ANNEX 69

EBC
Energy in Building and Communities Programme

International Energy Agency

Strategy and Practice of Adaptive Thermal Comfort in Low Energy Buildings (EBC Annex 69) Deliverable 4: Guidelines for Personal Comfort Systems in Low Energy Buildings

Energy in Buildings and Communities Technology Collaboration Programme

February 2021

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Strategy and Practice of Adaptive Thermal Comfort in Low Energy Buildings (EBC Annex 69) Deliverable 4: Guidelines for Personal Comfort Systems in Low Energy Buildings

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February 2021

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Preface

The International Energy Agency

The International Energy Agency (IEA) was established in 1974 within the framework of the Organisation for Economic Co-operation and Development (OECD) to implement an international energy programme. A basic aim of the IEA is to foster international co-operation among the 31 member countries and 11 association countries, and to increase energy security through energy research, development, and demonstration in the fields of technologies for energy efficiency and renewable energy sources.

The IEA Energy in Buildings and Communities Programme

The IEA co-ordinates international energy research and development (R&D) activities through a comprehensive portfolio of Technology Collaboration Programmes (TCPs). The mission of the IEA Energy in Buildings and Communities (IEA EBC) TCP is to support the acceleration of the transformation of the built environment towards more energy efficient and sustainable buildings and communities, by the development and dissemination of knowledge, technologies and processes and other solutions through international collaborative research and open innovation. (Until 2013, the IEA EBC Programme was known as the IEA Energy Conservation in Buildings and Community Systems Programme, ECBCS.)
The high priority research themes in the EBC Strategic Plan 2019-2024 are based on research drivers, national programmes within the EBC participating countries, the Future Buildings Forum (FBF) Think Tank Workshop held in Singapore in October 2017 and a Strategy Planning Workshop held at the EBC Executive Committee Meeting in November 2017. The research themes represent a collective input of the Executive Committee members and Operating Agents to exploit technological and other opportunities to save energy in the buildings sector, and to remove technical obstacles to market penetration of new energy technologies, systems and processes. Future EBC collaborative research and innovation work should have its focus on these themes.
At the Strategy Planning Workshop in 2017, some 40 research themes were developed. From those 40 themes, 10 themes of special high priority have been extracted, taking into consideration a score that was given to each theme at the workshop. The 10 high priority themes can be separated in two types namely 'Objectives' and 'Means'. These two groups are distinguished for a better understanding of the different themes.

Objectives - The strategic objectives of the EBC TCP are as follows:

– reinforcing the technical and economic basis for refurbishment of existing buildings, including financing, engagement of stakeholders and promotion of co-benefits;
– improvement of planning, construction and management processes to reduce the performance gap between design stage assessments and real-world operation;
– the creation of 'low tech', robust and affordable technologies;
– the further development of energy efficient cooling in hot and humid, or dry climates, avoiding mechanical cooling if possible;
– the creation of holistic solution sets for district level systems taking into account energy grids, overall performance, business models, engagement of stakeholders, and transport energy system implications.

Means - The strategic objectives of the EBC TCP will be achieved by the means listed below:

– the creation of tools for supporting design and construction through to operations and maintenance, including building energy standards and life cycle analysis (LCA);
– benefitting from 'living labs' to provide experience of and overcome barriers to adoption of energy efficiency measures;
– improving smart control of building services technical installations, including occupant and operator interfaces;
– addressing data issues in buildings, including non-intrusive and secure data collection;
– the development of building information modelling (BIM) as a game changer, from design and construction through to operations and maintenance.

The themes in both groups can be the subject for new Annexes, but what distinguishes them is that the 'objectives' themes are final goals or solutions (or part of) for an energy efficient built environment, while the 'means' themes are instruments or enablers to reach such a goal. These themes are explained in more detail in the EBC Strategic Plan 2019-2024.

The Executive Committee

Overall control of the IEA EBC Programme is maintained by an Executive Committee, which not only monitors existing projects, but also identifies new strategic areas in which collaborative efforts may be beneficial. As the Programme is based on a contract with the IEA, the projects are legally established as Annexes to the IEA EBC Implementing Agreement. At the present time, the following projects have been initiated by the IEA EBC Executive Committee, with completed projects identified by (*) and joint projects with the IEA Solar Heating and Cooling Technology Collaboration Programme by (☼):

Annex 1: Load Energy Determination of Buildings (*)
Annex 2: Ekistics and Advanced Community Energy Systems (*)
Annex 3: Energy Conservation in Residential Buildings (*)
Annex 4: Glasgow Commercial Building Monitoring (*)
Annex 5: Air Infiltration and Ventilation Centre
Annex 6: Energy Systems and Design of Communities (*)
Annex 7: Local Government Energy Planning (*)
Annex 8: Inhabitants Behaviour with Regard to Ventilation (*)
Annex 9: Minimum Ventilation Rates (*)
Annex 10: Building HVAC System Simulation (*)
Annex 11: Energy Auditing (*)
Annex 12: Windows and Fenestration (*)
Annex 13: Energy Management in Hospitals (*)
Annex 14: Condensation and Energy (*)
Annex 15: Energy Efficiency in Schools (*)
Annex 16: BEMS 1- User Interfaces and System Integration (*)
Annex 17: BEMS 2- Evaluation and Emulation Techniques (*)
Annex 18: Demand Controlled Ventilation Systems (*)
Annex 19: Low Slope Roof Systems (*)
Annex 20: Air Flow Patterns within Buildings (*)
Annex 21: Thermal Modelling (*)
Annex 22: Energy Efficient Communities (*)
Annex 23: Multi Zone Air Flow Modelling (COMIS) (*)
Annex 24: Heat, Air and Moisture Transfer in Envelopes (*)
Annex 25: Real time HVAC Simulation (*)
Annex 26: Energy Efficient Ventilation of Large Enclosures (*)
Annex 27: Evaluation and Demonstration of Domestic Ventilation Systems (*)
Annex 28: Low Energy Cooling Systems (*)
Annex 29: ☼ Daylight in Buildings (*)
Annex 30: Bringing Simulation to Application (*)
Annex 31: Energy-Related Environmental Impact of Buildings (*)
Annex 32: Integral Building Envelope Performance Assessment (*)
Annex 33: Advanced Local Energy Planning (*)
Annex 34: Computer-Aided Evaluation of HVAC System Performance (*)
Annex 35: Design of Energy Efficient Hybrid Ventilation (HYBVENT) (*)
Annex 36: Retrofitting of Educational Buildings (*)
Annex 37: Low Exergy Systems for Heating and Cooling of Buildings (LowEx) (*)
Annex 38: ☼ Solar Sustainable Housing (*)
Annex 39: High Performance Insulation Systems (*)
Annex 40: Building Commissioning to Improve Energy Performance (*)
Annex 41: Whole Building Heat, Air and Moisture Response (MOIST-ENG) (*)
Annex 42: The Simulation of Building-Integrated Fuel Cell and Other Cogeneration Systems (FC+COGEN-SIM) (*)
Annex 43: ☼ Testing and Validation of Building Energy Simulation Tools (*)
Annex 44: Integrating Environmentally Responsive Elements in Buildings (*)
Annex 45: Energy Efficient Electric Lighting for Buildings (*)
Annex 46: Holistic Assessment Tool-kit on Energy Efficient Retrofit Measures for Government Buildings (EnERGo) (*)
Annex 47: Cost-Effective Commissioning for Existing and Low Energy Buildings (*)
Annex 48: Heat Pumping and Reversible Air Conditioning (*)
Annex 49: Low Exergy Systems for High Performance Buildings and Communities (*)
Annex 50: Prefabricated Systems for Low Energy Renovation of Residential Buildings (*)
Annex 51: Energy Efficient Communities (*)
Annex 52: ☼ Towards Net Zero Energy Solar Buildings (*)
Annex 53: Total Energy Use in Buildings: Analysis and Evaluation Methods (*)
Annex 54: Integration of Micro-Generation and Related Energy Technologies in Buildings (*)
Annex 55: Reliability of Energy Efficient Building Retrofitting - Probability Assessment of Performance and Cost (RAP-RETRO) (*)
Annex 56: Cost Effective Energy and CO2 Emissions Optimization in Building Renovation (*)
Annex 57: Evaluation of Embodied Energy and CO2 Equivalent Emissions for Building Construction (*)

