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Personal Comfort System Approach Associated with Fan Usage: A Review

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ABSTRACT

Due to the significant energy consumption of the air conditioner (AC), an alternative energy-saving method is required. To achieve this objective, the design of a building's heating, ventilation, and air conditioning (HVAC) systems must comply to the energy consumption criteria without sacrificing occupant comfort. In this instance, the personal comfort system (PCS) provides a promising means of meeting the demand. This paper aims to summarize the recent discoveries and research on personal comfort systems combined with fan usage. The PCS in conjunction with fan use, which is regarded as the most prevalent thermal adaptation behaviour, offers advantages in terms of conditioning the indoor thermal environment, modulating the person's interaction with the surrounding environmental control system, and reducing the excessive use of energy on HVAC.

1. Introduction

Population growth, climate change, and rapid urbanisation all contribute to the worldwide energy demand increase. The United Nations reports that about half of the world's population resides in urban areas. This percentage is predicted to reach 60% by 2030 [1,2]. Countries in Southeast Asia have experienced the most rapid urbanisation. The rapid urbanisation of Southeast Asian nations is fuelled by the increasing need for improved health, education, and housing services, as well as the expanding number of job openings. These appealing potentials will draw urbanisation and immigration from both domestic and international sources [3,4]. Half of the world's population is predicted to live in tropical regions [5].

Due to tremendous urban expansion, major tropical cities are growing denser and hotter, resulting in the formation of microclimates. Additionally, the changeover increases daily energy consumption, especially when it comes to the operation of the heating, ventilation, and air conditioning (HVAC) system [6,7].

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Moreover, according to a number of studies, HVAC usage in the building sector, which includes commercial, residential, medical, and educational buildings, accounts for about half of overall energy usage [8-14]. In this instance, air conditioning is used to create a thermally comfortable indoor environment. This is because buildings in tropical areas are heavily exposed to solar radiation, resulting in an indoor environment that is hot and humid and can be relieved by reducing the setpoint temperature of the air conditioner [15-17].

Increased air conditioning use in the building sector in tropical Southeast Asian nations such as Indonesia, Malaysia, Singapore, and the Philippines, as well as middle-income nations such as Brazil, India, Bangladesh, Pakistan, and Nigeria, is frequently associated with adverse environmental impacts and high carbon emissions [18-20]. One of the most important strategies to lessen the environmental impact of a building's indoor cooling is to lower the quantity of air conditioning utilised without compromising occupants' thermal comfort. To achieve this, the HVAC design must conform to both the thermal comfort standard and the thermal perception of the passengers in order to create a comfortable interior environment with the least amount of air conditioning [15,21,22]. Therefore, future research should concentrate on the development of alternate cooling strategies to lessen reliance on air conditioning.

2. Objective and Structure of the Review

Thermal comfort has undergone development and improvement processes, more importantly, the PCS approach. Utilizing the personal comfort (PCS) approach with fans is one of the strategies for achieving this objective. The PCS application offers prospective advantages in terms of regulating the indoor thermal environment, changing personal contact with the surrounding environmental control system, and decreasing the excessive use of air conditioning [23]. The use of fans in office buildings had piqued the interest of numerous academics, who conducted field and simulation investigations. According to previous researches, the combination of the PCS technique and a desk fan in the office enhanced thermal comfort and energy savings, as well as decreased the feeling of warmth in the space when exposed to high temperatures [24-26]. Considering the above description, this article provides a summary and evaluation of the PCS technique paired with the use of fans.

The literature described in this paper is compiled based on the available scientific database, for instance, Elsevier, Science Direct, Scopus, and Springer Link. The keywords used “thermal comfort” for a general understanding of thermal comfort, followed by “personal comfort system” and “fan usage” for more specific results on PCS combined with fan usage. The reviewed articles range from 1979 to 2022, published in journals such as Energy Buildings, Building and Environment, Urban Climate, and so on, and conference papers. The articles are then screened based on the correlation of their abstract, result, and analysis with the topic, resulting in 48 papers being selected and reviewed.

