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Radiant Cooling, Solar Energy, and Vegetation for Office Space Cooling

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KURZFASSUNG

Die Auswirkungen von Klimawandel und städtischen Wärmeinseln haben zu einem erhöhten Kühlenergiebedarf von Gebäude geführt. Herkömmliche Kühlgeräte stellen aufgrund ihres erheblichen Energieverbrauchs keine geeignete Lösung für diese aktuelle Herausforderung dar. Aus diesem Grund werden alternative Strategien benötigt, um Gebäude zu kühlen. Strahlungskühlsysteme stellen eine mögliche Lösung dar. Einer ihrer Vorteile ist die Energieeffizienz. Darüber hinaus können Strahlungskühlungstechnologien den thermischen Komfort von Gebäudenutzern verbessern. Trotz ihrer Vorteile sind klassische Strahlungskühlungselemente möglicherweise nicht überall und unter allen Umständen einsetzbar. Eine Herausforderung im Zusammenhang mit klassischen Lösungen ist, dass die Kühlleistung des Elements möglicherweise aufgrund des Kondensationsrisikos begrenzt werden muss. Ziel dieser Masterarbeit war es, eine Anzahl von zuvor vorgeschlagenen alternativen Strahlungskühlungselementen zu überprüfen. Diese sollen ebenfalls solare Energien nutzen. Drei wichtige Konzepte sind für diese Vorschläge relevant: *i)* Strahlungskühlpaneele näher an die Nutzer bringen, *ii)* Senkung der Oberflächentemperaturen des Elements indem Kondensation zugelassen wird, und *iii)* Verwendung von Vegetation im Design. Das Potenzial dieser Lösungen wurde anhand von zwei Fallstudien untersucht. Beide beschäftigen sich mit dem thermischen Komfort von Gebäudenutzern. Eine der Beiden wurde für die klimatischen Bedingungen in einem Büro in Wien durchgeführt. Die Ergebnisse zeigen, dass das nutzerzentrierte Strahlungskühlpaneel das Potenzial hat, den thermischen Komfort der Nutzer zu verbessern. Durch die Verwendung eines zweiten Strahlungskühlelements oder einer zusätzlich erhöhten Luftgeschwindigkeit kann der thermische Komfort weiter verbessert werden.

Keywords

Klimawandel, Kühlbedarf, Strahlungskühlung, Thermischer Komfort, Kondensat

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ABSTRACT

The combined effects of climate change and urban heat islands have led to an increased cooling energy demand for buildings. Conventional air conditioning systems do not represent an appropriate solution for this issue. A reason is their significant energy consumption. Consequently, alternative strategies are needed to cool architectural spaces. Radiant cooling can be a possible solution for this challenge. It offers several advantages. One of them is the energy efficient operation. Furthermore, radiant cooling technologies have the potential to improve occupants' thermal comfort. However, classical radiant cooling solutions may not be feasible under all circumstances. Some challenges related to classical systems involve, for instance, humidity control and that the cooling capacity of the elements may need to be limited due to water vapor condensation risk. An aim of this master thesis was to examine a set of previously proposed alternative radiant cooling solutions. They are expected to deploy solar energy and address the aforementioned challenges. Three main concepts are involved in these proposed solutions: *i)* bringing radiant cooling elements closer to occupants, *ii)* lower surface temperatures of the radiant element by allowing condensation to occur, and *iii)* incorporating vegetation into the designs. The potential of the solutions was explored via a preliminary potential assessment as well as a computational case study. Both of them are pertaining to thermal comfort. The case study was conducted for the climatic conditions in an office area in Vienna, Austria. The results suggest that the user-centric radiant cooling panel has the potential to improve occupants' thermal comfort. By using a second radiant element, or an additional fan, thermal comfort is further improved.

Keywords

Climate Change, Cooling Demand, Radiant Cooling, Thermal Comfort, Condensation Risk

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1 INTRODUCTION

1.1 Overview

Climate change as well as urban heat islands have a significant effect on the cooling related energy consumption of buildings. About 20% of the total electricity which is used in buildings refers to electrical fans and air-conditioning units (IEA 2018a). It is expected that this trend will further increase. No other end use in buildings grows faster than the energy used to cool indoor spaces. In this context, the global sales of air-conditioning systems are growing steadily as well. Currently roughly 1.6 billion of those systems are in use (IEA 2018b). However, over half of them are being used in just two countries. These are China and the United States (IEA 2018a). It is noticeable that only 8% of the people that are living in the worlds warmest regions own an air-conditioning system. Due to the fact that the living standards and incomes are increasing, more people want to have the possibility to cool their indoor spaces (IEA 2018b). A broader access to cooling is important in many regions as it can increase human's health and well-being. However, this will significantly affect buildings' energy demand.

Some projections for the future of cooling are provided by the IEA (2018a). A baseline scenario suggests that the energy which is needed to cool indoor spaces will triple by 2050. In this context, figure 1 shows some projections the global air conditioner stock.

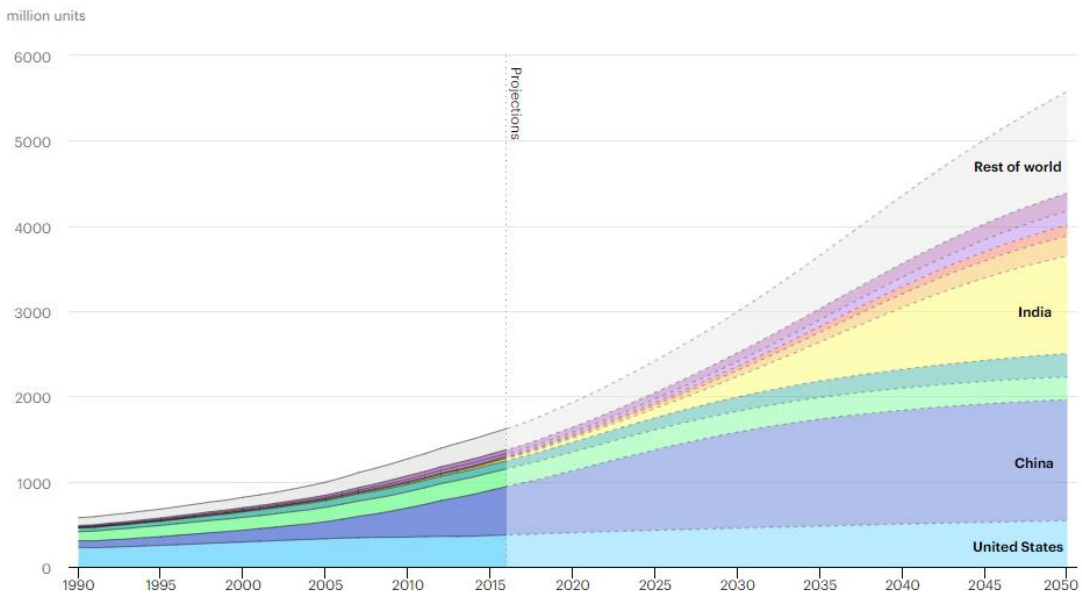

Figure 1 Global air-conditioning stock with predictions for future (IEA 2018a)

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For all those reasons, there is a necessity to develop energy efficient solutions to cool architectural spaces. A possibility are solar cooling systems which use the sunlight as a renewable energy source within the cooling process (Xu et al. 2018; Mugnier et al. 2017). Another potential solution are radiant cooling systems. Studies have shown that they are not only more energy efficient than conventional all-air cooling systems, but they provide a higher thermal comfort for the occupants (Rhee et al. 2017).

In this context, the aim of this master thesis is to evaluate a set of previously proposed alternative solutions to cool buildings (Mahdavi and Teufl 2020). They will include radiant cooling elements, indoor vegetation, and deploy solar energy. The developed designs will be evaluated within two computational study that are related to occupants' thermal comfort.

1.2 Approach

In a first step, this master thesis provides relevant background information. This includes research with regard to passive cooling strategies. Moreover, radiant cooling systems are described based on their operating principle, types of application, benefits, as well as limitations and challenges. Detailed information on the current state of solar cooling is provided as well. This includes also an overview on solar thermal and solar electric refrigeration processes. Furthermore, information of indoor vegetation and thermal comfort is given.

In a next step, the aforementioned radiant cooling solutions (Mahdavi and Teufl 2020) are described. This is followed by information with regard to the implementation of these strategies. It includes, for instance, details on the water supply and used materials.

The solutions are evaluated within two computational case studies. First, the approach for a preliminary potential assessment is described. Afterwards, the results are shown and discussed. Moreover, the second computational case study is presented. It assesses occupants' thermal comfort for the climatic conditions within an office area in Vienna, Austria. This is done for multiple scenarios including different numbers of radiant panels, changed air flow speed, as well as with and without potential surface condensation.

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2 BACKGROUND

2.1 Passive Cooling Solutions

2.1.1 Overview

A good thermal design of buildings can reduce or sometimes even eliminate the energy that is required for cooling systems. Passive cooling solutions have the potential to improve the indoor conditions by using no or only a small amount of energy. In general, passive cooling solutions can be classified into three different types. These are heat protection, heat modulation, and heat dissipation (Bhamare et al. 2019; Santamouris and Kolokotsa 2013).

Heat protection

This concept pertains to protect the building from direct solar heat gains. It can be differentiated between microclimate and solar control-based methods. The latter includes solar shading technologies. Furthermore, the glazing type of windows is also important. Microclimate-based methods refer to the use of vegetation (e.g., trees) and water surfaces close to the building (Bhamare et al. 2019).

Heat modulation

This strategy refers to reducing a buildings heat gain with the thermal storage capacity of the used building materials. An example is the usage of thermal mass. This can be an effective solution to reduce cooling load peaks and indoor temperature (Bhamare et al. 2019).

Heat dissipation:

The excess heat of the building is disposed for example to the lower temperature ambient air, water, or sky. Convective cooling, evaporative cooling and radiative cooling are examples for this technique (Bhamare et al. 2019; Santamouris and Kolokotsa 2013).

Two exemplary strategies are described in more detail in following paragraphs. These are solar shading and cool envelope materials.

2.1.2 Solar Shading

The aim of this passive cooling technique is to protect buildings from unwanted solar heat gains. Shading devices can reduce the transmitted solar radiation through

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windows. There are several types of shading systems. They can be classified based on their position or whether they are movable or fixed. Three different positions of shading systems are possible. They can be mounted to the exterior or interior of a building or intermediate between glass layers (Kirimtat et al. 2016). When it comes to solar shading, external solutions are generally more effective. Nonetheless, they need to resist environmental conditions such as rain or wind (Kuhn 2017).

Types of application

Several types of shading systems are available. External shading devices are for instance, horizontal or vertical louvers, overhangs that are mounted over a window, or egg-crate shading systems. Internal or intermediate devices are for example venetian blinds, vertical blinds, or roller shades (Kirimtat et al. 2016; Kuhn 2017). Recently studies have explored the potential of novel shading techniques such as the usage of solar photovoltaic elements as an overhang. The photovoltaic module can on the one hand generate electricity. On the other hand, the solar heat gain will be reduced due to the shading effect (Zhang et al. 2017).

Performance

Several studies evaluated the performance of different shading devices. Ali Ahmed (2012) conducted a study on the potential of vertical shading devices for residential buildings in Egypt. The results suggested that a 2 K indoor temperature reduction is possible by using exterior louvers.