Annex 58: Reliable Building Energy Performance Characterisation Based on Full Scale Dynamic Measurements (*)
Annex 59: High Temperature Cooling and Low Temperature Heating in Buildings (*)
Annex 60: New Generation Computational Tools for Building and Community Energy Systems (*)
Annex 61: Business and Technical Concepts for Deep Energy Retrofit of Public Buildings (*)
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Annex 89: Implementing Net Zero Emissions Buildings

Working Group - Energy Efficiency in Educational Buildings (*)
Working Group - Indicators of Energy Efficiency in Cold Climate Buildings (*)
Working Group - Annex 36 Extension: The Energy Concept Adviser (*)
Working Group - HVAC Energy Calculation Methodologies for Non-residential Buildings (*)
Working Group - Cities and Communities (*)
Working Group - Building Energy Codes

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Glossary

ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
CFD	Computational Fluid Dynamics
Clo	Clothing Insulation (1 clo = 0.16 m^2K/W)
CTM	Computational Thermal Mannequin
EBC	Energy in Buildings and Communities
HVAC	Heating Ventilation and Air Conditioning
IEA	International Energy Agency
MET	Metabolic Rate (1 MET = 58 W/m^2)
NTM	Numerical Thermal Mannequin
PCS	Personal Comfort System
PMV	Predicted Mean Vote
$T_{PCS\text{-}air}$	PCS Air Temperature
$T_{PCS\text{-}surface}$	PCS Surface Temperature
T_{room}	Room Air Temperature
V_{PCS}	PCS Air Velocity at the occupant level

1. Introduction

Building operation is one of the most energy-intensive processes globally, accounting for about 40% of the total anthropogenic CO_2 emissions [1]. A significant fraction of the energy used in building operation is spent in maintaining comfortable indoor thermal conditions using active modes of heating, ventilation, and air conditioning (HVAC) [2].

Conventional HVAC technologies follow a total-volume conditioning approach, i.e., they are designed and operated to maintain homogeneous thermal conditions and air quality throughout the built volume. This approach is accepted as business-as-usual due to its simplicity and scalability; however, despite the prevalence of this approach, it lacks at two fronts – it wastes energy on conditioning the unoccupied or transitory spaces and it does not cater to the individual thermal and air-quality preferences of all the occupants.

In order to remediate energy inefficiency and dissatisfaction associated with thermal comfort and air quality, the conventional HVAC technologies were reimagined for a localized application in the form of Personal Comfort Systems (PCS). PCS operate by focussing their conditioning on the immediate surroundings of an occupant and allowing the unoccupied zones to remain in an unconditioned or semi-conditioned state. They also allow an occupant to control the air velocity, temperature, direction, and state of operation of the PCS device. The reduction of the conditioned air volume helps reduce the overall energy use, while the provision of individual control helps improve the thermal comfort and air quality for the occupants.

PCS can serve as retrofit solutions in existing buildings or be integrated within the form of modern-day buildings; such buildings are poised to have a high energy efficiency vis-a-vis heating and cooling while offering their occupants a comfortable, personalized thermal experience.

1.1. Using the guideline

This guideline, developed under the Subtask-B of IEA EBC Annex 69, is intended to introduce the topic of PCS to researchers, design engineers, building services engineers, architects, HVAC manufacturers, or end-users who wish to explore an energy-efficient solution for optimum occupant thermal comfort.

The guideline introduces the theoretical basis of the PCS approach, types of PCS devices, and factors affecting PCS performance in Section 2. It expands upon the choice of PCS devices based on the usage and lays device-specific considerations in Section 3. It concludes with a discourse on the methods to assess PCS performance and references to relevant studies in Section 4.

This guideline attempts to answer the following questions in the corresponding sections:

i.	What is a PCS?	-	Section 2.1
ii.	What are the types and categories of PCS?	-	Section 2.2
iii.	What are the characteristics of PCS?	-	Section 2.3
iv.	How to choose the appropriate PCS?	-	Section 3.1

v.	What should be the operating conditions for various kinds of PCS?	-	Section 3.2
vi.	How can one experimentally assess PCS performance?	-	Section 4
vii.	Where can one find more about PCS?	-	Section 4.5

2. PCS Types and Characteristics

2.1. What is a PCS?

A Personal Comfort System (PCS) can be defined as a device or a combination of devices used with or without a total-volume background room-conditioning strategy to provide localized thermal conditioning with or without fresh air supply through one or multiple modes of heat transfer to an occupant who can control the state of operation of the PCS and may also control the PCS-associated parameters such as temperature, air velocity, or orientation as per their preference.

It is important to note that the term 'PCS' is synonymous with the terms like 'Personal Environmental Control Systems', 'Task/Ambient Conditioning Systems', 'Localized Thermal Distribution Systems', or 'Personalized Air Conditioning Systems', as used by researchers globally.

Due to the recent emergence of PCS, a well-quantified understanding of their characteristics is limited to the design context of open-plan office space with an occupant seated on a moveable chair against a partition-separated desk. In the future, studies are poised to explore the applicability of PCS across varied architectural contexts.

2.2. Types of PCS

PCS are versatile and can be operated for heating, cooling, or ventilation; they can also be combined for simultaneous operation. Based on their usage, they are divided into five categories:

i. Heating PCS
ii. Heating and Ventilation PCS
iii. Cooling PCS
iv. Cooling and Ventilation PCS
v. Ventilation PCS

Heating PCS and Cooling PCS rely on heat transfer without air movement using the heat transfer modes of conduction, radiation, or both, while Ventilation PCS utilize convection to cool the occupants by either recirculating the indoor air or providing fresh air. Heating and Ventilation PCS along with Cooling and Ventilation PCS can be regarded as combination PCS since they utilize all the three modes of heat transfer to condition the localized thermal zone and often involve two or more PCS devices.

It is also important to further distinguish between the Cooling, Cooling and Ventilation, and Ventilation PCS. Conventionally when a PCS provides coolth using a radiant sink or a thermally conductive medium, it is characterized as a Cooling PCS; when a PCS provides coolth by supplying air cooler than the ambient air, it is characterized as a Cooling and Ventilation PCS. These two PCS categories generally utilize compressive cooling (i.e., using the vapour compression cycle) for reducing the temperature of the cooling media. In contrast, Ventilation PCS provides coolth by supplying air at the ambient air temperature – this supply can either be fresh air or recirculated indoor air; when operated at low velocities, they can also be used for improving the air quality without creating a cooling effect.

2.2.1. Heating PCS

Heating PCS include devices such as radiant panels, heated garments, palm warmers, heated seats, foot-warmers, etc., as shown in Figure 1. They utilize conduction and radiation for heat transfer.

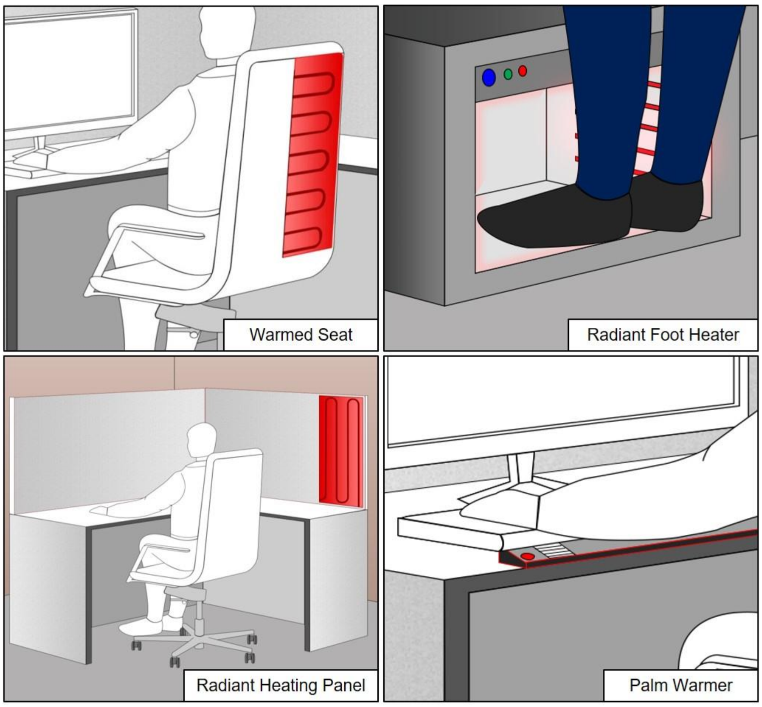

Figure 1. Commonly used Heating PCS devices [3].