This paper is organised into 6 sections, with the introduction, objective, and structure specified in sections 1 and 2. The following sections will be the result, starting with section 3 which reviews the basic concept of PCS, and the difference between PCS and the general thermal comfort approach. Section 4 focuses on the example of the application of a fan on PCS. Furthermore, section 5 reports the existing research on the energy-saving potential of PCS usage. Section 6 is the discussion and summary section, including the possible future trend of PCS research.

3. Working Principle of PCS

The typical thermal comfort model emphasises the study of providing comfort for the entire room, whereas the personal comfort system (PCS) emphasises the approach to boosting comfort on an individual level [23]. PCS is based on the premise that occupants of a particular building or location spend the majority of their time at their own work desks and just a little amount of time in other zones. This thermal comfort strategy has various advantages over the conventional one in terms of interior thermal environment, occupant comfort, and HVAC system energy efficiency [23,27].

As practiced by the PCS, local thermal conditioning exploits the psychophysiological phenomena known as alliesthesia, a pleasant psychological sensation resulting from the elimination of physiological thermal stresses [28,29]. Alliesthesia is the simultaneous occurrence of abnormal temperature conditions in many bodily areas. Based on this criterion, occupants can achieve a comfortable environment by using the thermal adaptation method to sensitive body areas [28,29]. Therefore, this comprehension allows for the use of personal cooling devices such as desk fans. For example, the wind breeze from a tropical office desk fan application on the front or rear of the body may chill and relax the body. In chilly climates or throughout the winter, the use of personal heating devices on specific body parts can be quite beneficial [28].

The PCS application can have a beneficial effect on energy efficiency. The standard HVAC system used to alleviate temperature discomfort in an entire office building or room typically consumes a substantial amount of energy, over half of the facility's total energy consumption [16,17]. The PCS technique can reduce the amount of air conditioning used in a whole office by deploying personal cooling devices to specific body regions [28]. This will present options for energy efficiency without compromising thermal comfort.

4. PCS Related to Fan Usage

There are numerous categories of PCS applications, including cooling, heating, and ventilation. The ventilation PCS has received the greatest attention from researchers. This model makes extensive use of devices, including fans, clothing, nozzles, and seating [23]. This PCS mode reduces the skin temperature of the subjects or occupants by increasing airflow over their bodies and promoting the evaporation of perspiration, which provides a cooling sensation.

Yu *et al.,* [30] investigated personalised desk fan usage in an AC-controlled shared office environment with an AMDRL-based control algorithm to assess energy efficiency. This proposed model is a simulation based on the real world that demonstrates convergence, adaptability, robustness, and variety [30]. The simulation demonstrated that by modifying the AC temperature and fan speed, the algorithm might propose a 0.7% - 4.2% reduction in energy consumption and a 64.1%-72% reduction in thermal comfort deviation [30]. Hasama *et al.,* [31] demonstrated the influence of wind velocity (*Va*) on the body part temperature of a thermal manikin in seated and standing positions in a hot and humid environment where a ceiling fan was paired with horizontal airflow simulation using CFD. The convective heat transfer coefficient is seen to rise in lockstep with Va. The convective heat transfer coefficient for a bespoke ceiling fan for the whole-body part is 59-92% at Va 1.48 m/s in comparison to horizontal airflow. The lower body's convective heat transfer coefficient as a result of the ceiling fan is also lower than that of horizontal airflow. According to this study, the body's rate of heat transmission would benefit more from a specially designed ceiling fan and horizontal airflow [31]. In an ambient environment with two responders present at once, Hasama *et al.,* [31] studied the ceiling, and Zhai *et al.,* [32] analysed the PCS. The relative humidity (RH) was kept at 50% while the chamber was set to 26°C, 28°C, and 30°C. Two respondents are shown doing a field measuring session in a room with a bespoke ceiling fan. Respondents are asked to rate ocular dryness, acceptable air movement, relative humidity, and thermal feeling and comfort during the field test, which lasts for 2 hours and 15 minutes. The results show that the perceived air quality is greatly improved by the ceiling fan's airflow (PAQ). More than 80% of respondents preferred a 28°C indoor temperature with a RH setting of 80% and a 30°C indoor temperature with a RH setting of 60% and 80% compared to the results without additional air movement.

