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A Review of Technological Developments in Cooling System for Different Climates

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Abstract: Energy saving remains a vital issue amid the increasing environmental problems. Heating, ventilation and air conditioning (HVAC) system has become one of the major contributors to the global energy consumption. For hot-climate countries, the application of cooling systems is important for occupants to fulfil their desired indoor thermal comfort. Passive cooling and active cooling are the two main types of cooling systems. Passive cooling includes the application of natural processes and passive technologies without the usage of a conventional cooling system. Natural processes involve convection, evaporation and radiation in removing heat while passive technologies utilise building envelops design. Conversely, active cooling requires energy or a power source to provide the cooling effect. The efficiency of cooling systems needs to be emphasised, especially when energy consumption is taken into consideration. Commonly used cooling systems such as standard room air conditioner have proven to be power consuming and costly. Therefore, effective cooling techniques should be studied to improve the current cooling systems. This paper aims to present the thermal comfort expectations of different climates and to review the development of cooling system designs, which include different cooling techniques.

Key words: Cooling system・Thermal comfort・Passive cooling・Active cooling・Passive technologies

INTRODUCTION

Power usage in buildings accounts for 30% to 40% of global energy consumption [1-6]. The energy consumed by the building sector is mainly used to maintain indoor comfort levels and to supply power to electrical applications [4]. The bulk of energy consumption in buildings goes to heating, ventilation and air conditioning (HVAC) systems, which use almost 50% of the total supplied energy [1-3, 7]. Among the HVAC components, cooling systems use the largest amount of energy [8].

The popularity of air conditioning systems has grown due to increased demand for better indoor comfort [9-11]. Air conditioning is becoming essential in many types of buildings such as offices, airports, factories and houses [2]. Thus, the energy consumption for cooling system increases [7], leading to the growth of greenhouse gas emissions [2-4]. From the statistics, 40% to 50% of the world's greenhouse gas emissions are attributed to the building sector [4-6].

Cooling systems can be divided into two types: passive cooling system and active cooling system [12]. The active cooling system requires a power source to operate while the passive cooling system relies on natural heat-sinks to remove heat either without energy or with minimum usage of electricity [13, 14]. Passive cooling is recognised to be more energy efficient as it can reduce the cooling load and minimise the heat gains within a space [4].

The objective of this paper is to review the home cooling system designs. Section 2 discusses thermal comfort while Section 3 explains how the cooling system works. The conclusion of this review is presented in Section 4.

Thermal Comfort: International standards like ASHRAE Standard 55 and ISO 7730 Standard are used to determine the conditions of thermal comfort in a building. Thermal comfort is defined in ISO 7730 Standard [15] as being "that condition of mind which expresses satisfaction with the thermal environment". Most people agree on this

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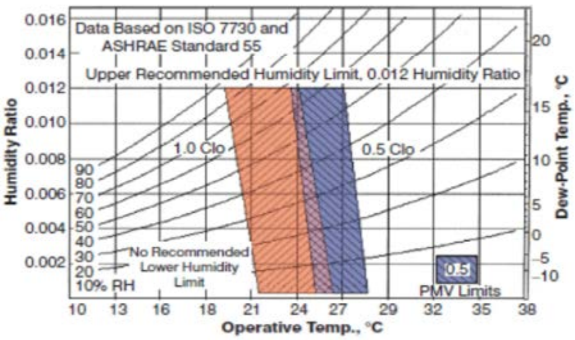

Fig. 1: Acceptable range of operative temperatures and humidity for people in typical summer and winter clothing during light and primary sedentary activities [17].

Table 1: Recommendations of ASHRAE Standard [18, 20, 21].

Season	Operative Temperature	Acceptable range
Winter	22°C	20-23°C
Summer	24.5°C	23-26°C

definition but find it difficult to express it using physical parameters [16]. Based on the psychometric chart stipulated by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), the thermal comfort zone is in a region where all the conditions can satisfy 80% of the occupants. The thermal comfort zone as stated by ASHRAE Standard 55 [17] is shown in Fig. 1.