2.2.2. Heating and Ventilation PCS

Heating and Ventilation PCS include devices such as movable air terminal devices, radiant panels with fans, desktop-mounted devices, heated and ventilated seats, fixed nozzle-based devices, etc., as shown in Figure 2. They utilize a combination of conduction, convection, and radiation for heat transfer.

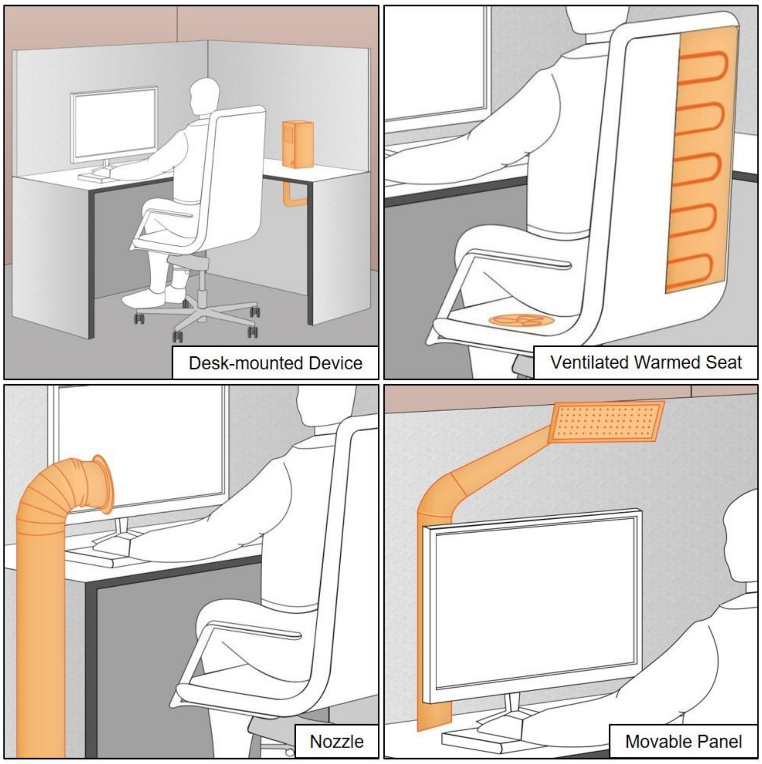

Figure 2. Commonly used Heating and Ventilation PCS devices [3].

2.2.3. Cooling PCS

Cooling PCS include devices such as radiant panels, cooled garments, cooled seats, etc., as shown in Figure 3. They utilize conduction and radiation for heat transfer.

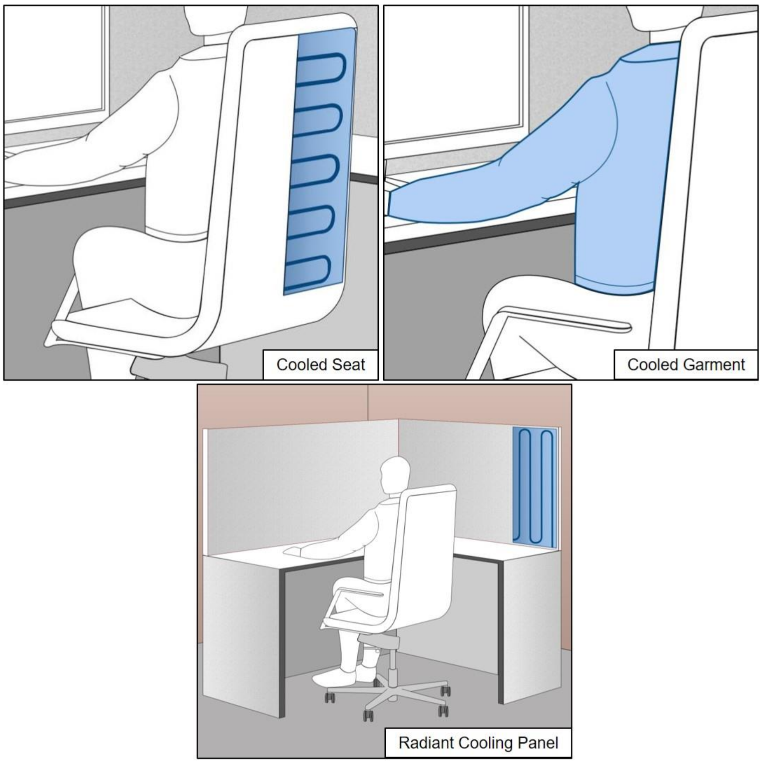

Figure 3. Commonly used Cooling PCS devices [3].

2.2.4. Cooling and Ventilation PCS

Cooling and Ventilation PCS include devices such as ceiling-mounted devices, floor-mounted devices, desktop-mounted devices, movable air terminal devices, radiant panels with fans, cooled and ventilated seats, fixed nozzle-based devices, etc., as shown in Figure 4. They utilize a combination of conduction, convection, and radiation for heat transfer.

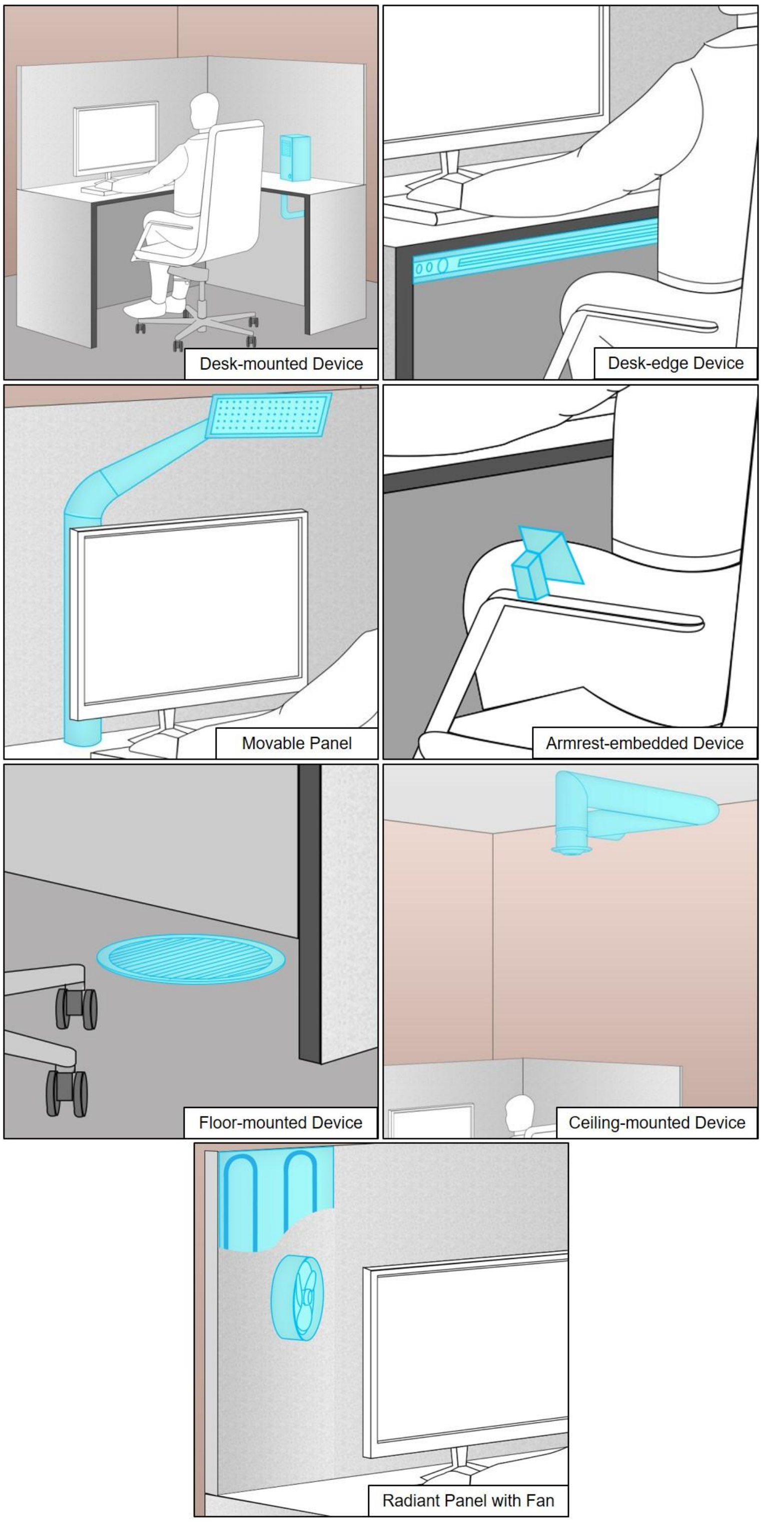

Figure 4. Commonly used Cooling and Ventilation PCS devices [3].