Yang *et al.,* [33] examined the application of fans directed at the face and neck in the office through field measurements. During the field measurement, the respondent wears both PCS devices in different sessions while they are free to engage in regular office activities [33]. The participants participated in 12 series of tests with two different air temperatures and three cooling alternatives, including no cooling configuration, face cooling with a face fan, and neck cooling with a neck fan. The results showed that the fan designs reduce the local skin temperature to 2.1^{o}C, with an overall TSV of 1.03-1.14 at 30^{o}C and 1.34-1.65 at 32^{o}C. In addition, there is a potential energy savings of 47.5% compared to traditional HVAC at 24.5^{o}C. Another comparable application of the customised fan. In this study, He *et al.,* [34] investigates the behaviour of occupants when utilising a fan and changing the air conditioning thermostat, as well as how occupants react in a shared office space with a personal desk fan. The field survey contains two respondents in a shared office space with air conditioning. According to Yang *et al.,* [33], the measurement is divided into two sections: the "no fan" configuration and the "with desk fan" configuration. In the "no fan" setup, the respondent has no control over the air conditioner. Nevertheless, the respondent has access to the AC control during the "desk fan" arrangement. The results indicate that the use of a desk fan reduces the respondents' perception of heat and increases thermal comfort at interior temperatures between 28°C and 30°C, but does not meet the comfort criterion [33].

In addition, Udayraj *et al.,* [27] conducted a field measurement within the environmental chamber to examine the personalised desk fan (DF) and the personalised air ventilation clothing (VC) in a warm environment. The chamber is maintained at 28^{o}C, 30^{o}C, 32^{o}C, and 50% relative humidity. Up to 32^{o}C, the cooling performance of the two devices satisfies expectations, providing an acceptable thermal sensation. In addition, there is no discernible change in the mean skin temperature between DF and CV. The research also revealed that CV provides a higher rate of torso cooling, hence providing additional benefits. Pasut *et al.,* [35] investigated additional applications of PCS devices by combining a cooling and heating chair with a tiny desk fan. In this field test, the chairs were placed inside the environmental chamber, which was set up at 16^{o}C, 18^{o}C, and 29^{o}C indoor temperatures. This study evaluated the results of chairs alone and chairs combined with a desk fan to determine the effect of the desk on the overall thermal sensation and level of comfort. According to the results, the temperature sensation of the combined setup is closer to "neutral" than that of the PCS chair. 96% of respondents also favoured PCS chairs with greater airflow. This study also highlighted the significance of airflow around the head, as the questionnaire results indicated that the airflow acceptability rose when the PCS chair was combined with a desk fan [35-37].

5. Energy-saving Potential of PCS

In addition, past studies indicate that the PCS has energy-saving potential, as initially demonstrated by Madsen and Saxhof [38], which indicates a 10% savings. According to Bauman *et al.,* [39], the use of desktop PCs might save up to 18% of cooling energy and 10% of overall electricity consumption in San Jose, United States. Glicksman and Taub [40] claimed that well-built occupant-controlled HVAC systems might lower energy consumption by 5-16%, and by up to 20% if the lighting and plug usage efficiency is also considered. Schiavon's *et al.,* [41] work on PCS in hot and humid regions demonstrates that, depending on the occupants, PCS in the form of tailored ventilation can result in energy savings of up to 51% compared to standard mixing ventilation. According to Zhang *et al.,* [42], PCS-assisted HVAC utilises 17 to 65% less seasonal energy. In addition, the research demonstrates annual energy savings of 30 to 40% for varied room temperatures ranging from 18 to 30°C. The review study by Veselý and Zeiler [43] revealed that the energy-saving potential for various tailored conditioning approaches ranges from 4 to 60%. When the cooling setpoint is increased from 2.5 to 6%, the research may also save energy by 4 to 51% for the specified cooling purpose. Consequently, the majority of research confirms that there is an energy-saving potential for PCS utilisation in varying percentage ranges [23]. The summary of PCS articles is presented in Table 1.