Palmero-Marrero and Oliveira (2010) conducted a simulation study to explore the effects of fixed louver shading devices on the cooling and heating loads of buildings. This was done for different locations (Mexico, Cairo, Lisbon, Madrid, and London) as well as various scenarios (different window areas and louver angles). The fixed external louvers were used as overhangs over the glazed surfaces on the south façade. For the windows facing east and west façade the louvers were positioned in front of them. The results suggest that the fixed louvers can lowered energy consumption for all analyzed locations. This was especially noticeable in cities with high solar radiation and ambient temperatures. For one of the simulated scenarios, energy savings were 60%, 50%, and 9% in Cairo, Lisbon, and Madrid, respectively. It was noticeable that in London the heating load was increased by using the shading element. This issue can be avoided if a movable shading element is used (Palmero-Marrero and Oliveira 2010).

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2.1.3 Cool envelope materials

An approach to reduce the cooling energy demand of a building is to increase the amount of solar radiation that is reflected by the building envelope. This can be achieved with the help of cool envelope materials. They have the capability to reduce the building envelope's radiative heat gain. In this context, cool materials can be characterized by a high solar reflectance (SR) as well as a high thermal emittance (TE). In comparison to materials with lower SR and TE values, cool materials that are exposed to solar radiation display lower surface temperatures, reducing thus the heat transmission into the building (Santamouris et al. 2011). The reduction of radiative heat gain is dependent on the properties of the applied cool material (SR and TE) and thus the surface temperature and the solar radiation intensity. Another measure to assess a cool material is the solar reflectance index (SRI). It estimates the coolness of a surface relative to a standard black (SR 5%, TE 90%) and a standard white surface (SR 80%, TE 90%) (ASTM 2019). The SRI result is 0 for a standard black surface and 100 for a standard white surface.

Types of application

A wide range of cool envelope materials are currently available. In general, it can be differentiated between cool roof and cool wall solutions. In case of cool roofs, most products and technologies focus on roofs that are either flat or have a minor inclination. However, solutions for pitched roofs have become available as well. Typically, specific coatings, paintings, metal roofs, shingles, tiles, and waterproof membranes are used for these cool material solutions (Pisello 2017). Cool roofs can be implemented as a single ply or applied liquid (e.g., white paints, elastomeric, polyurethane or acrylic coatings) (Pisello 2017).

Cool envelope materials can be an effective option for newly constructed buildings. Nonetheless, cool materials are usually also rather easy to implement in case of retrofit projects. A roof with a black asphalt surface can have an initial solar reflectance of 0.04. If this roof is coated with a smooth, white surface, the solar reflectance will be 0.80 (Levinson et al. 2005a; Levinson et al. 2005b; Santamouris et al. 2011).

In general, cool roof or walls can be used for different building types (both residential and non-residential). They are especially suitable for buildings located in hot or warm climates. In colder climates or in locations with a similar length of heating and cooling period, cool materials potentially result in heating energy demand increase (Synnefa et al. 2007). Advanced cool materials are an effective option for existing houses, which are not or poorly insulated. Studies suggest that the energy savings by applying

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cool materials to these houses are more effective in comparison to newer buildings (Santamouris et al. 2011).

Benefits and Limitations

The main benefit of advanced cool materials is their capability to reduce the surface temperature of the treated exterior building component. This can lead to a lower cooling energy use and improve summer-time indoor thermal conditions. This improvement potential has been documented in a number of publications (Levinson et al. 2005a; Levinson et al. 2005b; Revel et al. 2014a; Revel et al. 2014b; Synnefa et al. 2008; Santamouris et al. 2011).

Despite their advantages, cool envelope materials may also increase the heating energy demand in winter due to their high solar reflectance. However, different studies indicate that this increase is not as important as the cooling energy savings due to the usage of cool materials. The outcome are positive net savings for buildings in a moderate to warm climate (Hernández-Pérez et al. 2014; Santamouris et al. 2011; Synnefa et al. 2007). Switchable cool roof systems are being currently explored as another option to overcome this issue (Testa and Krarti 2017). In comparison to conventional static cool roofs, materials are intended to be highly reflective during the cooling season but highly absorbing during the heating season. This is achieved by using thermochromic or electrochromic coatings as the applied cool envelope material.

Many cool materials are white or light colored. In certain situations, such as pitched roofs and walls, materials with these colors may be not acceptable. A reason is that these white materials can potentially lead to glare problems (Hernández-Pérez et al. 2014).

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2.2 Radiant Cooling

2.2.1 Overview

Radiant cooling systems include temperature-controlled surfaces. Commonly, they maintain their temperature by chilled water (ASHRAE 2012). It circulates in a closed loop through elements such as pipes. They can be embedded or attached to a panel as well as a building component. The actively cooled surfaces can remove sensible thermal loads from a space. The heat transfer takes place by thermal radiation and natural convection (ASHRAE 2012). In comparison to conventional air conditioning technologies, ventilation is separated from the cooling function when it comes to radiant systems (Rhee and Kim 2015).

2.2.2 Types of application

Often, ceilings are used to attach radiant cooling systems. However, an application on floors or walls is possible as well. In general, there are three different construction types for hydronic radiant systems (Cubick 2017):

Radiant cooling panels:

Commonly, radiant cooling panels are suspended from ceilings. However, they can also be attached to walls. They are often produced as modular units which are mounted to a metal frame structure (Cubick 2017). The pipes are incorporated in the radiant cooling panels. The exterior surfaces of the panels are for example perforated or non-perforated metal plates (Hestermann and Rongen 2015). Figure 2 illustrates an instance for such a radiant cooling panel.

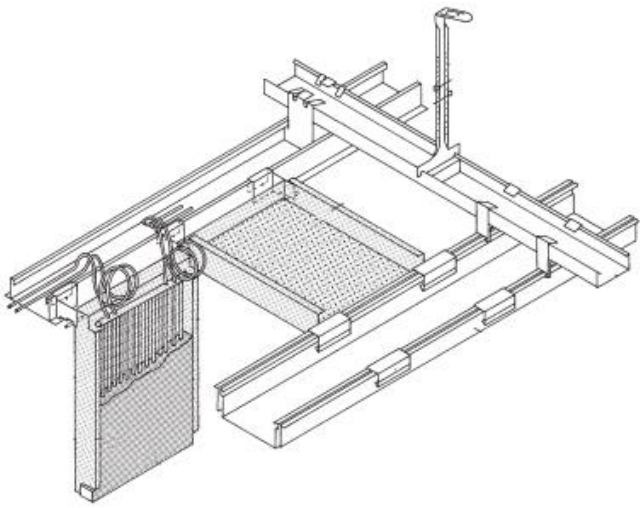

Figure 2 Radiant cooling panel with hinged cassettes attached to a metal frame structure (Hestermann and Rongen 2015)

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Embedded surface systems:

The water pipes are embedded in the surface layer of a building component, such as the floor, ceiling, or wall. The pipes can be placed for instance in a screed or the insulation layer. However, they are isolated from the main building structure (Cubick 2017). Figure 3 shows an example for such an embedded surface system.

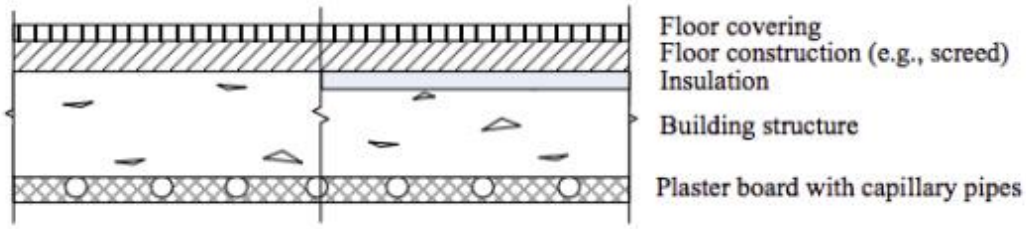

Figure 3 Embedded surface radiant cooling system for a ceiling (Cubick 2017)

Thermally active building systems:

The water pipes for this system are embedded in the main building structure which can be the center of a concrete slab. Due to an activation of thermal mass, the peak load can be reduced (Cubick 2017). Figure 4 illustrates a thermally active building system.

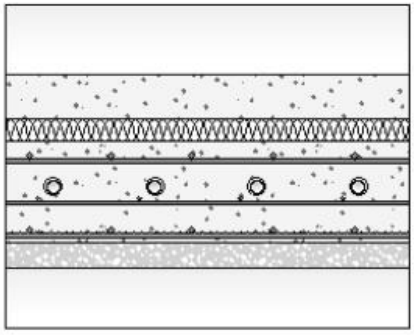

Figure 4 Thermally active building system (Olesen 2014)

A recent pilot study presented another novel type of application. It refers to a radiant cooling desk (He et al. 2017). Water-cooled panels are mounted to the back of the table and used as the tabletop. In the course of the study, the surface temperature of the panel was set in a way to avoid surface condensation. The results suggested that participants' thermal comfort was increased. However, the cooling effect mainly influenced the upper body parts (He et al. 2017).

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2.2.3 Benefits

In recent years, studies have been conducted to assess the performance of radiant cooling systems. In this context, several contributions compared conventional air-based systems to radiant cooling technologies. Many of those studies have highlighted the advantages of the latter system:

Energy efficiency

Radiant cooling has been promoted due to its potential for an energy efficient operation. Commonly, these systems use water as the thermal medium, which has a significantly higher thermal capacity in comparison to air. For this reason, radiant systems have a clearly lower transport energy consumption compared to air-based cooling technologies (Rhee et al. 2017). Moreover, radiant cooling systems are often operating at a water temperature that is close to the room temperature. Due to the higher operation temperature, the chiller can work at a higher efficiency. This results in a lower primary energy consumption (Rhee and Kim 2015).

Tian and Love (2009) conducted a simulation study that compared the energy performance of a radiant cooling system combined with a dedicated outdoor air system to a variable air volume system. This was done for different climate zones (moderate, hot and humid, and hot and dry climate). The simulation results suggest that by using the radiant cooling solution, the energy use is reduced by 10% to 40% depending on the climate zone.

A recent project in India incorporated two different cooling systems in one office building (Sastry and Rumsey 2014). The building consists of two similar structured parts. One half of the office area is cooled by a radiant cooling system with a dedicated outdoor air system. The other half includes a variable air volume system. The study was the world's largest HVAC side-by-side comparison. The results showed that the radiant cooling system used 34% less energy in comparison to the variable air volume system.

Olesen and Mattarolo (2009) conducted a study to evaluate the performance of thermally activated building systems, radiant panels, and radiant floor systems. They were compared to a conventional all-air system. The results suggest that the radiant systems were able to reduce the peak power demand by 26%, 20%, and 6% for thermally activated building systems, the radiant panels, and the radiant floor system, respectively.

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Table 1 presents a selection of other studies that explored the energy performance of radiant cooling systems (based on information provided in Rhee and Kim 2015).

Table 1 Selection of studies related to the energy performance of radiant cooling systems (based on information provided in Rhee and Kim 2015)

Reference	System	Location	Building type	Main findings
Stetiu 1999	Radiant Cooling	US	Office	The results suggest that in comparison to a conventional all-air system, the radiant cooling system can reduce the energy consumption by 30% and the peak power demand by 27%.
Niu et al. 2002	Radiant slab system	US	Office	The study showed that the cooling tower energy could be reduced by 55% if a radiant slab system with model predictive control is used. The pumping energy was reduced by 25%.
Memon et al. 2008	Radiant ceiling cooling	Pakistan	School	The results suggest the potential of reducing the energy consumption by 80% with the radiant cooling system.
Feng et al. 2015	Chilled ceiling and desiccant cooling	Hong Kong	Office	The results suggest that in comparison to a conventional all-air system, the analyzed chilled ceiling (and desiccant cooling) may save up to 44% of primary energy consumption.
Chiang et al. 2012	Cooling panel and air cooling	Taiwan	Office	Energy saving of 13.2% for the chiller as well as 8.0% for the whole cooling system were presented.