According to the above definition, thermal comfort is associated with a state of mind rather than the actual conditions [18]. Thus, comfort can be influenced by many inputs, which include physical, physiological, psychological and other factors [18, 19]. The perception of comfort can be different among occupants even in the same environment [18]. The recommended acceptable thermal comfort conditions by ASHRAE Standard are summarised in Table 1.

Thermal comfort is difficult to define as it can be affected by conditions of indoor or outdoor environments, climate types, human factor and geographic location of the countries. Table 2 summarises the indoor comfort temperature of various countries with different climates.

The comfort temperature for hot-climate countries appears to be higher than that for cool climate countries. This is due to frequent exposure of occupants to a hotter climate, which causes them to get accustomed to their own living surroundings. Occupants from cooler-climate countries often prefer a lower temperature while residents who live in hot climate countries are used to a warmer environment. Environmental condition is another factor affecting the desired comfort temperature of occupants even if they are experiencing the same climate. There has been a study conducted to compare the comfort temperature between air-conditioned and non-air-conditioned buildings located in the same geographical location [26]. The desired temperature for the air-conditioned building is found to be lower than that for the non-air-conditioned building. This result indicates that even in the same climate, occupants from a cooler environment still demand lower comfort temperature. Thus, it can be concluded that climate and environmental conditions will influence human perspective of thermal comfort.

The studies also show that Singapore, Malaysia and Indonesia have similar comfort temperature range as their geographical locations are all in the region of Southeast Asia. For countries located further north, such as China and Italy, their environmental atmospheres are cooler. Therefore, the desired comfort temperature is found to be lower than that of other countries. A geographic location defines local climate and subsequently affects the comfort temperature of different countries.

It is also discovered that India has the widest comfort temperature range with temperature difference of 6.5°C, followed by China, Malaysia, Brazil, Nigeria and Italy with a difference of around 4°C. Singapore has the smallest interval with a difference of 2.2°C. The variation in temperature range is due to human factor as different countries have different levels of acceptability.

Relative humidity and air speed have an impact on comfort temperature as well. Relative humidity will affect evaporative heat loss from a person, especially when more physical activities and a warmer environment are involved. Meanwhile, the presence of air speed can facilitate air ventilation and provide reliable air flow within a building. Occupants might feel comfortable under warm temperature if a suitable rate of air speed is introduced to the living space. From the findings, the acceptable temperature range for India, Malaysia and Brazil is more than 30 °C, which exceeds the comfortable range set by ASHRAE Standard. However, these occupants recognise this condition as comfortable due to the existence of air velocity within the indoor environment. Hence, it is proven that air movement can improve thermal comfort even under hot circumstances.

Cooling System: A cooling system is a system to remove heat in order to achieve the thermal comfort desired by occupants [30]. It is mostly applied when the temperature exceeds the thermal comfort range.

Table 2: Thermal comfort temperature for different climates

Country	Climate	Building type	Cooling type	Comfort temperature (°C)	Additional parameter	
					Relative Humidity (RH)	Air Speed (ms^{-1})
Central Southern China [22]	hot + humid	Residential house	Air conditioning and non air conditioning system	22.0- 25.9	44.3-90.1	0.01-0.14
Hyderabad, India [23]	hot + semihumid	Mid-rise apartment	Natural and mechanical ventilation, air coolers (minority)	26.0-32.5	26.7-66.1	0.40-0.50
Singapore [24]	hot + humid	Classrooms	Mechanical ventilation (fans)	27.1-29.3	60.0-90.0	-
Jogjakarta, Indonesia [25]	hot + humid	Low-rise houses	Natural and Mechanical ventilation (fans)	26.0	50.8-87.0	0.10
Johor Bahru, Malaysia [26]	hot + humid	Schools and clinic	Natural and Mechanical ventilation (fans)	26.0-30.7	49.5-75.3	0.40-0.80
		University	Air conditioner	23.1-25.6	60.0-72.0	-
Maceio, Brazil [27]	hot + humid	Classrooms	Natural and Mechanical ventilation (fans)	26.0-30.0	-	0.40-0.90
Bauchi, Nigeria [28]	hot + dry	Residential buildings	Natural and Mechanical ventilation (fans)	25.5-29.5	28.0-80.0	0.13
Turin, Italy [29]	hot to cool+ humid	Classrooms	Natural ventilation	23.3-27.4	-	-