Table 1
Summary of references related to personal thermal comfort from 2015 to 2022

Author	Location	Climate condition	Respondent	Type of fan	Measured building	Findings
Yu *et al.,* [30]	China Personalized desk fan in a shared office; simulation Parameters: T_{indoor}, T_g, RH	Summer	-	Desk fan	Office room	• Energy consumption reduction between 0.7%-4.18% • Thermal comfort deviation between 64.13%-72.08%
Hasama *et al.,* [31]	Singapore Field measurement and CFD simulation using thermal manikin Parameters: T_{indoor}, T_g, RH, T_{skin}	Hot and humid	-	Ceiling fan associated with horizontal airflow	Design studio	• Convective heat transfer on the whole body caused by ceiling fan 32-75% of horizontal airflow. • Convective heat transfer on the lower body caused by the ceiling fan is lower compared to horizontal airflow
Yang *et al.,* [33]	China Parameters: T_{indoor}, T_{skin}, RH, V_a, CO concentration	Warm	16	Face and neck fan	Office room	• The fan around the face and neck area reduces local skin temperature up to 2.1°C • Overall TSV at 30°C is 1.03-1.14, at 32°C is 1.34-1.66. • Energy saving potential 47.5% compared to conventional HVAC at 24.5°C set point
Imagawa *et al.,* [44]	Japan Parameters: T_{indoor}, RH, T_g, V_a	Hot and humid	244	Fan (not specific)	Dwelling	• Fan usage is highest in summer • The stochastic model of fan usage is explained by using outdoor air temperature
He *et al.,* [45]	Asia Europe US Australia	Hot and humid	-	Review study	Residential space, office, classroom, hybrid	• The main trigger of fan usage is the indoor or

	A review study on fan usage in several continents, in hot and humid countries					outdoor temperature, not the building type • Fan usage increases the average neutral temperature around 3K from 25.7° to 28.7°C, and from 27.5° to 30.7°C
Chen *et al.*, [46]	US. Parameters: V_a, Rpm (ceiling fan rotational speed), T_{amb}	Warm	-	Personalized ceiling fan	Office room	• The increase of fan rotational speed enhances the average airspeed, especially in the region below the fan blades • Rotational speed and ceiling fan height contribute more to the speed distribution than fan geometry and distance between fan and ceiling
He *et al.*, [34]	China Parameters: T_{indoor}, RH, V_a, P (electrical power)	Warm	16	Personalized desk fan	Office room	• The desk fan improved thermal comfort at temperatures 28°-30°C, but doesn't fully meet the comfort requirement in a warmer environment
Udayraj *et al.,* [27]	China Parameters: T_{indoor}, RH, V_a	Warm	14	Personalized desk fan Personal air ventilation clothing	Environmental chamber	• Airspeed of the desk fan measured around 1.98 m/s with a comfortable air temperature around 28-32°C • Air ventilation clothing is found to be more effective in cooling than conventional desk fans. • Air ventilation is recommended for a normal office environment and activity up to 32°C of temperature
Luo *et al.*, [28]	Climate chamber Office room simulated using climate chamber; thermal manikin and human subject test. Parameters: T_{indoor}, RH, T_{skin}, V_a	-	20	Desk fan Heating chair Heating pad Heating leg	Environmental chamber	• 80% of respondents accepted a temperature 29°C using a cooled wrist pad, desk fan, and cooled chair • PCS usage 'corrects' the neutral temperature as much as 6.5 K