2.2.5. Ventilation PCS

Ventilation PCS include devices such as ceiling-mounted devices, ceiling fans, movable air terminal devices, headrest-embedded devices, desktop-mounted devices, pedestal and table fans, ventilated garments, desk-edge-mounted devices, nozzle-based devices, floor-based devices, etc., as shown in Figure 5. They utilize convection for heat transfer.

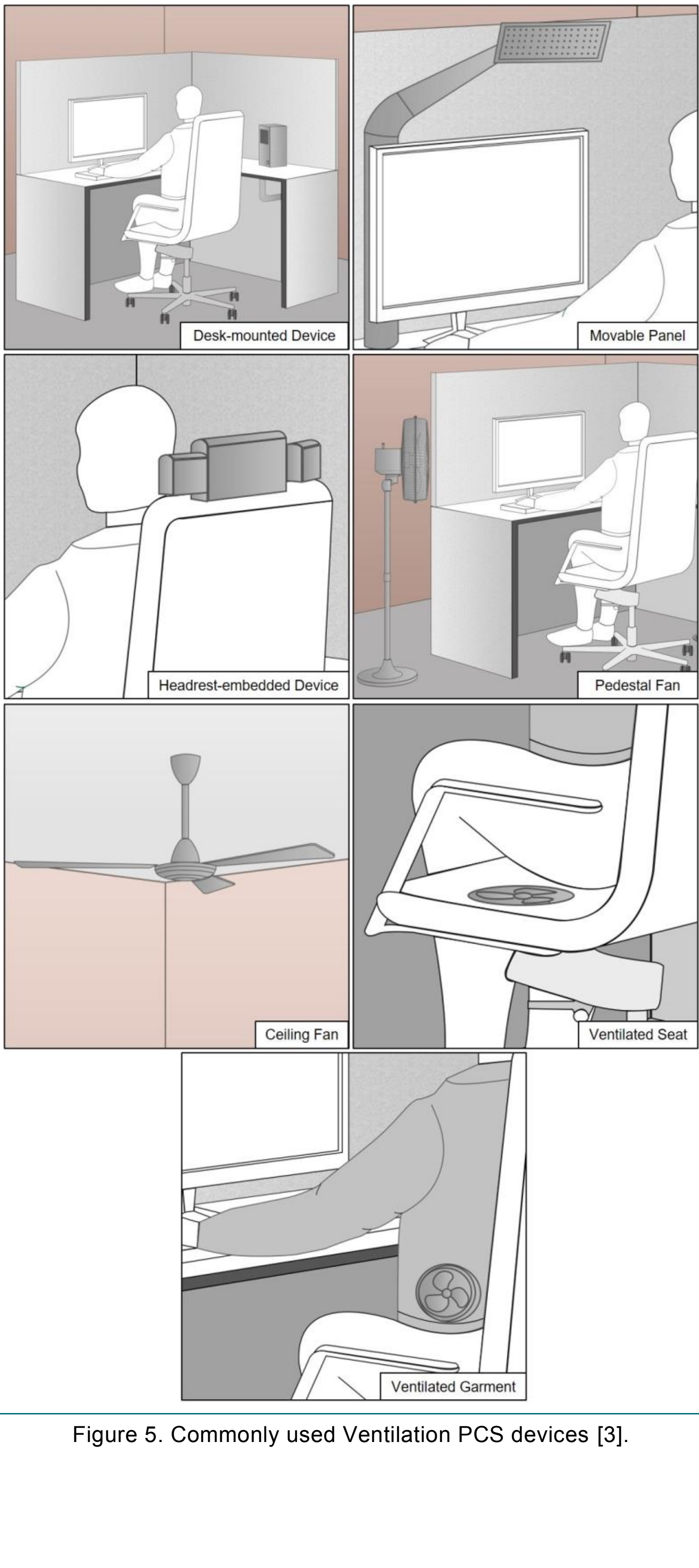

Figure 5. Commonly used Ventilation PCS devices [3].

2.3. PCS Characteristics

PCS performance can be better understood by quantifying the following characteristics:

i. **Room air temperature (T_{room})** determines the ambient conditions for PCS operation. T_{room} depends on various factors; however, outdoor air temperature and background ventilation strategy are the most prominent contributing factors. It is measured in °C (°F in IP Units).

ii. **PCS air/surface temperature ($T_{PCS\text{-}air}$ / $T_{PCS\text{-}surface}$)** determines the extent of heating or cooling effect of a PCS device. $T_{PCS\text{-}air}$ is applicable for the combination PCS, while $T_{PCS\text{-}surface}$ is commonly applicable for Heating PCS and Cooling PCS. $T_{PCS\text{-}air}$ is the same as T_{room} for Ventilation PCS. It is measured in °C (°F in IP Units).

iii. **PCS air velocity (V_{PCS}) at the occupant's body level** determines the extent of convective heat loss. V_{PCS} is critical for the design and operation of Ventilation PCS and combination PCS. It is measured in m/s (ft/s in IP Units).

iv. **Body parts targeted by PCS operation** determine the possibility of local thermal discomfort or spatial alliesthesia. For conduction-dominated PCS, this stands for the body parts in direct contact with the PCS surface; for convection-dominated PCS, this stands for the body parts in line with the PCS airflow; for radiation-dominated PCS, this stands for the body parts contributing to the view factor between the PCS surface and the occupant. It is important to note that the effect of PCS is not limited to the targeted body parts but is rather dominant in comparison to the other body parts.

v. **Position of the PCS with respect to the occupant** determines the location of the PCS device from a design perspective. For radiation-dominated PCS, the position and geometry of the PCS surface helps calculate the crucial parameter of the radiant view factor. For conduction and convection-dominated PCS, the position and geometry of the PCS directly influence which body parts are most affected by PCS operation.

vi. **Restriction of occupant's movement due to PCS operation** determines the allowable range of effect of the PCS. The occupant's movement range should be maximized with a regard to the device-specific constraints.

vii. **Manual control of PCS temperature, air velocity, and direction** determines the extent of control offered to the occupant. Conduction and radiation-dominated PCS can allow for the control of surface temperature alone, while convection-dominated PCS can allow for control of air temperature, air velocity, and possibly, direction.

viii. **Background ventilation strategy** determines the requirement of conditioning to complement the PCS operation. A background ventilation strategy is required if the PCS does not include ventilation or its effect is localized to limited body parts. It may be considered as optional for the PCS which can maintain the appropriate air exchange rates or for the PCS which can cater to whole-body thermal comfort through a trickle-down effect. Based on the outdoor conditions, the background ventilation strategies can include natural ventilation, mixed-mode, or air-conditioned operation.

3. Considerations for PCS Operation

3.1. General Considerations

The selection of PCS depends on multiple factors such as the desired thermal conditions and the design constraints of the conditioned space. Figure 6 helps ascertain the appropriate PCS category.