Table 3: Classification of passive cooling system

Type of passive cooling	Description	Application	Heat gains reduction	Drawbacks
Natural ventilation [35,36,37,38]	Eliminate heat through the flow of natural air	Buildings with low sensible load or periodic load, example: office	20-30 Wm^{-2}	-Not suitable for hot climate -Noise and air pollution -High heat gains
Radiant cooling [14,35]	Remove heat through radiant heat emission	Moderate sensible cooling load	Maintain heat gain below 40-60 Wm^{-2}	-High internal gains
Evaporative cooling [1,35]	Cool the air using the process of water evaporation	Buildings with low internal gains	-	-Not suitable for humid climate -Requires humidity control
Ground cooling [14, 35]	Utilises cooled soil for heat absorption	Buildings with suitable ground condition and moderate cooling demand	45 Wm^{-2}	-Great depth needed to reach cold water

Passive Cooling System: A passive cooling system cools buildings through the utilisation of ambient air, upper-atmosphere, water and under-surface soil [31-34]. The term "passive" also includes minimum usage of mechanical ventilation such as fan or pump when their application can enhance the performance [13, 14]. Passive cooling can be classified into natural ventilation, evaporative cooling, radiant cooling and ground cooling [14, 35]. Table 3 summarises the features of each passive cooling system.

A passive cooling system is useful in overcoming environmental problems. It decreases energy consumption [13] and greenhouse gas emissions [38]. About 2.35% of the world's energy usage could be avoided through the proper application of passive cooling concepts [39].

Natural ventilation has been increasingly incorporated in cooling system designs as this system is expected to save 10% of annual energy consumption [37]. Unlike other passive cooling techniques, natural ventilation takes advantage of air movement to reduce indoor temperature. This type of passive cooling is suitable for most households and buildings since it is easily available. However, natural ventilation is subject to the problems of noise and air pollution. Direct solar radiation from the openings or windows causes indoor temperature to exceed the comfortable limit. Therefore, the application of natural ventilation is not really appropriate for hot-climate countries.

Advanced natural ventilation can be achieved when solar chimney, windows and more openings are installed in a building [14, 38]. These elements are able to promote and enhance the heat dissipation process. Night ventilation is another type of natural ventilation. It cools the building at night and serves as a heat sink on the following day to offset the heat gains [14, 31, 35, 36, 38].

Water is one of the solutions to achieve the purpose of cooling, especially for countries that experience dry climate. Evaporative cooling is the answer to this problem since it has low operating cost. Humidity control is needed to control this cooling system to enhance its performance. Evaporative cooling utilises water vapour to cool the air directly or indirectly [1, 36, 40]. For indirect evaporative cooling, heat is exchanged with another medium separated by a heat exchange element before the cooled air is allowed into the building [40].

Radiant cooling operates differently compared with other passive cooling techniques. It requires a temperature-controlled surface to remove sensible heat through thermal radiation [14]. Cold energy is transferred to an indoor space by conduction or forced air flow [14]. Radiant cooling is efficient in terms of minimising the heat gains but it leads to high internal gain. Although temperature-controlled surface can prevent direct heat emission into an indoor environment, some of the heat absorbed will still dissipate into the living space. This phenomenon causes the increase in internal gain and contributes to higher cooling demand.

