **Figure 9(a).** The water mist and water showers should be produced from the top and two sides of the chamber. When the wind blows through the water mist or water showers, it vaporizes the water. Vaporizing the water needs energy and this energy is taken from air. Some of the heat is also absorbed by the water. As a result, the temperature of air drops few degrees and become cooler [26], and the water temperature rises. The water will be recycled and reused. To maximise vaporizing water and heat transfer from air to water, the chamber was partitioned like labyrinth as illustrated in **Figure 9(b).** Water mist was in first partition, and water shower was in the second and third partitions. It helped to avoid the water mist accidentally was carried by air into the room.

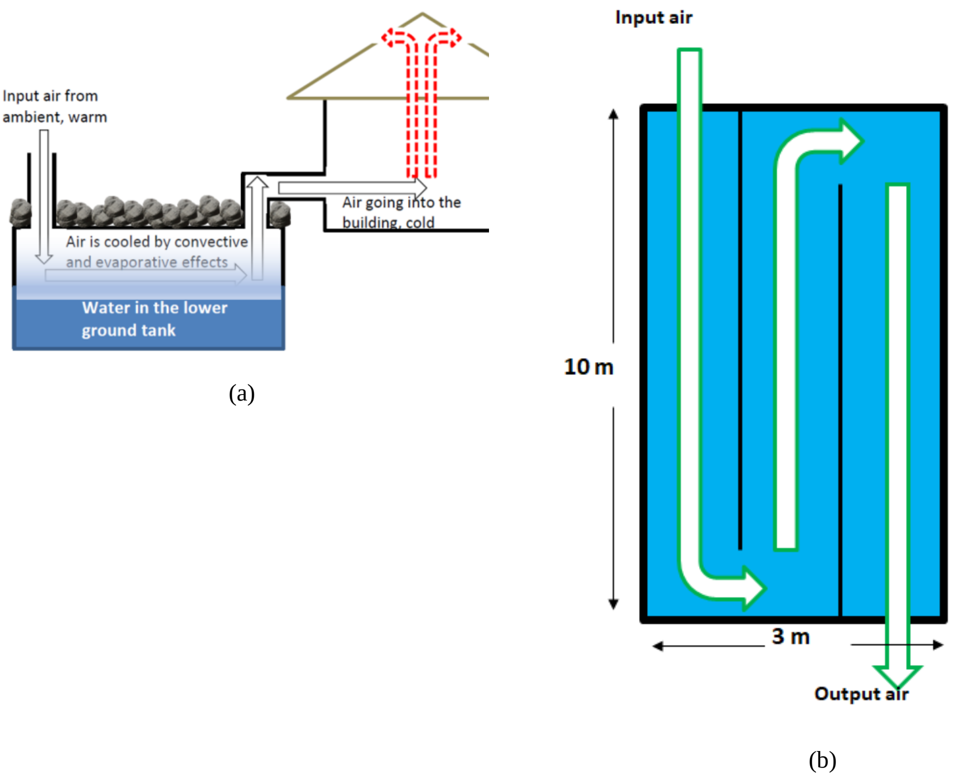


Fig. 9. (a) Illustration of direct evaporative cooler device, (b) The underground chamber was partitioned like labyrinth.

The problem of this research was taken from an office room of a factory in Central Java. This factory needed a cooling system that could support the brand as a green office. Hence, the cooling system had to be environmentally friendly and energy saving. As an office room, it needed ACH 10. The volume of the room was 2840 m^3. To achieve the requirement, evaporative underground chambers were installed. The total flow rate of evaporative underground chambers required was 28400 m^3/hr to provide ACH 10. Each evaporative underground chamber was designed to accommodate air flow rate 10800 m^3/hr. Cross section area of air passage inside the underground chamber was 0,5 m^2, so the air flow speed was 6 m/s. Hence, for the office room having volume 2840 m^3, three evaporative underground chambers were needed. How low the temperature drop due to evaporative underground chamber depends on the humidity of air, because it also depends on how much water can be vaporized [26]. Hence, the lower the ambient air humidity is, the bigger the temperature drop is. It is confirmed by the data shown in Table 3. Similar to fan system, and direct evaporative cooler, an evaporative underground chamber technique also creates air movement, so it also results in lower temperature sensation on the human skin as shown in Table 1 [18].