Enhanced thermal comfort

Multiple studies have shown that apart from energy savings, radiant cooling systems have also the potential to enhance thermal comfort. The occupants from the Indian office building that incorporated two different cooling systems, participated in a survey about thermal comfort (Sastry and Rumsey 2014). The results from the employees which are working in the part of the building that is cooled with a radiant cooling system were compared to the occupants from the variable air volume system's part.

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The outcome showed that 45% of the people from the radiant cooling building stated that they are “satisfied” or “very satisfied” with thermal comfort. In case of the variable air volume system’s building, only 45% selected on these two categories (Sastry and Rumsey 2014).

Moreover, Imanari et al. (1999) conducted a study on radiant cooling ceiling panels in office areas. The radiant elements were compared to a conventional air-conditioning system with regard to thermal comfort. In this context, human subjects participated in questionnaires. The results showed that the participants preferred when the radiant cooling system was used (Imanari et al. 1999).

Table 2 shows a selection of further studies that pertain to occupants’ thermal comfort with radiant cooling systems (based on information provided in Rhee and Kim 2015).

Table 2 Selection of studies related to thermal comfort with radiant cooling systems (based on information provided in Rhee and Kim 2015)

Reference	System	Location	Building type	Main findings
Tian and Love 2009	Radiant ceiling cooling	Canada	Office	The study showed that the radiant cooling system was able to lower the draft rate by 4% (the mean air velocity was 0.06 $m.s^{-1}$)
Vangtook and Chirarattananon 2007	Radiant ceiling cooling	Thailand	Residential	This contribution used the adaptive comfort model for a radiant cooling study in a residential building.
Memon et al. 2008	Radiant ceiling cooling	Pakistan	School	For the radiant cooling operation, 27°C water from a cooling tower was used.
Kim et al. 2005	Cooling panel	Japan	Office	Within the scenarios with a radiant cooling element, 30-40% of the total removed heat was by radiation.
Chiang et al. 2012	Cooling panel and air cooling	Taiwan	Office	A chilled ceiling temperature of 18°C (60% of the ceiling covered) was not able to achieve thermal comfort. Supplementary air cooling was needed.

Lower draft risk

In comparison to conventional air-conditioning systems, another benefit of radiant cooling systems their lower draft risk (Rhee et al. 2017).

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Quiet operation

A disadvantage associated with conventional all-air conditioning systems is the noise from the system operation. In comparison, radiant cooling technologies can offer a more quiet operation (Rhee and Kim 2015).

Space saving

Another advantage of radiant cooling system is the fact that they need less space in comparison to conventional air conditioning systems (Rhee and Kim 2015).

2.2.4 Challenges and Limitations

Despite their advantages, classical radiant cooling systems have their limitations. For this reason, they may not be feasible under all circumstances (Mahdavi and Teufl 2020). As a result, it is important to consider the following challenges for the utilization of radiant cooling systems.

Condensation Risk

Water vapor condensation risk can be a challenge for radiant cooling systems. To avoid condensation, the surface temperature of the radiant element must not fall below the dew point temperature of the adjacent air layer. This condition limits the cooling capacity of the radiant cooling elements. Specifically, for large-area chilled ceilings, condensation risk can be a challenge (Rhee and Kim 2015; Mahdavi and Teufl 2020).

Humidity Control

Humidity control is especially challenging for buildings in a hot and humid climate. At these locations, natural ventilation increases the condensation risk due to the high moisture content of the ambient air. An option is to use an additional ventilation system which dehumidifies the fresh air to reduce the condensation risk. In this context, it is important that building envelops are very tight to avoid a high air infiltration (Mahdavi and Teufl 2020).

Radiant asymmetry

Radiant cooling systems are promoted for their potential to provide enhanced thermal comfort. Nonetheless, it must be considered that occupants can perceive local discomfort due to radiant asymmetry. For this reason, large temperature differences between the radiant element and the surrounding surfaces are to be avoided (ISO 2006).

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2.3 Solar Cooling

2.3.1 Overview

Solar cooling systems use solar radiation as a renewable energy source within the cooling process. For this reason, they can be seen as a promising technology with regard to reducing conventional primary energy sources and greenhouse gas emissions (Mugnier et al. 2017). Moreover, another advantage of these systems is the fact that the availability of solar radiation matches commonly with the cooling needs. Thus, solar energy is most available when cooling is required the most (Xu et al. 2018).

Different options of solar cooling systems are available. In general, it can be differentiated between two refrigeration modes. These are solar photovoltaic refrigeration and solar thermal refrigeration (Xu et al. 2018). In case of the latter system, the cooling process is driven by heat that is generated with solar thermal collectors. Absorption or adsorption chillers can for instance be used for this procedure (Allouhi et al. 2015). Solar photovoltaic refrigeration uses electricity which was generated with photovoltaic modules for the cooling process. Commonly vapor compression chillers are used for this application form (Xu et al. 2018). Figure 5 illustrates an overview of the different solar cooling options.

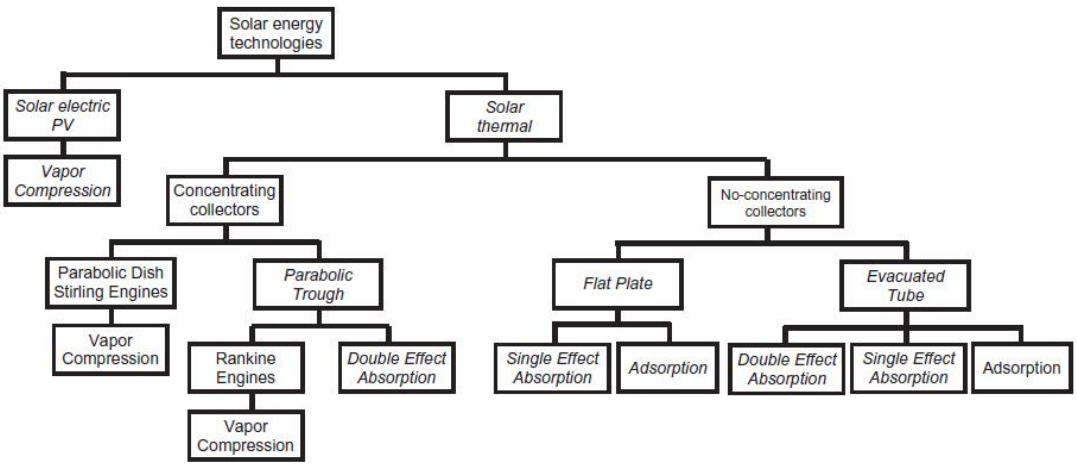

Figure 5 Solar cooling technologies (Lazzarin and Noro 2018)

2.3.2 Solar thermal refrigeration

Solar cooling systems consist roughly out of two main parts (Lazzarin and Noro 2018). The first one is the solar section which refers when it comes to solar thermal

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refrigeration to a solar collector. The second part is the cooling equipment. These can for instance be absorption or adsorption chillers.

Solar collectors

Various solar collectors are available. In general, there are two main types of solar collectors. These are non-concentrating which are usually stationary and concentrating collectors (Allouhi et al. 2015). Table 3 shows a number of different solar collectors, their indicative temperature range, as well as the absorber type (Kalogirou 2014).

Table 3 Types of solar collectors (Kalogirou 2014)

Motion	**Collector Type**	**Absorber Type**	**Indicative Temperature Range (°C)**
Stationary	Flat-plate collector	Flat	30 - 80
	Evacuated tube collector	Flat	50 – 200
	Compound parabolic collector	Tubular	60 - 240
Single-axis tracking	Compound parabolic collector	Tubular	60 - 300
	Linear Fresnel reflector	Tubular	60 - 250
	Cylindrical trough collector	Tubular	60 - 300
	Parabolic trough collector	Tubular	60 - 400
Two-axis tracking	Parabolic dish reflector	Point	100 - 1500
	Heliostat field collector	Point	150 - 2000

Common types of non-concentrating and stationary solar collectors are flat-plate collectors and evacuated tube collectors. The latter system offers slightly higher temperatures. Even higher initial temperatures are necessary when working for example with double or triple effect absorption chillers (Allouhi et al. 2015). In this case concentrating collectors need to be used. To reach these higher temperatures, the solar radiation is concentrated on a very small area. Movable options such as single-axis tracking, or two-axis tracking are available. They follow the sun to obtain higher temperatures (Allouhi et al. 2015). An example for a single axis tracking system

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is a parabolic through collector. A schematic illustration of this collector is shown in Figure 6.

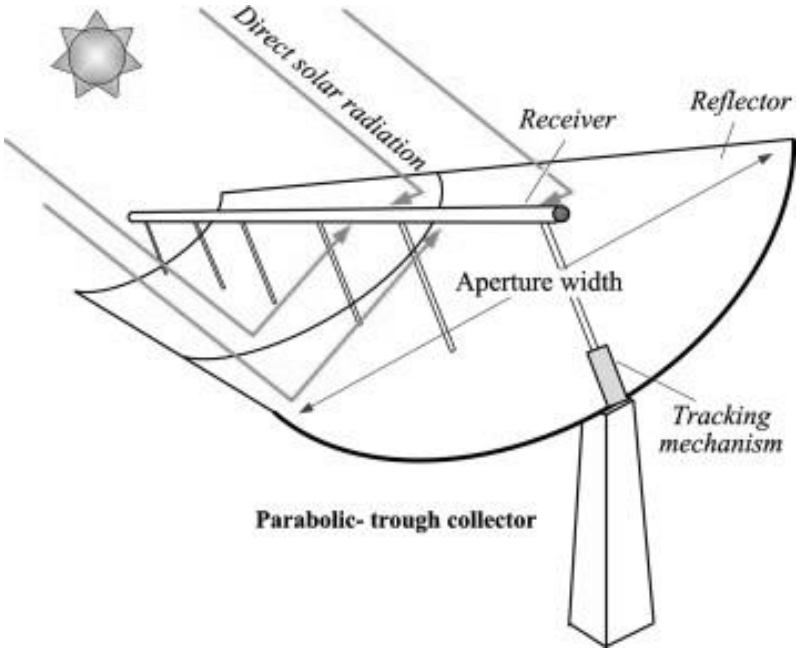

Figure 6 Schematic of a parabolic through collector (Cabrera et al. 2013)

Absorption cooling system

Absorption cooling is an instance of a system that can be used for solar thermal refrigeration. Instead of an electrically powered compressor, the systems use thermal energy for the cooling process. For the refrigeration effect, a pair of substances are needed. These are a refrigerant and an absorbent. Frequently, water and Lithium Bromide are used. In this case water is the refrigerant and Lithium Bromide the absorbent substance (Lazzarin and Noro 2018). Double or triple effect absorption chillers work more efficiently. However, they need higher initial temperatures for the cooling process. As a result, concentration collectors that follow the sun can be used in combination with these systems (Mugnier et al. 2017).