Table 4: Developments in passive cooling system

Country	Climate	Research Area	Cooling Type	Methodology	Results
Rajasthan, India [41]	hot + dry	Solar Passive Technique for Roof Cooling	Radiant and Evaporative	Thermal model simulation	-Lowering roof temperature at peak hours by 12°C-33°C
Malaysia [42]	hot + humid	Earth Pipe Cooling Technology	Ground Cooling	EnergyPlus simulation and experimental work	-Temperature drop by 6.4 °C - 6.9 °C between pipe inlet and outlet
Thailand [43]	hot + humid	Solar Chimney and Wetted Roof	Evaporative and Natural Ventilation	TRNSYS (Transient System Simulation Tool) simulation and experimental work	-Reduce indoor temperature by 2.0 °C - 6.2 °C compared with ambient air and 1.4°C-3.0 °C compared with controlled cell
United State of America (USA)[39]	hot to cold+ humid to dry	Cement-Based Roofs	Radiant	Experimental work	-Reduction in heat conduction between 65% and 85%
Japan [44]	hot to cold+ semi humid to humid	Cooling Wall	Evaporative	Experimental work	-Maximum cooling efficiency of 0.7 during daytime
Iran [10]	hot to cold+ humid to dry	Earth to Air Heat Exchanger (EAHE) and Solar Chimney	Natural Ventilation and Ground Cooling	Theoretical analysis and Mathematical model solved by MATLAB (Matrix Laboratory)	-Retain indoor temperature at 28.15 °C -31.94 °C
Malaysia [45]	hot + humid	Trombe Wall and Roof Solar Collector	Radiant	Experimental work	-Decrease the room temperature by around 3°C
Argentina [46]	hot to cold+ humid to dry	Roof Awning	Radiant	Thermal model simulation	-Reduce household cooling load by 40% during summer period
Guangzhou, China [47]	hot to warm+ humid	Building Envelope	Radiant and Natural Ventilation	TRNSYS simulation	-Annual energy demand is reduced from 1.82% to 2.64% through wall insulation -Annual energy demand is reduced from 19.36% to 33.89% through window insulation
Jordan [13]	hot to cool+ dry	Roof Design	Radiant	Experimental work	-Decrease the temperature of reinforced cement concrete roof by approximately 10°C
Malaysia [48]	hot + humid	Roof Pitch and Ceiling	Radiant	Experimental work	-The daytime indoor temperature is reduced between 0.4°C and 0.8°C
USA [49]	hot to cold+ semi humid to dry	EAHE and Solar Chimney	Natural Ventilation and Ground Cooling	Experimental work	-Maintain indoor temperature in the range of 21.3 °C to 25.1°C -Provide cooling capacity of 2582W
Malaysia [50]	hot + humid	Earth Tube and Solar Chimney	Natural Ventilation and Ground Cooling	Experimental work	-Generate cooling capacity of 4000W

The cooling concept of ground cooling is similar to natural ventilation. Both of these cooling systems involve the buoyancy effect, which enhances the ventilation flow of a building [10, 37]. The difference in ground cooling from other passive cooling systems is the requirement for suitable ground conditions, which normally include deep ground depth with cold ground temperature. This implementation can reduce the cooling demand of buildings, which in turn lower the amount of energy needed for the cooling system.

Developments of Passive Cooling System in Different Climates: Cooling effect can be improved by different types of passive cooling techniques. Roof, wall, ceiling, roof pitch, windows and solar chimney are some of the building elements used for the purpose of cooling. Table 4 summarises the research works of passive cooling systems used in different climates.

Based on Table 4, it can be observed that roof is the most popular passive cooling method. Different roof installations were done to validate their cooling abilities. From the results of the studies, roof is effective in reducing heat conduction, which in turn reduces the indoor temperature. Materials applied on roof also affect the cooling performance. Countries like Argentina, USA and Jordan have proven that roof temperature and indoor temperature can be reduced if appropriate materials are used in the roof designs.