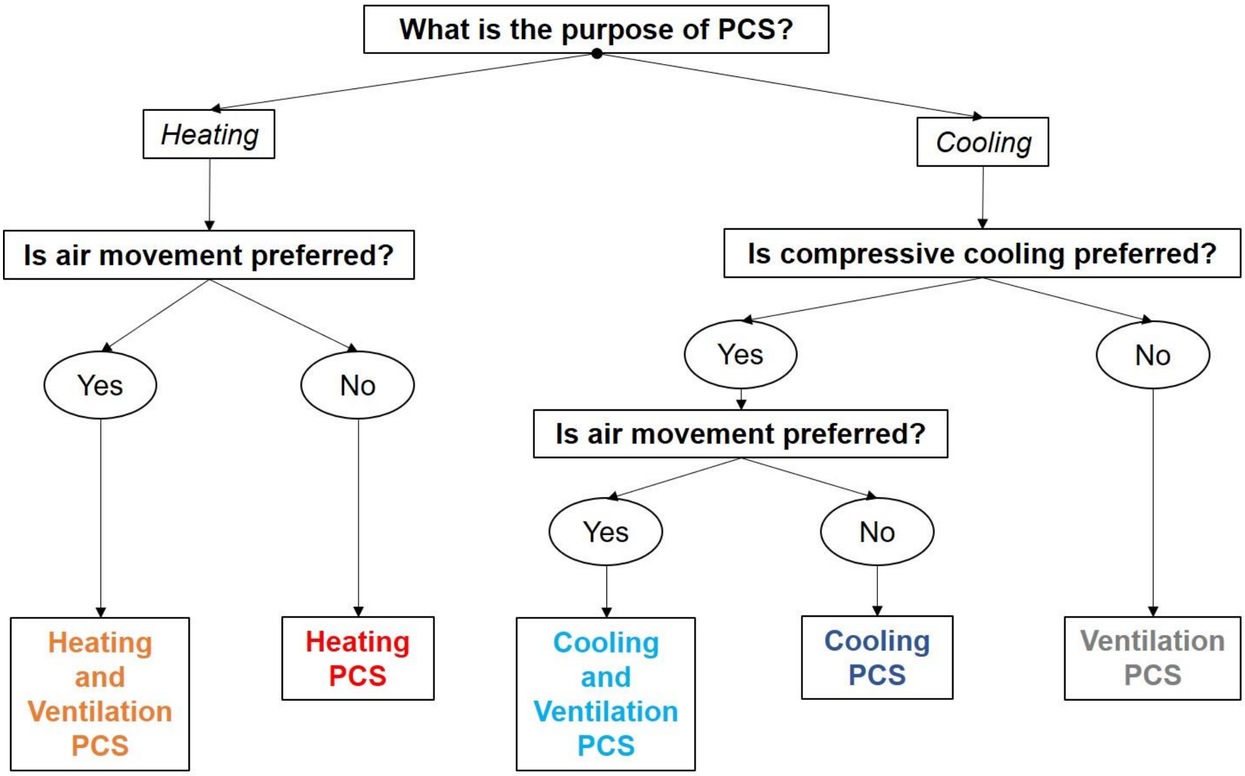

Figure 6. PCS selection flowchart.

Due to the variety of PCS devices, their operation characteristics vary largely with the type of device and the PCS category. However, there are a few general considerations that are consistent for most of the studied cases; the following considerations are applicable when the activity level is less than 1.3 MET (1 MET = 58 W/m^2) and clothing insulation is less than 0.7 clo (1 clo = 0.16 m^{2}K/W):

i. The difference between T_{room} and $T_{PCS\text{-}surf}$ should be less than 23 °C for Radiant Heating PCS and less than 10°C for Radiant Cooling PCS to avoid discomfort, as prescribed by ASHRAE Standard 55 [4].

ii. $T_{PCS\text{-}surf}$ of Radiant Cooling PCS must remain above the dew-point temperature to prevent condensation.

iii. For warm or cool PCS air supply, the difference between the local average T_{air} between the occupant's head and the ankle level should remain under 3°C to avoid thermal discomfort, as prescribed by ASHRAE Standard 55 [4].

iv. For warm or cool PCS air supply, the local average air velocity at the face level should remain less than 0.6 m/s to avoid discomfort due to air movement.

v. For PCS air supply at room temperature, the local average air velocity at the face level should remain less than 1.2 m/s to avoid discomfort due to air movement, as prescribed by ASHRAE Standard 55 [4].

3.2. Device-specific Characteristics

This section lists the characteristics of individual PCS devices mentioned in Section 2.2. The characteristics have been described in Section 2.3

3.2.1. Heating PCS Devices

Table 1. Considerations for Warmed Seat

Device Description	**Warmed Seat heated using electrical elements or embedded water tubes**
T_{room}	> 5 °C
$T_{PCS\text{-}surface}$	< 44 °C
V_{PCS}	N/A
Target Body Parts	Back, Buttocks, Thighs
PCS Position	As the occupant’s seat
Restriction of Movement	Occupant must remain in contact with the seat fabric
Manual Control	Temperature
Background Ventilation	Required

Notes:

- This table is based on the inferences from [5]–[9].
- The Warmed Seat is recommended to be used in combination with a foot heater.

Table 2. Considerations for Radiant Foot Heater

Device Description	**Radiant Foot Heater heated using electrical elements**
T_{room}	> 10 °C
$T_{PCS\text{-}surface}$	< 30 °C
V_{PCS}	N/A
Target Body Parts	Feet
PCS Position	~20 cm from the feet
Restriction of Movement	Feet must remain adjacent to the heated surface
Manual Control	Temperature
Background Ventilation	Required

Notes:

- This table is based on the inferences from [6], [10], [11].

- The Radiant Foot Heater should be operated in the range of T_{room}+10 °C to T_{room}+20 °C for optimum comfort.

Table 3. Considerations for Radiant Heating Panel

Device Description	Radiant Heating Panels placed as desktop partitions heated using electrical elements or embedded water tubes
T_{room}	> 19 °C
$T_{PCS\text{-}surface}$	< 23 °C
V_{PCS}	N/A
Target Body Parts	Face, Chest, Arms, Legs
PCS Position	~50 cm from the occupant, as the desk partition
Restriction of Movement	Occupant should remain in the field of view of the Radiant Panel
Manual Control	Temperature
Background Ventilation	Required

Notes:
- This table is based on the inferences from [12]–[14].
- The exposed surface area of the Radiant Heating Panel to the occupant should be optimized by placing more panels to the left and right sides of the occupant.

Table 4. Considerations for Palm Warmer

Device Description	Desktop-based Palm Warmers heated using electrical elements
T_{room}	> 18 °C
$T_{PCS\text{-}surface}$	< 35 °C
V_{PCS}	N/A
Target Body Parts	Palms
PCS Position	On the desktop, between the computer keyboard and the occupant.
Restriction of Movement	Palms must be in direct contact with the device surface
Manual Control	None
Background Ventilation	Required

Notes:
- This table is based on the inferences from [11], [12].
- The device must be placed such that it acts as a resting spot for the hands while typing.

3.2.2. Heating and Ventilation PCS Devices

Table 5. Considerations for Desk-mounted Device

Device Description	Desk-mounted air-terminal device supplying air warmed through compressive heating
T_{room}	> 19 °C
$T_{PCS\text{-}air}$	< 25 °C
V_{PCS}	< 1 m/s

Target Body Parts	Face, Arms, Chest, Front Thighs
PCS Position	~50 cm from the occupant, on the desktop
Restriction of Movement	Occupant must remain in the flow direction
Manual Control	Temperature, Air Velocity, Direction
Background Ventilation	Optional

Notes:
- This table is based on the inferences from [15]–[17].
- The device should be used in combination with a Foot-heating Panel; the airflow should not directly strike the eyes of the occupant as it might lead to dry-eye discomfort.

Table 6. Considerations for Ventilated and Warmed Seat

Device Description	**Warmed seat with embedded fans – the seat is warmed using electrical elements or embedded water pipes**
T_{room}	> 20 °C
$T_{PCS\text{-}air}$	< 45 °C
V_{PCS}	< 0.7 m/s
Target Body Parts	Neck, Back, Buttocks, Back Thighs
PCS Position	As the occupant's seat
Restriction of Movement	Occupant must remain in contact with the seat
Manual Control	Temperature, Air velocity
Background Ventilation	Required

Notes:
- This table is based on the inferences from [13], [14], [18].
- The device should be used in combination with a Foot-heating Panel

Table 7. Considerations for Nozzle

Device Description	**Nozzle-based air terminal device supplying air warmed through compressive heating**
T_{room}	> 19 °C
$T_{PCS\text{-}air}$	< 50 °C
V_{PCS}	< 1 m/s
Target Body Parts	Head, Neck
PCS Position	~1 m from the occupant, directed towards the head
Restriction of Movement	Occupant must remain in the flow direction
Manual Control	Temperature, Air velocity
Background Ventilation	Optional

Notes:
- This table is based on the inferences from [19].
- The air stream should enter the occupant's breathing zone parallel to the cheek, avoiding direct contact with the eyes.

Table 8. Considerations for Movable Panel

Device Description	Desk-mounted movable air terminal device supplying air warmed through compressive heating
T_{room}	> 20 °C
$T_{PCS\text{-}air}$	< 26 °C
V_{PCS}	< 1 m/s
Target Body Parts	Head, Neck, Chest, Arms
PCS Position	~50 cm from the occupant, directed towards the head
Restriction of Movement	Occupant is free to move within the flow region while adjusting the direction of the panel
Manual Control	Temperature, Air velocity, Direction
Background Ventilation	Optional

Notes:

- This table is based on the inferences from [20], [21].
- The air stream should enter the occupant's breathing zone parallel to the cheek, avoiding direct contact with the eyes.