Commonly, absorption cooling systems consists of a solar collector, hot water storage tank, absorption chiller, and cooling tower (Xu et al. 2018). The absorption chiller includes a generator, condenser, expansion valve, evaporator, and absorber. Important for the cooling process are different pressures within specific parts of the chiller. The working principle of an solar absorption cooling system is illustrated in Figure 7. In general, the following steps are necessary for the cooling procedure (Xu et al. 2018; Evans 2017):

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- The water in the solar collector is heated by solar radiation.
- The heated water is pumped from the storage tank to the generator of the absorption chiller. There, it heats the mixture of refrigerant and an absorbent substance (e.g., water and Lithium Bromide).
- The heat causes the refrigerant and an absorbent to separate.
- The hot absorbent substance (e.g., Lithium Bromide) flows down to the heat exchanger and afterwards it is sprayed in the absorber.
- The refrigerant (e.g., water) vaporizes in the generator and fills the condenser. There, it is cooled by a water loop from the cooling tower. This causes the water vapor to condense into liquid water.
- The liquid refrigerant is collected and brought to the evaporator which is at a very low pressure. The change in pressure causes the refrigerant substance to drop in temperature. As a result, it can cool the water from the chilled water loop of the building. The refrigerant substance will evaporate due to the low pressure of the chamber.
- Afterwards, the refrigerant mixes again with the absorbent substance and is pumped again through the heat exchanger to the generator to start the cycle again (Xu et al. 2018; Evans 2017).

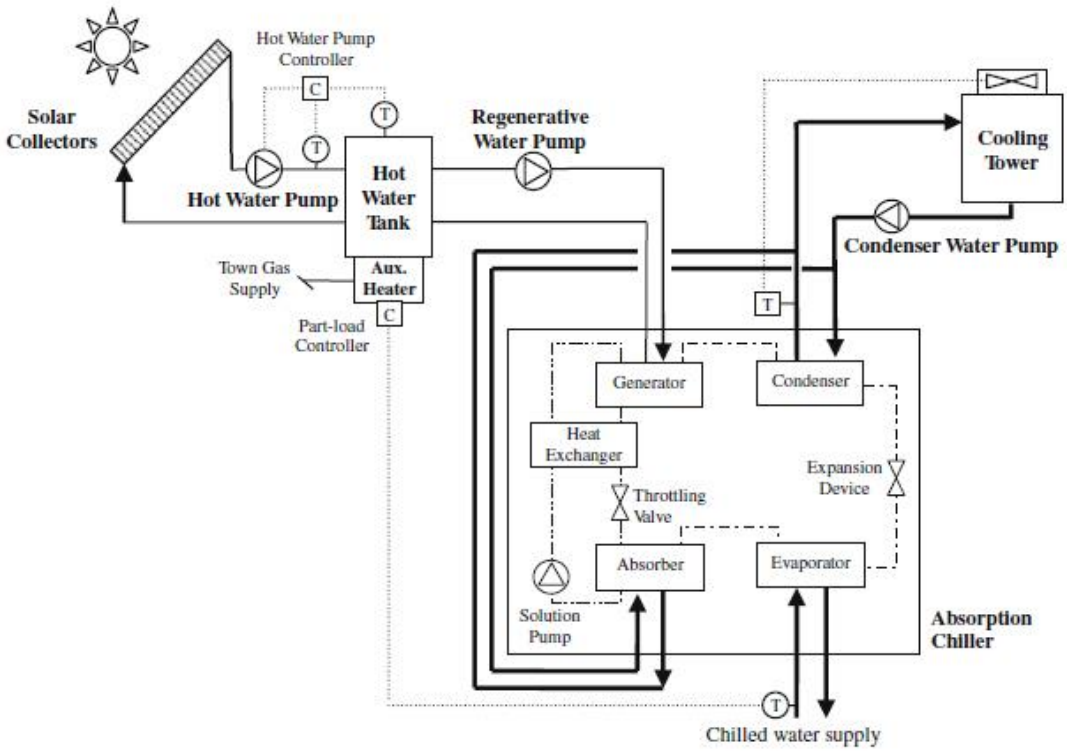

Figure 7 Working principle absorption cooling system (Fong et al. 2010)

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2.3.3 Solar electric refrigeration

Photovoltaic panels

Solar photovoltaic refrigeration uses electricity that was generated by photovoltaic modules for the cooling procedure. Several types of photovoltaic modules are available. Table 4 presents different photovoltaic technologies (Allouhi et al. 2015).

Table 4 Photovoltaic technologies (Allouhi et al. 2015)

Photovoltaic cells	Classification
Silicon	Si (crystalline)
	Si (multicrystalline)
	Si (thin film transfer)
III–V cells	GaAs(thin film)
	GaAs (multicrystalline)
Thin film chalcogenide	CIGS (cell)
	CdTe (cell)
Photochemical	Dye sensitized
	Organic thin film
Multijunction devices	GaInP/GaInAs/Ge
	a-Si/nc-Si (thin film cell)

Chiller/Heat pump

Different types of systems are available. In general, they are the following (Lun and Tung 2020):

i. Air to air system
ii. Air to water system
iii. Water to air system
iv. Water to water system

In the course of this thesis, the relevant systems are the ones that are able to generate cool water. A vapor compression cycle is commonly used. The main difference to the absorption chiller is the fact that an electrically driven compressor is used to move a refrigerant around the cooling system. The main components of the chiller are an evaporator, the compressor, condenser, and expansion valve (Xu et al. 2018). Some systems have the option to reverse the cycle. In this case, they can provide chilled water in summer as well as hot water in winter (Lun and Tung 2020).

A schematic illustration of a vapor compression refrigeration cycle is illustrated in Figure 8 (Daviran et al. 2017).

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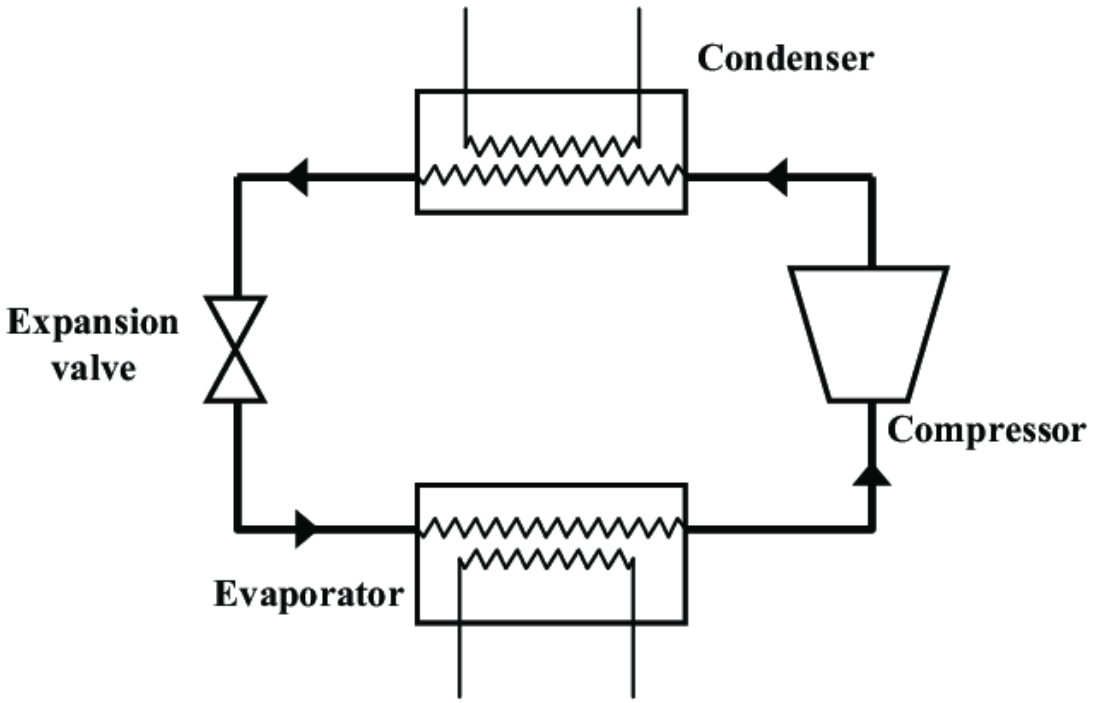

Figure 8 Vapor compression refrigeration cycle (Daviran et al. 2017)

2.3.4 Performance

Several studies explored the performance of solar cooling systems. A few of them are presented in the following paragraphs. Fong et al. (2010) compared five types of solar cooling systems in TRNSYS. The analyzed systems are solar electric compression refrigeration, solar mechanical compression refrigeration, solar absorption refrigeration, solar adsorption refrigeration, and solar solid desiccant cooing. The study was conducted for a typical office in Hong Kong (subtropical city). The outcome suggests that depending on the solar cooling technology, the annual primary energy savings are between 8.0% and 43.7% in comparison to conventional water-cooled refrigeration. The results of the solar absorption refrigeration (with evacuated tubes) as well as the solar electric compression refrigeration system (with photovoltaic panels) showed the highest energy savings (Fong et al. 2010).

Hartmann et al. (2011) performed a computational study to compare solar thermal and solar electric cooling systems to a conventional compression chiller. The study was conducted for a typical small office building in two European climates (Freiburg and Madrid). The results suggest that by using a large collector area, primary energy savings up to 40% are possible for Freiburg. In case of the office area in Madrid, up to 60% of the primary energy can be saved with a solar thermal or solar electric

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system. In this case study, the collector area of the solar thermal system had to be clearly larger to achieve similar primary energy savings as the solar electric system (Hartmann et al. 2011).

Eicker et al. (2015) conducted a simulation study with EnergyPlus to assess the performance of photovoltaic compression cooling systems and solar thermal cooling systems. This was done for an office building in various locations and in some instances different climatic conditions (Stuttgart, Cologne, Barcelona, Madrid, Jakarta, Riyadh). The outcome suggests that depending on for example the location, the primary energy consumption can be reduced by 21 to 70% by using solar electric or solar thermal cooling system (Eicker et al. 2015).

2.4 Indoor Vegetation

The indoor environmental quality in buildings has a main impact on the health, comfort, and productivity of occupants (Moya et al. 2019). Since people spend a lot of their time indoors, it is especially important that buildings can provide a good indoor environmental quality for their users (World Health Organization 2010). In this context, several studies have explored the effects of indoor vegetation on the air quality, occupant's well-being, as well as its cooling potential (Moya et al. 2019).

Wolverton et al. (1989) conducted a study on the potential of indoor plants to improve the air quality. The results suggest that the tested indoor plants can remove pollutants such as benzene, formaldehyde, and trichloroethylene from the indoor air.

Cetin and Sevik (2016) explored the impact of plants on the CO_2 concentration within an indoor space. Five different plants were analyzed (Ficus elastica, Yucca massengena, Sinningia speciose, Ocimum basilicum, and Codiaeum variegatum). To measure the amount of CO_2, the plants were positioned in an airtight compartment that incorporates a glass wall. The results showed that all of the indoor plants were able to reduce the CO_2 concentration to some extent. Ficus elastica and Yucca massengena may be a good option for office areas or other spaces that are occupied during the day. The reason is the fact that even though they CO_2 concentration is increased during night, it is significantly reduced at daytime (Cetin and Sevik 2016).

Lohr et al. (1995) explored the effects of indoor plants in an office environment on occupant's productivity and well-being. The results of the study suggest that indoor plants may increase people's productivity and lower their stress level.

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Qin et al. (2014) conducted surveys at an office area. The outcome of the survey showed that an office area with indoor plants was preferred. Moreover, the results suggest that indoor plants can improve human comfort.

Other studies suggest that plant's evapotranspiration may lower the temperature around them and thus can be used for air cooling and humidity control (Pérez-Urrestarazu et al. 2016; Davis and Hirmer 2015; Moya et al. 2019).