The evaporative cooling concept is another technique applied to roof designs. For instance, a tropical country like Thailand has shown encouraging results through this cooling method whereby indoor temperature decreases by 3.0°C. The cooling outcome is more obvious for India as the roof temperature can be lowered to a minimum of 33°C. Since roof is directly exposed to solar radiation, heat will be generated on top of the roof and transferred into the building through the process of radiation, conduction and convection. Therefore, lower roof temperature will ensure cooler indoor environment and help to reduce the cooling load.

Evaporative cooling can be utilised on walls as well. For example, Passive Evaporative Cooling Walls (PECW) constructed by porous ceramic with high water soaking-up ability was developed in Japan [44].

These ceramics are capable of absorbing water to a higher height level of 100 cm whereas general porous material can only reach a height of 30 or 40 cm. Therefore, water can be supplied from a rainwater tank below without a pump. The air passing through PECW is cooled to minimise the environment temperature. The purpose of conserving energy can be achieved through PECW since it does not require the usage of electrical equipment.

Recent studies also indicate the importance of ground cooling in cooling system designs. It has shown prospective contribution, especially in providing sufficient cooling capacity to buildings. Ground cooling operates well with solar chimney, which utilises natural ventilation [49, 50]. Research done in [50] investigated the performance of coupled geothermal cooling system with earth tube and solar chimney. The cooling output shows that the coupled system performed better with natural ventilation compared with the presence of forced air flow. Minimum electricity consumption is needed while most of the building cooling load can be covered through this type of cooling system.

Buildings can also be cooled by radiant cooling. The effect of radiant cooling is significant, especially for countries that experience different types of climates such as the USA and Argentina. However, this type of cooling system does not seem to be beneficial to tropical countries like Malaysia. It improves indoor thermal conditions but with limited effect. It is worth noting that radiant cooling can conserve energy by reducing the cooling power consumption.

Natural ventilation, radiant cooling and evaporative cooling are the most common techniques used in a passive cooling system. The findings indicate that the combination of different passive techniques can ensure better cooling outcome. Building envelopes also play an important part in a passive cooling system. Building elements such as roof, wall, ceiling and solar chimney are capable of providing cooling effect for indoor environments. The result is more promising when more building elements are involved in the cooling system design. Apart from cooling effect, the energy consumption of buildings can also be minimised through the application of building envelopes.

Active Cooling System: A cooling system which requires energy sources to operate is referred to as mechanical ventilation system or active cooling system [4, 12]. The most frequently used active cooling systems are ceiling fan, desk fan and standing fan. These systems can provide reliable airflows for occupants and maintain the comfort level in buildings [7].

Air conditioner is another active cooling device that is widely used [4]. Packaged Terminal Air Conditioner (PTAC), Air Handling Units (AHUs), desiccant cooling system and absorption cooling system are the main types of air conditioners used in modern buildings [4, 51, 52]. However, such cooling systems are expensive and have high power consumption [1].

Developments of Hybrid Cooling System in Different Climates: Table 5 shows the developments in a hybrid cooling system. Besides mechanical ventilation system, passive cooling techniques such as radiant cooling and evaporative cooling are applied together with active cooling system to achieve optimum cooling performance. The combination of passive cooling and active cooling are known as hybrid cooling system [8].

Radiant cooling panels, which incorporate a combination of the concept of evaporative cooling and radiant cooling, demonstrate efficient cooling performance. It is proven in Japan and Thailand that wall cooling panels adopting these cooling techniques consume less energy than the conventional cooling system. Ceiling cooling panels also show the competence in saving energy but are inferior if compared with wall cooling panels.

Solar window with forced flow water circuit is an innovative evaporative cooling system. Water passage in the window can lower inner glass temperature, decrease heat gain of indoor environment and thus, reduce air-conditioning electricity consumption. The cooling result is more obvious with tinted glass compared with reflective glass or clear glass. Tinted glass reveals higher water heat gain, which proves that more cooled air enters a building as most of the heat is absorbed by the water.