3.2.3. Cooling PCS Devices

Table 9. Considerations for Cooled Seat

Device Description	Seat cooling using embedded water pipes cooled using compressive cooling
T_{room}	< 45 °C
$T_{PCS\text{-}air}$	> 18 °C
V_{PCS}	N/A
Target Body Parts	Back, Buttocks, Thighs
PCS Position	As the occupant's seat
Restriction of Movement	Occupant must remain in contact with the seat fabric
Manual Control	Temperature
Background Ventilation	Required

Notes:

- This table is based on the inferences from [7]–[9], [22].
- It is recommended to use a movable Desktop Fan in combination with the Cooled Seat.

Table 10.Considerations for Cooled Garment

Device Description	Jacket-like garment using phase change materials or compressive cool air supply
T_{room}	< 34 °C
$T_{PCS\text{-}air}$	> 21 °C
V_{PCS}	N/A
Target Body Parts	Chest, Back, Shoulders

PCS Position	As the occupant's vest
Restriction of Movement	None
Manual Control	Temperature
Background Ventilation	Required

Notes:

- This table is based on the inferences from [23], [24].
- Typical Cooled Garments are battery-operated, with an average charge lasting for ~6 hours; they weigh around 3-5 kg; Cooled Garments with phase change materials typically perform better than those with embedded fans.

Table 11. Considerations for Radiant Cooling Panel

Device Description	**Radiant Cooling Panels placed as desktop partitions cooled using embedded water pipes using compressive cooling**
T_{room}	< 32 °C
$T_{PCS\text{-}air}$	> 17 °C
V_{PCS}	N/A
Target Body Parts	Face, Chest, Arms, Legs
PCS Position	~50 cm from the occupant, as the desk partition
Restriction of Movement	Occupant should remain in the field of view of the Radiant Panel
Manual Control	Temperature
Background Ventilation	Required

Notes:

- This table is based on the inferences from [25]–[27].
- The exposed surface area of the Radiant Cooling Panel to the occupant should be optimized by placing more panels to the left and right sides of the occupant.

3.2.4. Cooling and Ventilation PCS Devices

Table 12. Considerations for Desk-mounted Device

Device Description	**Desk-mounted air-terminal device supplying air cooled through compressive cooling**
T_{room}	< 30 °C
$T_{PCS\text{-}air}$	> 15 °C
V_{PCS}	< 1.5 m/s
Target Body Parts	Face, Neck, Chest
PCS Position	~50 cm from the occupant, on the desktop
Restriction of Movement	Occupant must remain in the flow direction
Manual Control	Temperature, Air Velocity
Background Ventilation	Optional

Notes:

- This table is based on the inferences from [14], [16], [28]–[30].

- The air stream should enter the occupant's breathing zone parallel to the cheek, avoiding direct contact with the eyes.

Table 13. Considerations for Desk-edge based Device.

Device Description	**Desk-edge mounted horizontal air terminal slits supplying air cooled through compressive cooling**
T_{room}	< 26 °C
$T_{PCS\text{-}air}$	> 20 °C
V_{PCS}	< 1 m/s
Target Body Parts	Face, Neck
PCS Position	~ 10 cm from the occupant, on the desk edge
Restriction of Movement	Occupant must remain directly above the device outlet
Manual Control	Temperature, Air Velocity, Direction
Background Ventilation	Optional

Notes:
- This table is based on the inferences from [31]–[34].
- The device should preferably provide a vertical airflow directly under the occupant's chin and should have adjustable vanes for manual adjustment of airflow direction.

Table 14. Considerations for Movable Panel

Device Description	**Desk-mounted movable air terminal device supplying air cooled through compressive cooling**
T_{room}	< 30 °C
$T_{PCS\text{-}air}$	> 20 °C
V_{PCS}	< 1 m/s
Target Body Parts	Face, Neck, Chest, Shoulders, Arms
PCS Position	~50 cm from the occupant, on the desktop
Restriction of Movement	Occupant is free to move within the flow region while adjusting the direction of the panel
Manual Control	Temperature, Air Velocity, Direction
Background Ventilation	Optional

Notes:
- This table is based on the inferences from [35]–[39].
- The air stream should enter the occupant's breathing zone parallel to the cheek, avoiding direct contact with the eyes.

Table 15. Considerations for Armrest-embedded Device

Device Description	**Seat armrest-mounted air terminal device supplying air cooled through compressive cooling**
T_{room}	< 25 °C
$T_{PCS\text{-}air}$	> 20 °C
V_{PCS}	< 0.7 m/s

Target Body Parts	Face, Neck, Chest, Arms
PCS Position	As the armrest of the occupant's seat
Restriction of Movement	Occupant must remain seated and the armrests must not be blocked
Manual Control	Temperature, Air Velocity
Background Ventilation	Required

Notes:
- This table is based on the inferences from [40], [41].
- The airflow should strike the occupant at a 45° angle from below.

Table 16. Considerations for Floor-mounted Device

Device Description	**Floor-mounted air terminal device supplying air cooled through compressive cooling, also known as underfloor air distribution**
T_{room}	< 27 °C
$T_{PCS\text{-}air}$	> 16 °C
V_{PCS}	< 1 m/s
Target Body Parts	Feet, Legs, Thighs, Buttocks
PCS Position	~50 cm from the occupant's seat, on the floor
Restriction of Movement	Occupant can move radially around the device
Manual Control	Temperature, Air Velocity
Background Ventilation	Optional

Notes:
- This table is based on the inferences from [29], [30], [42], [43].
- The device should be used in combination with a desk-mounted or movable panel device for better control.

Table 17. Considerations for Ceiling-mounted Device

Device Description	**Ceiling-mounted air terminal device supplying air cooled through compressive cooling**
T_{room}	< 29 °C
$T_{PCS\text{-}air}$	> 21 °C
V_{PCS}	< 0.8 m/s
Target Body Parts	Head, Neck, Shoulders
PCS Position	~1.5 m above the occupant's head, on the ceiling
Restriction of Movement	Occupant can move around the vertical flow
Manual Control	Temperature, Air Velocity
Background Ventilation	Optional

Notes:
- This table is based on the inferences from [44]–[46].
- The airflow should have a low turbulence intensity and long range.

Table 18. Considerations for Radiant Cooling Panel with Fan.

Device Description	Radiant panels placed as desktop partitions with embedded water pipes cooled using compressive cooling - used in combination with low-power desktop fans
T_{room}	< 28 °C
$T_{PCS\text{-}air}$	> 17 °C
V_{PCS}	< 1.5 m/s
Target Body Parts	Face, Neck, Chest, Arms
PCS Position	Radiant Panels as the desk partition ~50 cm from the occupant; Fan on the desktop, ~40 cm from the occupant
Restriction of Movement	Occupant must remain exposed to the radiant surface and can move fan as per comfort
Manual Control	Temperature, Air Velocity, Direction
Background Ventilation	Optional

Notes:

- This table is based on the inferences from [47], [48].
- The exposed surface area of the radiant panel to the occupant should be maximized; the airflow from the fan should not strike the desktop.

3.2.5. Ventilation PCS Devices

Table 19. Considerations for Desktop-based Devices

Device Description	Desk-mounted air-terminal device supplying (fresh or recirculated) air at room temperature
T_{room}	< 30 °C
$T_{PCS\text{-}air}$	Same as T_{room}
V_{PCS}	< 1.5 m/s
Target Body Parts	Face, Neck, Chest, Arms
PCS Position	~50 cm from the occupant, on the desktop
Restriction of Movement	Occupant can move while manually changing the airflow direction of the fan/device
Manual Control	Air Velocity, Direction
Background Ventilation	Optional

Notes:

- This table is based on the inferences from [28], [49]–[52].
- The airflow must not strike the desktop and the airflow pattern should preferably be kept as close to the natural wind pattern in terms of its turbulence and frequency of variability.
- Dry-eye discomfort should be mitigated by optimising the airflow pattern and direction.