Nonetheless, as stated by Moya et al. (2019, p. 305) there is still a lack of solid and relevant data available to understand the true pollutant-removal mechanisms and factors in these systems (plant species, microorganism types, gas composition, light source, number of plants), its cooling effect within indoor environments and the effect of these systems on the energy performance of the building.

2.5 Thermal Comfort

According to ASHRAE (2017, p.3), thermal comfort is that condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation.

Predicted Mean Vote (PMV)

A common indicator of thermal comfort is the Predicted Mean Vote (PMV). It was developed in the 1970s by Ole Fanger (Fanger 1970). The PMV represents a seven-point thermal sensation scale. It ranges from the subjective evaluation of "cold" (-3) to "hot" (+3). Table 5 shows this scale in more detail.

Table 5 PMV – seven-point thermal sensation scale (ISO 2006)

+3	+2	+1	0	-1	-2	-3
Hot	Warm	Slightly warm	Neutral	Slightly cool	Cool	Cold

The PMV calculation procedure includes the air temperature, mean radiant temperature, relative humidity, air speed, clothing insulation, and metabolic rate (ISO 2006; ASHRAE 2017). Typical summer indoor clothing refers to a clothing value of 0.5 clo. Table 6 illustrates the metabolic rate for typical task related to an office environment (ASHRAE 2017).

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Table 6 Metabolic rates for office activities (ASHRAE 2017)

	Metabolic rate	
Activity	**Met Unit**	**W.m^{-2}**
Reading, seated	1.0	55
Writing	1.0	60
Typing	1.1	65
Filing, seated	1.2	70
Filing, standing	1.4	80
Walking	1.7	100
Lifting/packing	2.1	120

Predicted Percentage of Dissatisfied (PPD)

Another indicator that is related to the PMV is the Predicted Percentage of Dissatisfied (PPD). It predicts the mean value of thermally dissatisfied people under the same thermal conditions (ISO 2006; ASHRAE 2017).

Elevated air speed method:

The procedure of the PMV with elevated air speed method is rather similar to the classical PMV calculation method. However, this method provided by the ASHRAE 55 standard (2017) calculates the PMV in a different way, if the air velocity is above 0.2 m.s^{-1}. The reason for this procedure is to take into account an assumed cooling effect of higher air speeds.

Radiant asymmetry and the percentage of dissatisfied (PD)

Local discomfort is to be avoided. A cause can be large temperature differences between the surfaces that surround the occupant (ISO 2006, ASHRAE 2017). For this reason, radiant asymmetry must be taken into account when applying for example radiant cooling elements. ISO (2006) offers a calculation procedure to determine the percentage of dissatisfied people due to radiant asymmetry. This process is dependent on whether a warm ceiling, a cool wall, a cool ceiling ´, or a warm wall is available in the indoor space.

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3 ALTERNATIVE RADIANT COOLING SOLUTIONS

3.1 Overview

A good thermal design of buildings can reduce or even eliminate the energy that is required for cooling systems. However, at specific climatic conditions, passive cooling strategies are not enough to ensure adequate indoor temperatures. In comparison to classical air-conditioning technologies, radiant cooling systems offer several advantages. One of them is their energy efficient operation. Furthermore, radiant cooling technologies have the potential to improve occupants' thermal comfort (Vangtook and Chirarattananon 2007; Rhee and Kim 2015; Rhee et al. 2017).

Nonetheless, classical radiant cooling solutions may not be feasible under all circumstances (Mahdavi and Teufl 2020). A common application form of radiant systems are chilled ceilings. Especially for these large-area ceilings, water vapor condensation risk can be a challenge. To avoid condensation, the surface temperature of the radiant element must exceed the dew point temperature of the adjacent air layer. This condition limits the cooling capacity of the radiant cooling systems.

Humidity control is specifically challenging in a hot and humid climate. In this context, natural ventilation results in an increased condensation risk due to the high moisture ambient air. With the help of an additional controlled ventilation system, the fresh air can be dehumidified to reduce this risk. However, this may not be cost effective. Unwanted air infiltration is another challenging issue. For this reason, the envelope of buildings in hot and humid climates must be very tight. Thus, placing classical radiant cooling systems in existing buildings with a high air infiltration may not be an appropriate solution.

The mentioned challenges highlight the necessity for alternative radiant cooling solutions. Specifically, low-tech building or indoor spaces that are located in hot and humid climates can benefit from strategies that overcome these issues.

An aim of this thesis was to more closely examine a set of previously proposed alternative radiant cooling solutions (Mahdavi and Teufl 2020). They will incorporate vegetation and deploy solar energy. Furthermore, they will address the aforementioned challenges.

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3.2 Radiant Cooling Designs

A set of possible cooling techniques were considered. They incorporate radiant cooling elements and deploy solar energy. In this context, three main concepts have guided the development of the proposed solutions:

1.) Bringing radiant cooling elements closer to occupants

The first concept has been also pursued in some previous research efforts (He et al. 2017). It aims at positioning radiant cooling elements closer to occupants. As a result, the developed designs will differ from common radiant cooling application forms, such as chilled ceilings. Close proximity to users can for instance be achieved by vertically positioned radiant panels. Thereby, the view factor from the occupant to the radiant element is increased.

This approach offers several benefits. First of all, the efficiency is increased. Furthermore, it allows more personal control opportunities. This is especially beneficial in offices or other indoor spaces with multiple occupants. People can individually change the settings of their personal radiant panel depending on their thermal preferences. Moreover, the radiant cooling panels can also provide privacy by blocking the view between the occupants of an office area.

2.) Lower surface temperatures of the radiant element

The second concept aims at designs that do not avoid but accommodate surface condensation. As a result, the temperature of the radiant panels is not restricted to stay above the dew point temperature. It can be clearly lower in comparison to conventional radiant cooling solutions. Furthermore, if the radiant elements can handle potential condensation, natural ventilation options are also possible in regions which are highly humid.

To achieve that, the radiant elements need to fulfill some requirements. First of all, they must be water-resistant. Furthermore, they need to be positioned vertically and incorporate specific elements to accommodate potential surface condensation (e.g., drainage systems) (Mahdavi and Teufl 2020).

Nonetheless, is has to be mentioned that the radiant asymmetry has to be considered, especially when the panel's surface temperature is significantly decreased. The reason is to avoid discomfort due to highly different temperatures of the surrounding surfaces. A procedure to calculate the percentage of dissatisfied people with regard to the radiant asymmetry is provided in the ISO 7730 standard (2006). More details on this topic are also presented in chapter 2.5.

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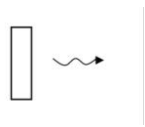
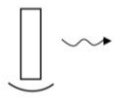
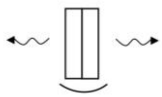
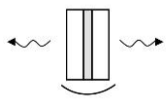
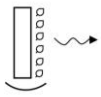
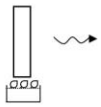
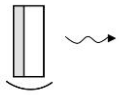
3.) Incorporating vegetation in the radiant panel designs

The third concept aims at incorporating vegetation in the radiant panel designs (Gau 2005). On the one hand, this can improve the indoor climate (Moya et al. 2019). On the other hand, vegetation can also benefit from the aforementioned second concept. The idea is to use potential surface condensation to water the plants. For this purpose, a flower box can be positioned below the radiant panel. As a result, no additional drainage systems are needed.

Table 7 shows a highly schematic overview of a number of radiant cooling solutions that incorporate the three aforementioned concepts (Mahdavi and Teufl 2020). In this context, the presented base-element refers to a vertical, occupant-centric radiant cooling panel. Another solution uses the same base-element and offers an additional drainage system for potential surface condensation. A two-sided radiant panel is possible as well. It can be positioned for instance between two office desks. As a result, the panel can provide privacy while improving occupants' thermal comfort. Another solution includes an additional PCM layer behind or between the radiant panels. Furthermore, solutions that incorporate vegetation are also presented. By offering an additional drainage element or a flower box, these solutions have the capability to handle surface condensation.

Table 7 Schematic illustration of multiple solutions for the design of radiant cooling elements (Mahdavi and Teufl 2020)

			
Base-element	Base-element + drainage element	Two-sided base-element + drainage element	Two-sided base-element + PCM + drainage element
			
Base-element + vegetation	Base-element + vegetation + drainage element	Base-element + flower box	Base-element + PCM + drainage element

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3.3 Implementation

3.3.1 Water supply

The water, which is needed for the radiant cooling process, is chilled in a central area of a building. This, for instance, can be done in a plant room. From there, the chilled water is distributed via pipes to the individual rooms of the building. The space behind a suspended ceiling can be used for this process. This allows the water to be transported to a specific position within a room. In case multiple radiant cooling panels are placed in one room, this concept can be particularly helpful. Especially for existing buildings, a suspended ceiling can be a suitable solution. The reason is the fact that they can even be installed after construction if they are not already available. However, an appropriate room height is necessary for this procedure. For newly constructed buildings, an alternative is to use the floor for the water distribution process.

3.3.2 Materials of the Radiant Cooling Element

For the selection of materials, it is important to take into account that condensation can occur within some of the aforementioned radiant cooling strategies. For this reason, the selected materials must be water-resistant. This is to prevent the elements from being damaged.

The pipes that circulate the cool water are part of the radiant cooling element. They are mounted in loops on the backside of a panel. These pipes can be made of copper, but plastic ones are also possible to use. The aforementioned panel that faces the occupant and is made of metal. Additionally, insulation can be applied to the backside of the panel, behind the pipes. Furthermore, a suitable climbing aid for the plants is also part of some of the cooling elements. For this purpose, a metal grid or mesh is attached to the flower box.

3.3.3 Indoor Vegetation

Studies have shown that indoor vegetation can have a positive effect on occupants' well-being as well as improve the indoor climate (Moya et al. 2019). However, not all plants can be used for the aforementioned radiant cooling solutions. They need to meet certain requirements (Gau 2005). One the one hand, they must be able to deal with the cool temperatures of the radiant panel. This is particularly important because

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the plants are positioned very close to the cold surface. On the other hand, it is necessary that the selected plants can handle the amount of condensation, which is used to water them. A selection of indoor plants, which can be used for the presented radiant cooling solutions, are described in the following paragraphs (Gau 2005):

Philodendron

Philodendron is an evergreen plant that prefers room temperatures from 15 °C (Gau 2005). For this reason, Philodendron represents an appropriate solution for the user-centric radiant cooling elements. It is recommended to water this plant regularly in smaller quantities because it prefers to be evenly moist (Steinkopf 2017). The plant is very robust and easy to care for. Another important aspect is that it can survive even at low light conditions. Furthermore, it is very fast growing (DelPrince 2013; Steinkopf 2017). Due to the fact that it is a climbing plant, an additional grid or mesh is necessary to support it, if it is used for one of the user-centric radiant cooling panels. Figure 9 shows a picture of a Philodendron.

Figure 9 Philodendron (Steinkopf 2017)

Hedera helix

Hedera helix is an evergreen climbing plant. A room with low to medium lighting conditions as well as a relatively high humidity is ideal for this plant (Steinkopf 2017; DelPrince 2013). It is important to water it regularly to keep it evenly moist. However, the soil is not supposed to be too wet (DelPrince 2013). The plant is very robust and easy to care for (Steinkopf 2017). Figure 10 illustrates a Hedera helix.