The energy consumption of mechanical ventilation can be controlled by the introduction of air movement into the indoor space. The results show a reduction in cooling power from 10% to 28% [30] due to the increase in air movement. Therefore, more energy can be saved from the cooling system. Air movement can be increased by using fans, windows and personal ventilation systems. Different fans show different energy usage patterns and this will affect the amount of energy saved.

Cooling performance of ventilation controller is comparable to other cooling techniques. The operation of a ventilation controller is based on the comfort band set by users. The findings discovered in [29] indicate that the application of a ventilation controller with mechanical ventilation can lead to superior TDR, which implies better cooling performance.

Table 5: Developments in hybrid cooling system

Country	Climate	Research Area	Cooling Type	Methodology	Results
Japan [53]	hot to cold+ semi humid to humid	Radiational Panel Cooling and Wind-Driven Cross Ventilation	Radiant, Evaporative and Natural Ventilation	Computational Fluid Dynamics(CFD) simulation	-Reduce the cooling load by 4000W, around 2.5 times lower than the underfloor air conditioning system.
California, (USA) [31]	hot to cold+ semi humid to dry	Smart Ventilation Controller	Mechanical Ventilation	Experimental work	-Achieve temperature difference ratio (TDR) of 16.3% to 31.9%
Thailand [11]	hot + humid	Radiant Cooling Panel	Radiant and Evaporative	TRNSYS simulation	-Save 56% (2469 kWh) of thermal energy and experimental work compared with conventional air-conditioning system
European and Mediterranen Cities [54]	hot to cold+ humid to dry	Air Movement	Mechanical Ventilation	EnergyPlus simulation	-Cooling energy savings in the range of 17% to 48% in the case of elevated air velocity
China [55]	hot to cold+ humid to dry	Innovative Solar Window	Evaporative	Experimental work	-Enhance thermal and visual comfort -Reduce room heat gain to 196 Wm^{-2} and increase water heat gain by 271 W^{-2} to improve heat absorption
Taipei, Taiwan [56]	hot to warm + humid	Cooling Ceiling	Radiant and Evaporative	CFD simulation and	-Yield energy saving of 13.2% (891 W) experimental work for the chiller and 8.0% (212 W) for the whole cooling system
Venice, Italy [57]	hot to cool + humid	Thermal and Comfort Control	Radiant	MATLAB simulation	-Reduce 12.1% of the cooling energy (539 MWh) and 17.1% (208 Mwh) of the electric energy

From Table 5, it is evident that the active cooling system no longer focuses on mechanical ventilation system alone. The concepts of passive cooling are used not only to enhance performance but also to increase the diversification of the active cooling system. The results also show that cooling system designs integrated with various cooling techniques can save more energy and provide more cooling effect than the design which focuses on just one type of cooling method.

A combination of passive cooling system and active cooling system has shown significant results in saving energy. This cooling system, which is also known as hybrid cooling system utilises the advantages of passive concepts and mechanical cooling technology to optimise its ventilation performance. Further research should be done on this particular cooling system as it ensures higher degree of comfort with lower energy consumption.

CONCLUSION

Comfortable conditions as suggested by ASHRAE standard are not applicable to all countries. The desired thermal comfort varies between climates and is affected by different factors. Thermal comfort is one of the indispensable factors in designing cooling systems. Energy-efficient cooling systems are needed to replace the current electrical air conditioners used in most commercial and residential buildings. This type of cooling system contributes largely to the greenhouse gas emission, which has adverse effects on the environment.

Environmental problems have brought about the utilisation of passive cooling techniques in cooling system designs, which include the application of building elements. Passive cooling systems can save cooling energy and provide good thermal comfort without causing much pollution to the surroundings. Building elements can contribute to cooling outcomes if they are oriented to take full advantage of local climate.

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