Table 20. Considerations for Movable Panel

Device Description	Desktop based movable air-terminal device supplying (fresh or recirculated) air at room temperature
T_{room}	< 28 °C

$T_{PCS\text{-}air}$	Same as T_{room}
V_{PCS}	< 0.7 m/s
Target Body Parts	Face, Neck, Chest, Arms
PCS Position	~50 cm from the occupant, on the desktop
Restriction of Movement	Occupant is free to move within the flow region while adjusting the direction of the panel
Manual Control	Air Velocity, Direction
Background Ventilation	Optional

Notes:
- This table is based on the inferences from [13], [48], [53]–[55].
- The air stream should enter the occupant's breathing zone parallel to the cheek, avoiding direct contact with the eyes.

Table 21. Considerations for Headrest-embedded Device.

Device Description	Seat headrest-based air-terminal device supplying recirculated air at room temperature
T_{room}	< 26 °C
$T_{PCS\text{-}air}$	Same as T_{room}
V_{PCS}	< 0.6 m/s
Target Body Parts	Face
PCS Position	As the seat headrest, next to the cheeks
Restriction of Movement	Occupant must keep the head on the headrest.
Manual Control	Air Velocity
Background Ventilation	Required

Notes:
- This table is based on the inferences from [56]–[59].
- Air terminal devices with a large opening area require low air velocity and vice versa.

Table 22. Considerations for Pedestal Fan

Device Description	Pedestal fan supplying recirculated air at room temperature
T_{room}	< 30 °C
$T_{PCS\text{-}air}$	Same as T_{room}
V_{PCS}	< 2.5 m/s
Target Body Parts	Whole Body
PCS Position	~ 1.5 m from the occupant
Restriction of Movement	Occupant is free to move within the flow region while adjusting the direction of the fan
Manual Control	Air Velocity, Direction
Background Ventilation	Optional

Notes:

- This table is based on the inferences from [60]–[63].
- The fan direction should be kept such that it does not cause discomfort by displacement of light-weight objects on the desktop.
- Dry-eye discomfort should be mitigated by optimising the airflow pattern and direction.

Table 23. Considerations for Ceiling Fan.

Device Description	Ceiling-mounted fan supplying recirculated air at room temperature
T_{room}	< 30 °C
$T_{PCS\text{-}air}$	Same as T_{room}
V_{PCS}	< 1 m/s
Target Body Parts	Head, Shoulders
PCS Position	~1.5 m above the occupant, on the ceiling
Restriction of Movement	Occupant must remain in the flow direction
Manual Control	Air Velocity
Background Ventilation	Optional

Notes:

- This table is based on the inferences from [64]–[67].
- To optimize the effect of the fan, it should be placed on the ceiling right above the desktop, with the rotating blades at an angle of 30-45° from the ceiling.

Table 24. Considerations for Ventilated Seat

Device Description	Ventilated seat embedded with fans supplying recirculated air at room temperature
T_{room}	< 32 °C
$T_{PCS\text{-}air}$	Same as T_{room}
V_{PCS}	< 2 m/s
Target Body Parts	Buttocks, Back, Thighs
PCS Position	As the occupant's seat
Restriction of Movement	Occupant must remain in contact with the seat fabric
Manual Control	Air Velocity
Background Ventilation	Required

Notes:

- This table is based on the inferences from [68]–[71].
- The occupant’s body should not block the complete airflow and it should reach the breathing zone.

Table 25. Considerations for Ventilated Garment

Device Description	Jacket-like garment embedded with low-wattage fans supplying recirculated air at room temperature
T_{room}	< 34 °C
$T_{PCS\text{-}air}$	Same as T_{room}

V_{PCS}	Equivalent to a flow rate of < 22 L/s
Target Body Parts	Chest, Back
PCS Position	As the occupant's vest
Restriction of Movement	No restriction in movement
Manual Control	Air Velocity
Background Ventilation	Required

Note:

- This table is based on the inferences from [72], [73].
- A typical battery-operated ventilated garment operates up to 7 hours on 60% output power.

4. Assessing PCS Performance

PCS performance in terms of their efficiency in providing satisfactory thermal and air quality conditions can be examined using simulations and physical experiments. The simulation approach involves the modelling of the PCS and its ambient conditions in a digital environment and calculating the desired parameters using mathematical models and Computational Fluid Dynamics (CFD) packages. In comparison, the physical experiment approach involves real-world measurement of PCS parameters subject to thermal mannequins and human subjects. This approach can be executed in a climate-controlled laboratory environment or operational buildings with their respective occupants.

A major volume of the present-day studies on PCS focus on the physical experiment approach in controlled conditions using thermal mannequins. However, in order to establish a refined understanding of the nuances of any PCS device, the thermal mannequin study should be accordingly coupled with a human subject study. A combination of these two approaches does not involve complex mathematical modelling or high processing power and sufficiently captures the subjectivity of occupant-associated performance parameters. Nevertheless, based on the scope of the study, one can opt for either of the following approaches to assess PCS performance.

It is important to note that this guideline does not deal with other aspects of PCS performance, such as energy efficiency, occupant health, occupant productivity, air quality, etc. Understanding these aspects is crucial for a holistic evaluation of PCS, while simultaneously, the literature on these aspects is scarcely available; one can refer Rawal et al. [74] for a corresponding disucssion.

4.1. Simulations

The simulation approach digitally replicates the geometry of a representative enclosure, PCS assembly, relevant building components, and the occupant using a 3-D modelling package. The boundary conditions of ambient temperature, humidity, enclosure surface temperature, etc. are defined along with the direction and magnitude of the PCS air velocity, background ventilation, and pollution sources. The modelled setup is meshed, i.e., discretized into small elements which serve as local approximations of the entire domain. The desired parameters are calculated for these elements subject to the specified boundary conditions, turbulence model, and convergence criteria.

One of the most crucial considerations under this approach is defining a realistic numerical model of the occupant; it is also termed as a numerical thermal mannequin (NTM) or a computational thermal mannequin (CTM). These models incorporate the findings from experimental research on the thermal properties of the human body as well as thermoregulation models. JOS-3 is the latest version of a well-validated thermoregulation model which accounts for the human thermoregulatory mechanisms of vasoconstriction, vasodilation, perspiration, and shivering, while providing insight into the skin temperature, core temperature, heat flux, and associated output parameters for individual body parts in transient and non-uniform thermal environments [75]. These parameters can be used to predict the thermal sensation and comfort of the occupant at the specified boundary conditions using numerical psychological models subject to the varied boundary conditions for PCS operation [76].

In addition to accounting for the thermal and comfort-associated parameters, this approach helps account for the air quality parameters such as pollutant concentration, air change effectiveness, ventilation effectiveness, personal air utilization efficiency, intake fraction, personal exposure effectiveness, re-inhaled exposure risk, cross-infection risk, and pollution exposure reduction index.

This approach offers flexibility through repeatable parametric analysis with cost-effectiveness. It also provides a deeper insight into the heat transfer processes and fluid flow fields around the occupant with an unparalleled granularity. However, this approach requires advanced domain expertise and understanding of the underlying simulation parameters to realistically simulate a real-world scenario.

The study by Gao et al. can be referred to as an example of this approach [77]. The study simulated a movable panel-based device with the background ventilation strategies of displacement ventilation and mixing ventilation. The setup, as shown in Figure 7, was simulated with the help of body-fitted coordinates and unstructured grids, with a finer mesh closer to the numerical thermal mannequin. The CFD simulation employed a standard k-ε turbulence model. The thermal properties of the mannequin were defined using the CBE thermoregulation model [78] and it was coupled with the CFD simulation and validated against the PMV model. After setting up the simulation successfully, the study simulated the overall thermal sensation and comfort for a combination of PCS operation modes to derive relevant conclusions.