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Figure 10 Hedera helix (DelPrince 2013)

Epipremnum aureum

Epipremnum aureum is an evergreen plant, which is originally from the tropical regions of Asia. It can be considered to be particularly easy to care for. Furthermore, it is able to improve the indoor climate (Gau 2005). Epipremnum aureum can tolerate low light conditions but prefers a bright place (DelPrince 2013; Steinkopf 2017). It is best to keep the plant at a temperature between 15 and 25 °C (gartenlexikon 2020). Moreover, it is important to water it regularly. A suitable climbing aid is necessary so that the plant can grow upwards (Greiner and Weber 2016). Figure 11 shows a picture of an Epipremnum aureum.

Figure 11 Epipremnum aureum (Steinkopf 2017)

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4 PRELIMINARY POTENTIAL ASSESSMENT

4.1 Approach

A preliminary computational study was conducted to assess the potential of the user-centric radiant cooling strategies (Mahdavi and Teufl 2020). These solutions are described in more detail in chapter 3. The focus of this study was to analyze occupants' thermal comfort if the radiant panel is positioned close to a user. In this context, the PMV, which is a common indicator of thermal comfort, was used. The purpose of this study was to illustrate at which thermal conditions (e.g., ambient air temperature) the PMV is still in the recommended range. According to ISO 7730 (2006), this range is between -0.5 and +0.5. If the cooling element is not enough to keep the PMV below +0.5 (e.g., if the ambient air temperatures are high), the panel can be supported by an additional fan. This study is also expected to show the needed air speed at specific temperatures to keep the PMV lower than +0.5.

Within this preliminary potential assessment, the PMV calculations are conducted for two specific procedures:

i. The classical PMV calculation method (ISO 2006; ASHRAE 2017),
ii. The PMV with elevated air speed method (ASHRAE 2017).

The procedure of these two methods is rather similar. However, the second calculates the PMV in a different way, if the air velocity is above 0.2 $m.s^{-1}$ (ASHRAE 2017). The reason for this procedure is to take into account an assumed cooling effect of higher air speeds. Both methods are described in more detail in chapter 2.5.

To conduct this study, specific assumptions had to be made. Furthermore, the calculations were performed for two cases. These cases differ in the assumed relative humidity. For one of them a relative humidity of 50% was used. For the other case, the PMV was calculated by using a relative humidity of 70%. All other input parameters stayed the same for both cases. A clothing value of 0.5 was used. This value corresponds to typical summer indoor clothing. Furthermore, a metabolic rate of 1.1 met was assumed. This refers to an occupant who is typing (ASHRAE 2017). To estimate the mean radiant temperature, the shape factor from the occupant to the cooling element was calculated. The surface temperature of the vertical radiant cooling panel was 15 °C. For the purpose of this study, all other surrounding surfaces were assumed to have a surface temperature which is equal to the ambient air temperature.

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Figure 12 shows the dimensions of the cooling panel that was used within the calculation procedure. The size of the radiant element is 2.25 m². It is located 0.75 m from the occupant.

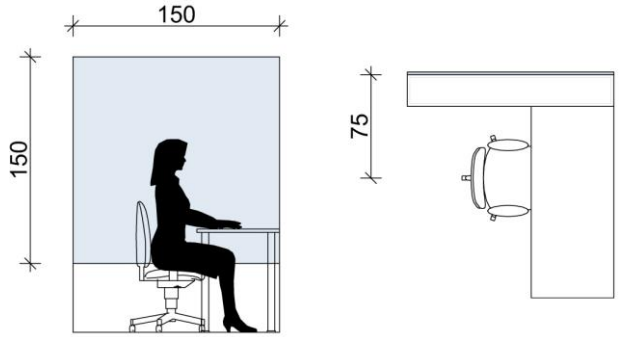

Figure 12 Arrangement for the radiant panel next to a workstation (dimensions in cm)

4.2 Results and discussion

Figure 13 as well as Table 8 and 9 illustrate the needed air speed at given temperatures to keep the PMV below +0.5. These results are presented for both PMV calculation procedures and for an assumed relative humidity of 50 as well as 70 percent. Given the used input parameters, it is not necessary to activate the radiant cooling system, if the ambient air temperature is below 27 °C. Afterwards, the PMV is kept within its recommended range, if the radiant cooling element is used. At certain ambient air temperatures, an increased air speed provided by an additional fan can contribute to keep the PMV below +0.5. The necessary air velocity is depended on the used calculation procedure as well as the assumed relative humidity.

For the calculations that used a relative humidity of 50%, the PMV is below +0.5 at an air temperature of 29 °C and 31 °C for the classical calculation method (ISO 7730 2006) and the elevated air speed method (ASHRAE 55 2017), respectively. In case of the classical calculation procedure, an additional fan is necessary to provide an air speed of 0.5 $m.s^{-1}$. If the PMV with elevated air speed method is used, an air velocity of 0.85 $m.s^{-1}$ is needed to keep the PMV within its recommend range.

If a relative humidity of 70% is used within the classical calculation procedure, the PMV does not exceed the recommended limit at an ambient air temperature of 29 °C. Nonetheless, an additional air velocity of 1 $m.s^{-1}$ is necessary to achieve this result.

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In case of the method which is provided in the ASHRAE 55 document, an air speed of 0.7 m.s^{-1} is needed at an air temperature of 30 °C to keep the PMV below +0.5.

Furthermore, it has to be mentioned that due to the assumed relative humidity levels, surface condensation occurs when the cooling element is activated. Consequently, the cooling panel must be designed in a way to accommodate condensation. A possible solution can be realized via integrated drainage elements.

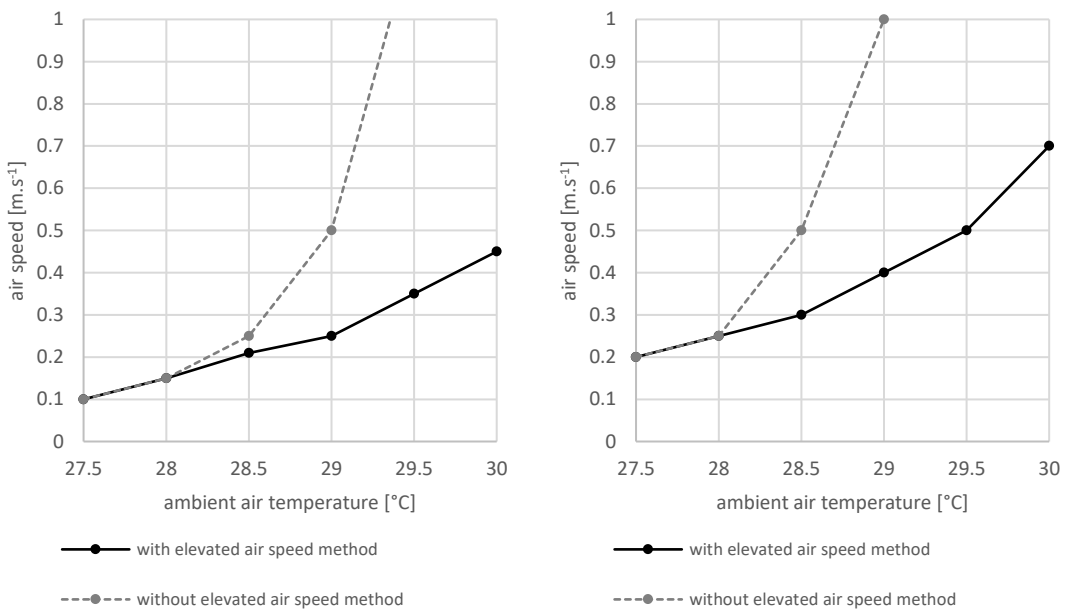

Figure 13 Necessary air speed at specific temperatures to keep PMV below +0.5 (RH=50% (left), 70% (right); clo=0.5; met=1.1; surface temperature radiant panel= 15°C)

Table 8 Necessary air speed at various temperatures to keep PMV below +0.5 (RH=50%; clo=0.5; met=1.1; surface temperature radiant panel=15°C)

Ambient air temperature [°C]	**≤ 26**	**≤ 27**		**≤ 28**		**≤ 29**		**≤ 30**	
Air speed [m.s^{-1}] Method with elevated air speed	0.1	0.15	0.1	0.25	0.15	0.4	0.25	0.7	0.45
Air speed [m.s^{-1}] Method without elevated air speed	0.1	0.15	0.1	0.35	0.15	-	0.5	-	-
Radiant cooling panel	-	-	✓	-	✓	-	✓	-	✓
Surface condensation	no	no	yes	no	yes	no	yes	no	yes

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Table 9 Necessary air speed at various temperatures to keep PMV below +0.5 (RH=70%; clo=0.5; met=1.1; surface temperature radiant panel=15°C)

Ambient air temperature [°C]	**≤ 26**	**≤ 27**	**≤ 28**		**≤ 29**		**≤ 30**
Air speed [m.s^{-1}] Method with elevated air speed	0.1	0.2	0.4	0.25	0.6	0.4	0.7
Air speed [m.s^{-1}] Method without elevated air speed	0.1	0.2	0.6	0.25	-	1.0	-
Radiant cooling panel	-	-	-	✓	-	✓	✓
Surface condensation	no	no	no	yes	no	yes	yes

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5 A CASE STUDY

5.1 Method

5.1.1 Overview

A computational case study with regard to the aforementioned user-centric radiant cooling panels was conducted. The aim was to evaluate occupants' thermal comfort if these alternative radiant cooling elements are positioned close to the users.

Selected office area and its location

Within this study, thermal data from an office was used. The selected indoor space is located in an educational building in Vienna, Austria. Figure 14 shows a floor plan of this office environment. The open-plan office room, which was used to conduct the computational study is marked in grey.

The air temperature as well as the relative humidity is available for the warmest months (June – August) of three different years (2017 – 2019). They were used in the calculation procedure to assess occupants' thermal comfort.

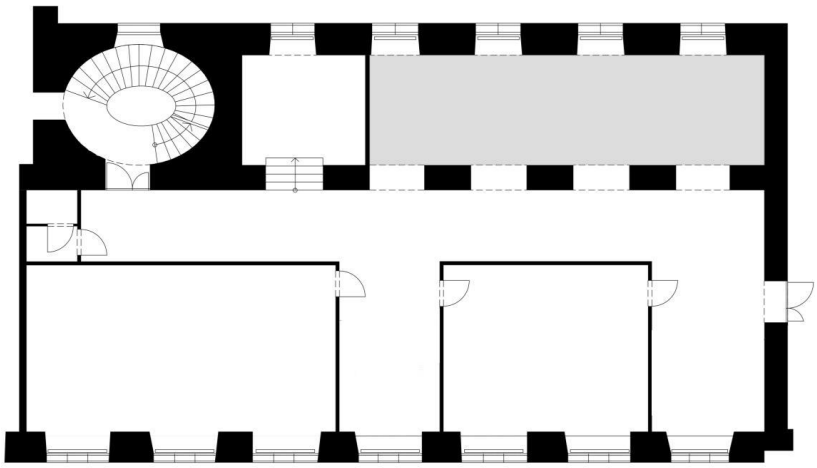

Figure 14 Floor plan of the selected office area

Arrangement of radiant cooling panels

This study explores the potential of a vertical radiant cooling panel. The user-centric radiant cooling solution allows to accommodate potential surface condensation. Further details with regard to the cooling panel are presented in chapter 3. Figure 15 shows a selection of arrangement possibilities of these radiant cooling elements within

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the office area. Thereby, one or two panels can be placed next to a workstation. The panels can provide privacy by blocking the view between the employees. Furthermore, more personal control opportunities are offered by this approach.