Table 3. Temperature drop due to evaporative underground chamber

Intake relatif Air humidity	**Supply air temperature °C**			
	30	**31**	**32**	**33**
	Output air temperature of Evaporative Underground Chamber			
40	22	23	-	-
50	23.5	24.5	-	26.5
60	-	26	27	28
70	26.5	27.5	28.5	29

Ground-Cooling Heat Exchanger

Ground Cooling Heat Exchanger (GCHE) is particularly promising for a location that has big temperature difference between day and night [27]. The GCHE strategy uses bore holes and underground piping network to let underground soil extract heat from working fluid inside the heat exchanger [28][29]. Basically, GCHE is a heat exchanger that is buried underground and there is heat exchange between soil and fluid flowing inside the heat exchanger pipe. The fluid inside the GCHE can be water or air. Besides energy efficient, GCHE is environmentally friendly. Efficiency of GCHE as cooling device depends on the local underground temperature. GCHE is usually placed at least at 7 m depth underground in which the soil temperature relatively constant, not affected by daily fluctuation of ambient air temperature. The underground soil temperature is lower than the ambient air temperature in daytime and higher than the ambient air temperature at night [30]. Hence, in daytime when warm room air flows through GCHE, its temperature will drop because its heat is absorbed by the ground. On the other hand, at night when cool room air flows through GCHE, its temperature will rise because it absorbs heat from the ground. Therefore, it is expected by using GCHE as air conditioner that the room air temperature stays convenient all the time, day and night [31].

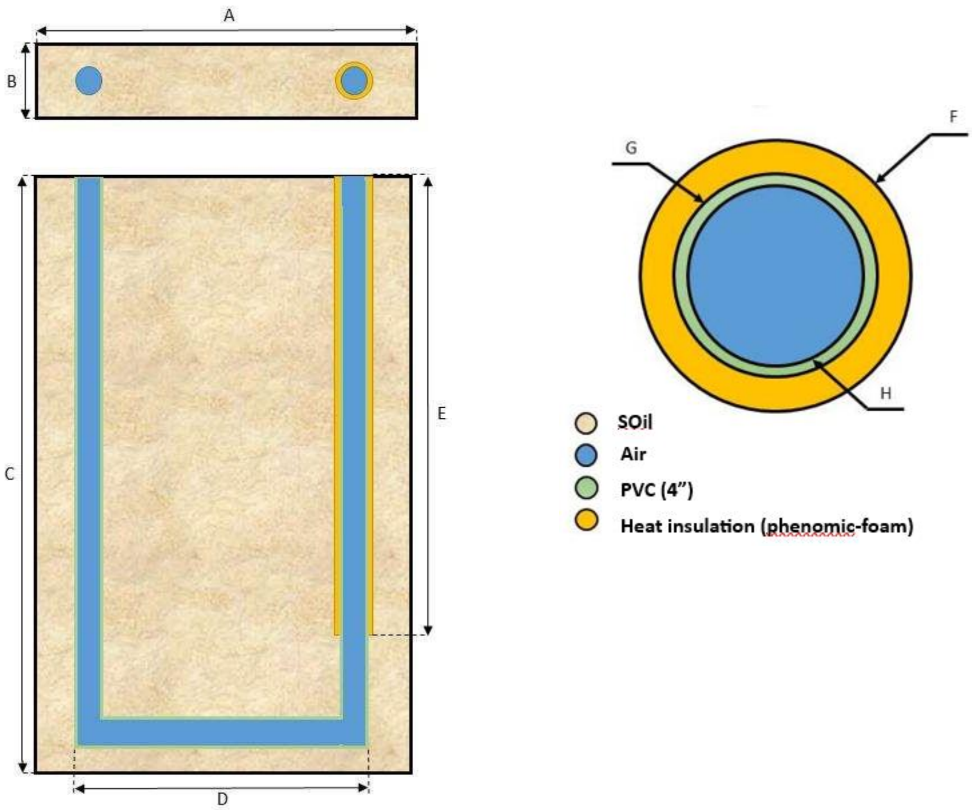
In this research, a simple GCHE design for application in Bandung, west Java, was examined with ANSYS software. At the location, the highest air temperature is 30.5 °C, and the lowest was 18.8 °C. Underground temperature was estimated using equations (2) and (3) [32]

$$T_s = T_a + \left[\frac{H r_a H}{\rho_{air} C_p}\right] \tag{2}$$

where T_a is ambient air temperature (K), $r_a H$ is transfer resistance (s/m), H is sensible heat flux (W/m^2), ρ_{air} is moist air density (1.27 kg/m^3), and C_p is heat capacity of air at constant pressure (1.004 J/kg K)

$$T_{soil(z,tyear)} = T_m - T_{amp} * \exp\left(-z\sqrt{\frac{\pi}{365*\alpha}}\right) * \cos\left(\frac{2\pi}{365}\left(t_{year} - t_o - \frac{z}{2}\sqrt{\frac{365}{\pi*\alpha}}\right)\right) \qquad (3)$$

where $T_{soil(z,tyear)}$ is ground temperature at depth z and year t; T_m is yearly average temperature at ground surface (◦C); T_{amp} difference of maximum and minimum temperature at ground surface (◦C); z is the depth of ground from surface (m); α is ground heat diffusivity (m^2/h); t_{year} is time (month number); and t_o is time shift (number of the days when the surface temperature is minimum).



Where A = 2.2 m; B = 0.3 m; C = 5.2 m; D = 2 m; E = 4 m; F = 0.134 m; G = 0.114; dan H = 0.104 m.