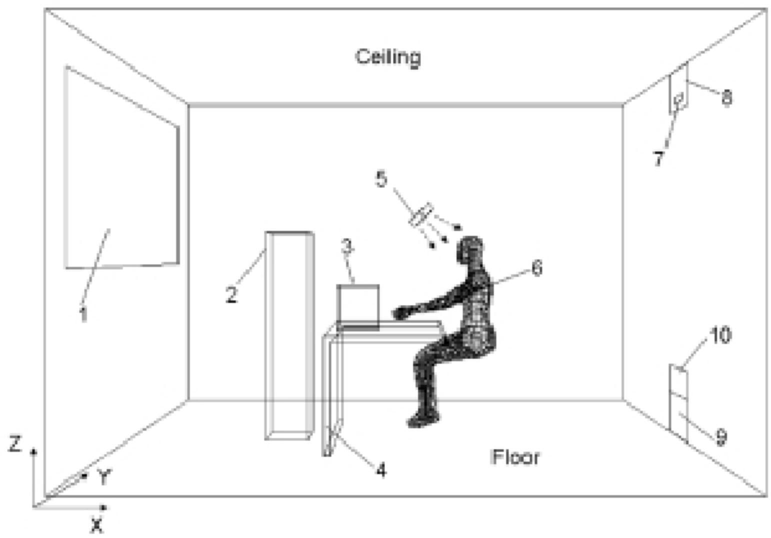

Figure 7. Simulation setup with a numerical thermal mannequin, taken from Gao et al. [77]

4.2. Laboratory Experiments with Mannequins

This approach assesses PCS performance in a climate-controlled environment using thermal mannequins. The thermal mannequins are designed to replicate the thermal properties of a human body and exchange heat with their thermal ambience. The mannequins provide direct outputs of thermal and comfort parameters like skin temperature, heat flux, equivalent temperature, PMV, etc. for the whole body and the local body parts. These parameters are recorded at the steady-state conditions, i.e., as the variation in the parameters stabilizes in response to the climate-controlled environment. The thermal parameters of the climate-controlled environment are maintained within a narrow band of the desired value using a feedback-controlled setup. The environment is also ensured to be homogeneous in regard to the air temperature and air velocity using spot and long-term monitoring.

As an advantage over humans, thermal mannequins can be subjected to long-term testing without the concern of fatigue. Given their inanimate nature, they offer a high degree of controllability over the nature of the experiment (through variable clothing, posture, PCS orientation, etc.) and ensure an objective evaluation of PCS. The laboratory-mannequin approach provides a common ground for the comparison of the performance of various PCS. This approach has a few limitations centred on subjectivity – it does not account for the sick-building symptoms an occupant might encounter and it generalizes the physical properties of the occupants as an individual form, leading to a likely disconnect with the real-world effect of the PCS. This approach also does not allow the study of the effects of human movement.

The study by Rawal et al. can be referred to as an example of this approach [79]. The study examined a radiant cooling PCS using experiments on a thermal mannequin in a climate-controlled chamber, as shown in Figure 8. The thermal mannequin was based on a female body and provided local values for skin temperature and heat flux for 22 individual body parts. The mannequin was operated in 'comfort mode', i.e., the mannequin's heat transfer was controlled to achieve comfortable conditions. The study measured the comfort and cooling thermal energy variation of the PCS subject to 15 cases involving a combination of ambient air temperatures and PCS surface temperatures.

Figure 8. Laboratory experiment setup with a thermal mannequin, taken from Rawal et al. [79]

4.3. Laboratory Experiments with Human Subjects

This approach assesses PCS performance in a climate-controlled environment using acclimatized human subjects. Unlike the laboratory-mannequin approach, the key outputs from this approach are the subjective responses of thermal comfort, thermal sensation, thermal preference, thermal acceptability, air movement acceptability, and eye/nose irritation. This approach can also involve the measurement of overall and local skin temperature and core temperature of the subjects along with their productivity level. Similar to the laboratory-mannequin approach, the thermal parameters of the ambient environment under this approach are regulated using a feedback-controlled setup and ensured to be homogeneous.

This approach offers a more realistic understanding of occupants' response to PCS through a subjective quantification of the comfort parameters in comparison to the laboratory-mannequin approach. It also gives an insight into the aspects of local thermal discomfort and factors like dry-eye-discomfort. However, there are multiple limitations of this approach. Firstly, this approach is time-intensive since any statistically significant result requires a significant sample size. Secondly, it offers limited flexibility in regard to the extreme experimental conditions; for instance, subjects might show reluctance to prolonged exposure to elevated or reduced indoor setpoints. Thirdly, it increases the complexity in capturing the dynamic real-world thermal environment of open-plan office spaces with variable metabolic rates, variable clothing, occupant movement, and other factors.

The study by Kaczmarczyk et al. can be referred to as an example of this approach [80]. The study examined the performance of a movable panel-based PCS, as shown in Figure 9, in combination with mixing ventilation using surveys of 60 human subjects. The subjects were trained on operating the PCS and responding to the thermal comfort survey; however, they were not informed about the test conditions to prevent bias. In addition to assessing the thermal characteristics, the study also included an indoor polluting source. The study monitored the subjects' thermal comfort, sensation, preference, perceived air quality, and sick building symptoms.

Figure 9. Laboratory experiment setup with the seat for a human subject, taken from Kaczmarczyk et al. [80]

4.4. Field Experiments with Human Subjects

The field experiment approach assesses PCS performance in a real-world environment through human subjects. Similar to the laboratory-human approach, this approach accounts for the subjective responses of thermal comfort, thermal sensation, thermal preference, thermal acceptability, air movement acceptability, eye/nose irritation, and workplace productivity. This approach may not allow the control of the indoor thermal parameters; however, they are monitored on a long-term basis. The subjects may also be allowed to participate in the activities characterized by their day-to-day habits. The extent of control over the subject's action is unique to the scope of the study.

This approach offers the most realistic understanding of occupants' response to PCS among all the experimental approaches. It gives an insight into the behavioural aspect of occupants in real-world conditions. However, despite offering the most realistic understanding of PCS, this approach has certain limitations. It is the most time-intensive and resource-intensive approach among all. To add, owing to the degree of randomness associated with uncontrolled real-world conditions, this approach may not necessarily offer a clear quantification of the extent of factors affecting the subjective parameters and only in exceptional cases permits the analysis of cause-effect relationships.

The study by Kim et al. can be referred to as an example of this approach [81]. The study monitored a seat-based PCS integrated with fans and heating strips controlled using a digital controller, as shown in Figure 10. The network of 37 seat-based PCS, spread across two floors of an open-plan building, was connected to the internet for instantaneous data monitoring and control. The study monitored the PCS operation, PCS occupancy status, air temperature, and relative humidity near the occupant. Additionally, the occupants were surveyed for thermal comfort, sensation, and preference in the presence of the PCS. The study also recorded the general feedback of the occupants on using the PCS.

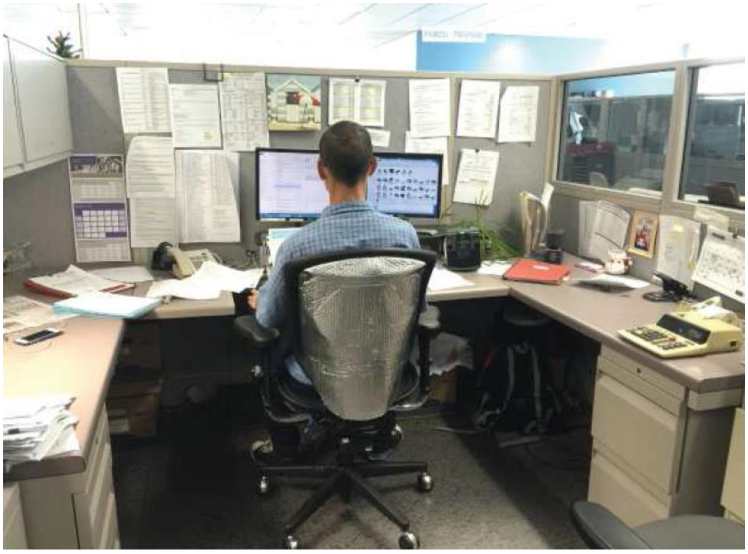

Figure 10. Field experiment setup with a seated human subject/occupant, taken from Kim et al. [81]

4.5. Additional Resources

In addition to the studies cited in the above sections, Table 26 lists the review studies, technical reports, and research projects, which can be referred to for further insights into the topic of PCS.

Table 26. Additional resources.

Review Studies	Rawal et al., 2020	[74]
	Warthmann et al., 2018	[82]
	Zhang et al., 2015	[83]
	André et al., 2020	[84]
Technical Reports	Bauman et al., 1996	[85]
	Rønneseth, 2018	[86]
Research Projects	IEA EBC Annex 69	[87]
	IEA EBC Annex 79	[88]

5. Conclusion

Personal Comfort Systems (PCS) come in a variety of types and can be used for heating, cooling, ventilation, or a combination of uses. This guideline categorizes the types of PCS, identifies and defines the important PCS characteristics on a device-by-device basis, and explains the research methods for assessing PCS performance. The document draws its findings from the latest peer-reviewed publications and includes sources for additional exploration. Overall, PCS offer a significant potential to improve the occupants' thermal comfort perception while reducing the energy-intense conditioning requirements.

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ANNEX 69

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