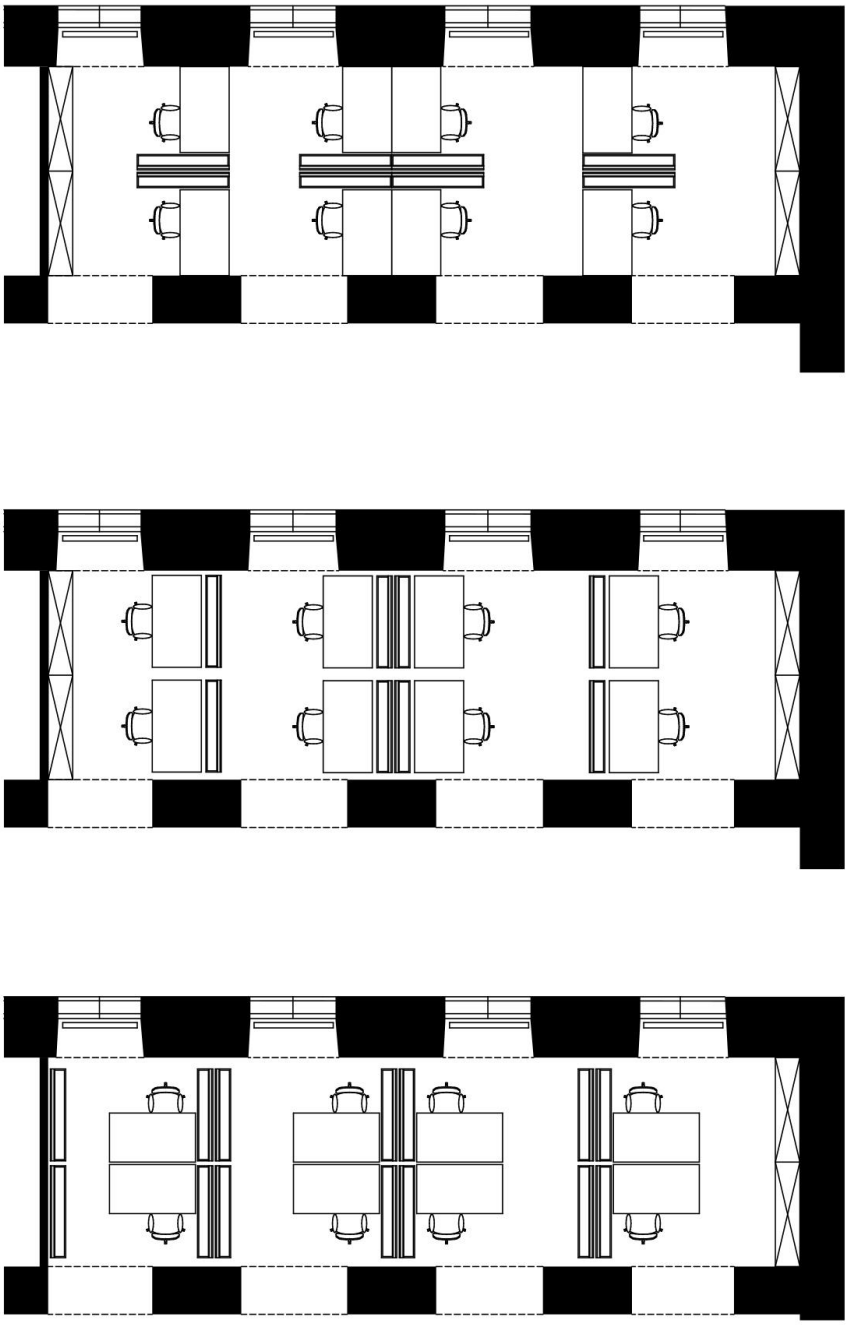

Figure 15 Selection of arrangement possibilities of the radiant cooling panels within the office area

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The dimensions of the cooling element that was used within the calculation procedure are shown in Figure 16. It is illustrated for both, one and two panels next to a workstation. The size of a panel is 2.25 m². The radiant surface of the first element is located 0.75 m from the occupant. The optional second panel is positioned 1.0 m from the user.

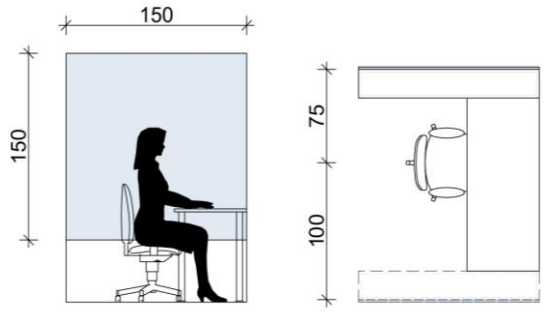

Figure 16 Arrangement for one or two (dashed line) radiant panels (dimensions in cm)

5.1.2 Thermal conditions without a cooling system

In a first step, the thermal conditions within the office area were analyzed. The reason was to get an overview on the initial situation without an active cooling system. For this purpose, the air temperature as well as the relative humidity of the indoor space were examined. This was done for the cooling seasons of three different years (2017 – 2019). The analysis is expected to show how often a specific indoor temperature occurs. Thereby, special attention is paid to the occupied times of the office area (8:00 am - 6:00 pm).

5.1.3 Thermal comfort evaluation

<u>Calculation procedure</u>

Occupants' thermal comfort was evaluated based on the aforementioned panel arrangement within the Viennese office area. In this context, the PMV and PPD were used as the performance indicators for thermal comfort (ISO 2006). They were calculated on an hourly basis for the specified cooling period (June – August) of three different years (2017 – 2019). In the course of this study, the classical PMV method according to ISO 7730 (2006) was used. The calculations were performed for multiple cases:

i. Without a radiant cooling panel
ii. For one radiant cooling panel
iii. For two radiant cooling panels

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The measured temperature and relative humidity values from the office area are used for the PMV and PPD calculation. Regarding other necessary input variables, an air flow speed of 0.2 $m.s^{-1}$ was assumed. Moreover, the clothing value was set to 0.5 clo. This refers to typical summer indoor clothing. The metabolic rate was assumed to be 1.1 met. It corresponds to an occupant who is typing (ASHRAE 2017). The effects of an additional fan were analyzed as well for all three cases. For this purpose, the generated air velocity was assumed to be 0.5 $m.s^{-1}$.

To estimate the mean radiant temperature, it was necessary to calculate the shape factor from the occupant to the cooling panel. All surrounding surfaces, except for the radiant element, were assumed to have a surface temperature, which is equal to the ambient air temperature. The surface temperature of the cooling panel was adjusted depending on the thermal conditions within the indoor space. In this context, every time the PMV exceeded the recommended limit of +0.5, the cooling system was activated. As a result, the surface temperature of the radiant element was reduced. This process continued until the calculated PMV is within its recommended range, or if one of the following conditions occurred. The PMV calculations are conducted for two main scenarios. Depending on the scenario, the aforementioned conditions are specified:

<u>Scenario without surface condensation</u>

- *Condensation Risk:* Condensation is to be avoided within this scenario. As a result, the surface temperature of the radiant cooling panel must not fall below the dew point temperature.
- *Radiant asymmetry:* The second condition of this scenario refers to the radiant asymmetry (ISO 2006). Large temperature differences between the surfaces that surround the occupant are to be avoided. For this reason, it was specified that the difference between the ambient air temperature and the surface temperature of the cooling element must not exceed 15 K. This maximum value refers to a percentage of dissatisfied (PD) of about 19.2%.

<u>Scenario with surface condensation</u>

- *Radiant asymmetry:* In this scenario, only one condition hinders the surface temperature of the panel from being reduced. It refers to avoiding discomfort due to radiant asymmetry (ISO 2006). Again, the difference between the air temperature and the panels' surface temperature must not exceed 15 K.

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5.1.4 Research Questions

The outcome of this computational study will be analyzed based on the following four research question:

Q1 What are the effects of one radiant cooling panel on occupants' thermal comfort?

The results of this study are expected to show to what extent occupants' thermal comfort can be improved with the proposed radiant cooling element. More specifically, the percentage of time in which the PMV exceeds a value of +0.5 or +1.0 will be analyzed. Thereby, the focus is on the occupied times of the space (8:00 am - 6:00 pm). The results are compared to the base case which does not include any radiant cooling elements.

Q2 What are the effects of two radiant cooling panels on occupants' thermal comfort?

The impact of an enlarged radiant surface area is analyzed as well. In case of this study, the larger area is achieved by a second radiant cooling panel on the other side of the occupant. Again, the extent of improvement of occupants' thermal comfort is to be identified. The approach is similar to Q1. However, in this case the analysis is expected to document the difference of positioning two radiant panels in comparison to one element.

Q3 What are the effects of an elevated air flow speed on occupants' thermal comfort?

On the one hand, the effects of convective cooling options in form of a fan will be compared to the proposed radiant cooling strategies. On the other hand, the study is expected to document the impact if the radiant cooling elements are additionally supported by a fan. In this context, the percentage of time in which the PMV exceeds a value of +0.5 or +1.0 is compared for the different cases (with and without an additional fan). The calculation of those values involves only the occupied times within the cooling season.

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Q4 To what extent can occupants' thermal comfort be improved by allowing surface condensation on the radiant panel?

The study also aims at investigating the impact of lower radiant surfaces temperatures. They can be achieved by allowing condensation to occur. In order to evaluate the effect of these lower surface temperatures on occupants' thermal comfort, all calculated cases without condensation are compared to the scenarios with surface condensation. More specifically, the calculated time in which the PMV is higher than its recommended limit is used for this comparison. Furthermore, the percentage of time in which condensation occurs is documented for all three years.

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5.2 Results

5.2.1 Thermal conditions without a cooling system

Figures 17 to 19 show the thermal conditions within the office area. The temperature as well as the relative humidity is illustrated for the warmest months of the three examined years.