Fig. 10. Illustration design of GCHE

Due to cost constraint, the depth of the designed GCHE was chosen only 5.2 m. The distance between the inlet pipe and the outlet pipe was selected 2 m. The design of GCHE is illustrated in **Figure 10.** The fluid used for the simulation was air at atmospheric pressure. The pipe was Polyvinyl Chloride (PVC), and the type of soil was clay. The PVC pipe was insulated using Phenolic Foam (PF). The material parameters can be seen in Table 4. The speed of air inside the GCHE was 5 m/s.

Table 4. Material properties

Material	Density (kg/m^3)	Heat Specific (J/kg.k)	Heat conductivity (W/m.k)
Clay	1450	880	1.28
PVC	1380	880	0.19
PF	35	1000	0.08
Air	1.225	1006.43	0.0242

Figure 11 shows that when the air input temperature of GCHE is 29.94 ^oC, the air output temperature of GCHE is 25.49 ^oC. Figure 12 shows that when the air input temperature of GCHE is 18.92 ^oC, the air output temperature of GCHE is 24 ^oC. **Figures 11 and 12** indicate that GCHE can control air temperature in convenient temperature (not hot and not cold). The input air is fresh air from outside of the room.

Besides keeping convenient temperature, GCHE also supplies fresh air (not recycled air) with relatively high oxygen content to the room. The room cooled using GCHE needs well ventilated. The warm air inside the room is pushed out and replaced by the cool fresh air from GCHE. As a result, the air in the room is comfortable and high oxygen content with low operational cost.

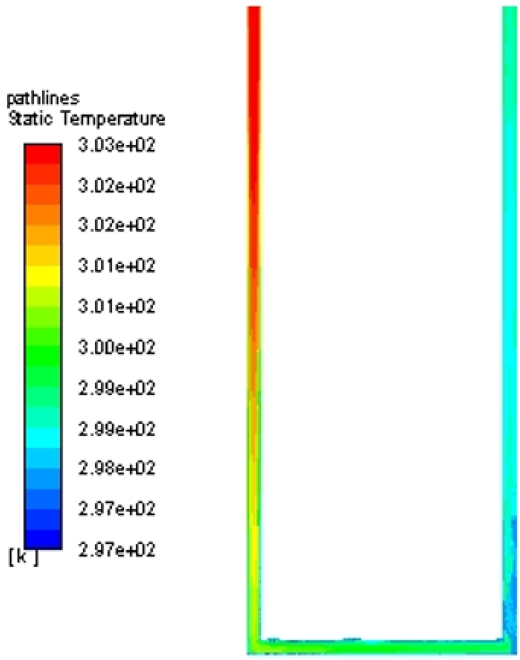


Figure 11. Temperature contour in GCHE when air input temperature is higher than surrounding ground temperature.

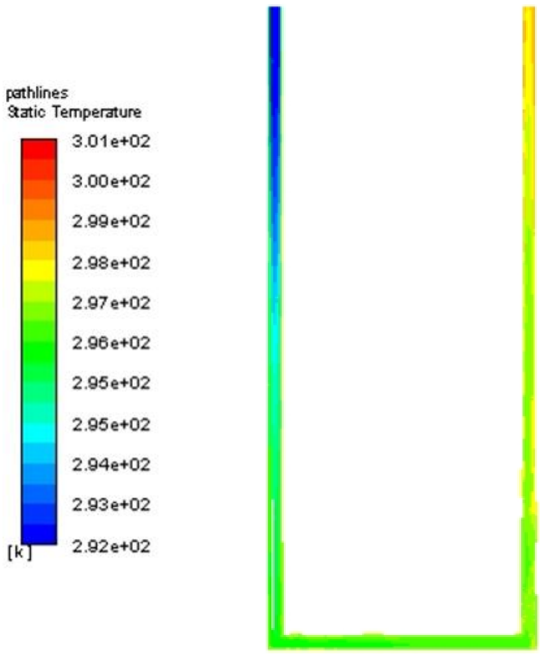


Figure 12. Temperature contour in GCHE when air input temperature is lower than surrounding ground temperature.

4 Conclusions

An AC system is not the only way to make a room become comfortable. Other approaches, such as well-arranged fans, direct evaporative cooler device, underground evaporative cooler chamber, and ground cooling heat exchanger can also improve the comfort of working areas. The fan system is not a cooling system, but it can lower the sensation temperature on human skin. The drop of sensation temperature depends on the speed of wind flowing on the surface of human skin. The direct evaporative cooler device and underground evaporative cooler chamber can lower the air temperature about 5 ^{o}C, but it depends on the air humidity and temperature. The ground cooling heat exchanger can also drop air temperature, but it highly depends on underground temperature that depends on local air temperature. All these techniques create air movement, wind, so they also cause the drop of sensation temperature on human skin.

Because these air cooler techniques use fresh air from ambient, the room air is fresh and high oxygen content. However, the rooms using these techniques must be well ventilated to let the warm air inside the rooms flow through ventilations to outside of the rooms. All of these techniques are lower operational and capital cost compared to AC technology because they only need fans and/or blowers, not compressors. They are also more environmentally friendly than AC system because they are more energy saving and do not need chemical.

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