Mihara *et al.,* [47]	Singapore	Tropic	Manikin study	Ceiling fan	Climate chamber	• Two ceiling fans formed circulation airflows around each fan. Uniform environment • The cooling effect decreases the skin temperature from 1.3°C to 3.3°C
	Field measurement using a ceiling fan and thermal manikin; Va from 0.02 m/s to 2.26 m/s; parameters: T_{indoor}, RH, V_a, T_{skin}					
Lipczynska *et al.,* [48]	Singapore	Tropic	15	Ceiling fan	Office building	• T_{comf} around 26°C – 27°C • Working performance is more related to thermal satisfaction than the room temperature
	Parameters: T_{indoor}, RH, V_a					
Zhai *et al.,* [24]	US.	-	24	Ceiling fan	Environmental chamber	• Respondents choose greater fan speed at higher temperatures 28°C – 30°C • Personal control over air movement has
	Office room simulated using an environmental chamber; parameters: T_{indoor}, RH, V_a					
Zhai *et al.,* [49]	US.	-	16	Ceiling fan	Environmental chamber	• Acceptable wind speed around 0.05-1.8m/s • Air movement significantly improves comfort and lowers humidity sensation without eye-dryness. • Acceptable room temperature around 28°-30°C with humidity around 60-80%
	Field measurement and survey in an office room simulated using an environmental chamber. Parameters: T_{indoor}, RH, T_{skin}, V_a					
Pasut *et al.,* [35]	US	-	23	Cooling char Heating chair	Environmental chamber	• A heated/cooled chair influences the thermal sensation • No significant difference between gender • 92% comfortable at the temperature around 19°C – 29°C
	Field measurement and survey in an office room simulated using an environmental chamber. Parameters: T_{indoor}, RH, V_a					

(T_{indoor} = indoor temperature (°C), T_g = globe temperature (°C), T_{skin} = skin temperature (°C), T_{amb} = ambient temperature (°C), RH = relative humidity (%), V_a = wind speed (m/s))

6. Discussion and Summary

This research highlights the ability of PCS coupled with fan utilisation to provide thermal comfort in a variety of interior environments. In summary, the cited literature reaffirms that the use of PC fans has advantages for preserving thermal comfort. The application of fans is also a broad and promising issue, as there are numerous fan-like devices that can be used with PCS to provide personal comfort, as previously discussed. The simplest and most prevalent example is the use of a desk fan in the office setting. The airflow from the desk fan provides additional cooling to the personal workspace of the occupants, thereby enhancing thermal comfort. This mechanism functions by enhancing the heat exchange between the body and the surrounding environment, but it especially targets the desk's occupant. As a result, the tenant would be able to manage the personal thermal area surrounding him or her, so enhancing productivity and thermal happiness.

In addition, the above-mentioned literature analysis uncovered a strong correlation between the use of fans and the PCS approach to comfort. This benefit can be attained by directing the airflow that provides a cool sensation to the body areas that are sensitive to changes in temperature. For example, when the PCS is combined with a desk fan, the airflow from the desk fan targets the front portion of the body, which, according to past research, is one of the most sensitive areas. Due to the alliesthesia phenomena, the temperature sensation will be enhanced by the extra airflow on this body location. A further illustration is the use of a cooling vest for PCs that provides an even better thermal experience than a desk fan. The cooling vest makes use of the airflow provided by the little fans attached to it. This benefit increases the evidence for the efficacy of alliesthesia, as the airflow from air ventilation gear hits sensitive body areas directly.

The increased airflow provided by the fan application on the PCS improves thermal comfort even in environments with temperatures exceeding 30°C. This demonstrates the capacity of greater air flow to reduce skin temperature, hence reducing the impression of heat during hot weather or indoor activities. Additionally, the airflow generated by the fan will maintain the skin's humidity level and prevent the thermal discomfort caused by high humidity. This is due to the fact that high temperatures, particularly in confined spaces such as office buildings, may be followed by a humid atmosphere, resulting in additional discomfort due to excess humidity. Therefore, by employing the PCS strategy in conjunction with fan devices, people will be more tolerant of hot environments.

Since the PCS application offers energy-saving potential of up to 60% when using a combined approach, future PCS research should focus on the combination between fans and other PCS devices or between PCS devices and other mechanisms, such as the use of air conditioners with a higher temperature setting or other types of ventilation. Future research will be more fruitful due to the possibilities of inter-disciplinary collaboration in order to develop more energy-efficient mechanisms and optimise PCS applications involving fans.

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