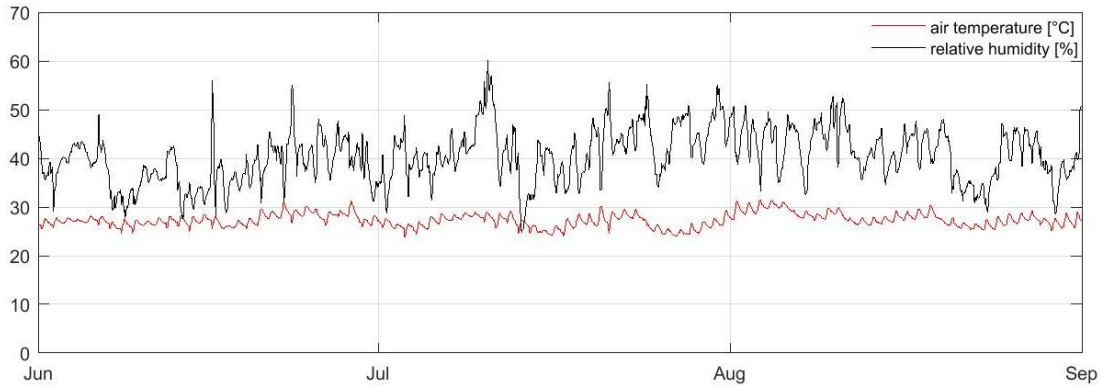

Figure 17 Temperature and relative humidity within the office area in 2017

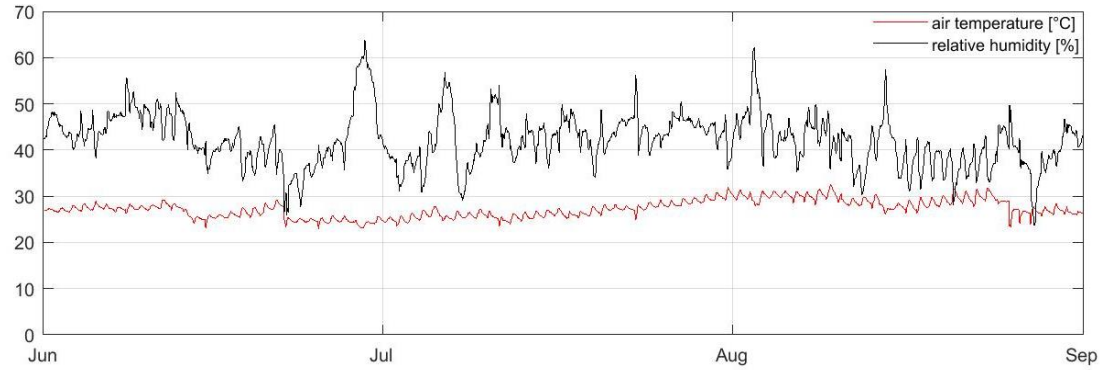

Figure 18 Temperature and relative humidity within the office area in 2018

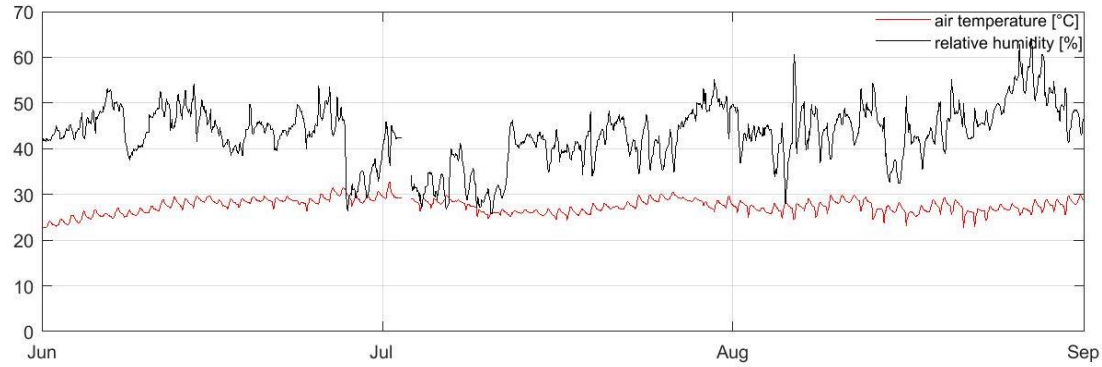

Figure 19 Temperature and relative humidity within the office area in 2019

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Figures 20 to 22 illustrate the frequency of specific air temperatures within the office area. Note that these graphs consider only the occupied times (8:00 am - 6:00 pm).

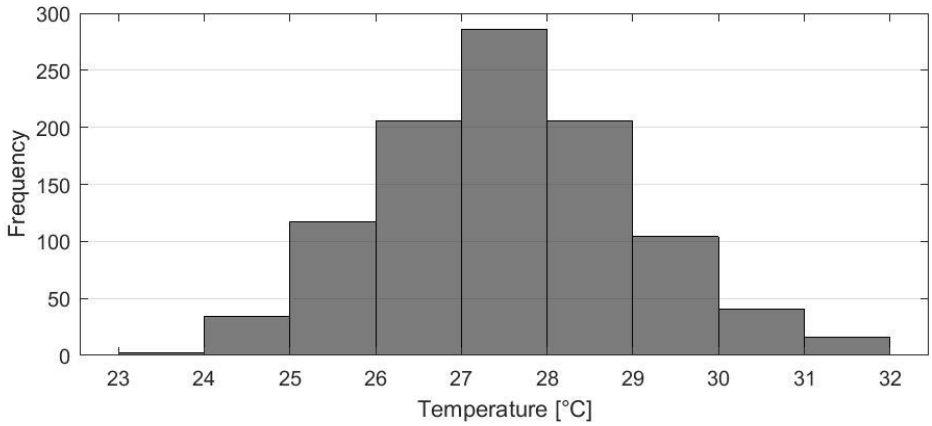

Figure 20 Frequency of specific air temperatures within the working hours from June – August of 2017

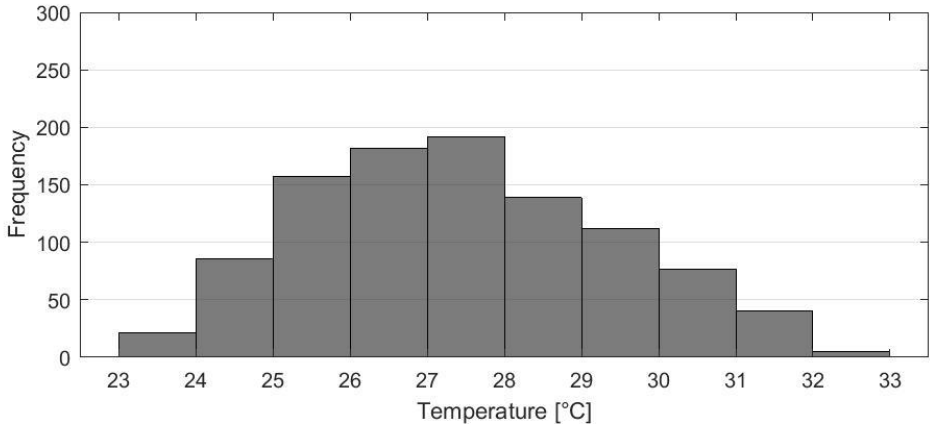

Figure 21 Frequency of specific air temperatures within the working hours from June – August of 2018

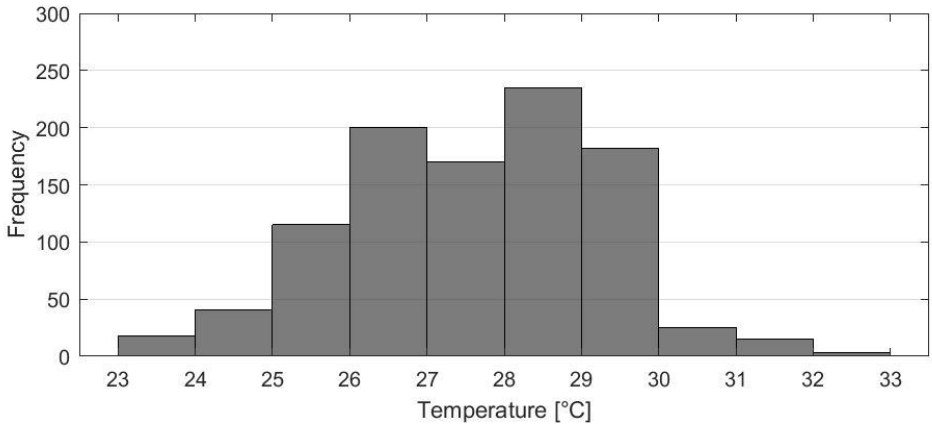

Figure 22 Frequency of specific air temperatures within the working hours from June – August of 2019

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5.2.2 Thermal comfort evaluation

Scenario without surface condensation

Figures 23 - 26 present the results for some of the calculated cases of one exemplary year. More specifically, the results are shown for the cooling season of 2017. The outcome for the other examined years and cases is presented in more detail within the Appendix. The graphs show the PMV, PPD, and PD, which were calculated on an hourly basis. The dynamically adjusted surface temperature of the radiant cooling panel is illustrated as well.

Figure 23 illustrates the outcome of the base case without a radiant cooling panel and no additional fan. It is noticeable, that the PMV exceeds the recommended limit of +0.5 in several situations. Frequently, the PMV reaches a value of 1. This refers to the subjective evaluation of “slightly warm”. In some situations, the PMV almost reaches a value of 2, which corresponds to a subjective evaluation of “warm” (ISO 2006).

Consequently, the predicted percentage of dissatisfied people is often also increased. On a few days in late June and early August, the PPD is higher than 50%.

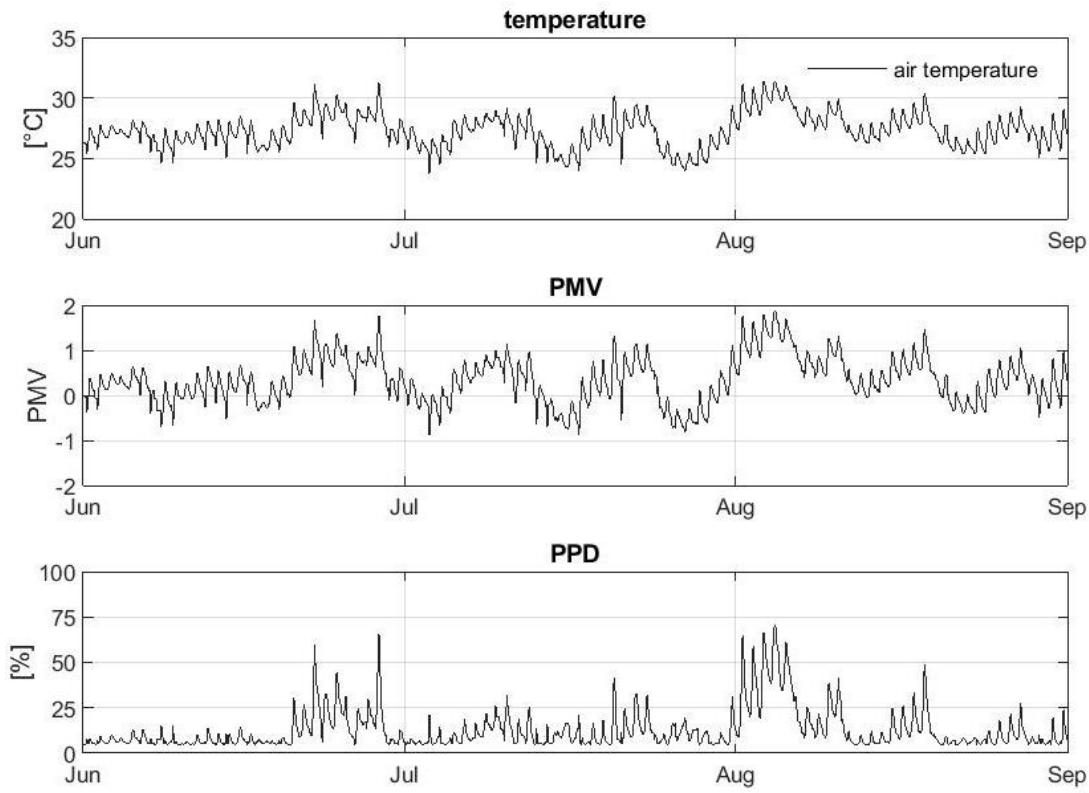

Figure 23 2017 - no radiant panel; vel= 0.2 m.s^{-1}

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Figure 24 shows the results if one radiant cooling element is positioned in close proximity to the occupant. In the course of the cooling period it was not necessary to continuously activate the cooling panel. However, the panel was frequently used at high ambient air temperatures. As a result, the surface temperature of the cooling element was repeatedly reduced. Often, this was done until shortly before the surface temperature would fall below the dew point temperature. It can be noticed that the PMV is often within its recommended range and rarely exceeds a value of 1. The PPD exceeds 50% only once during the entire cooling season. This occurs at the beginning of August.

Figure 25 illustrates the outcome if an additional fan is used in combination with one radiant cooling panel. In several cases, the PMV is below +0.5. Only in rare situations it exceeds a value of 1. The PPD is never higher than 50%.

The calculation results for two radiant cooling panels and no additional fan are presented in Figure 26. It is noticeable that the PMV is almost always below the recommended limit of +0.5. Only in exceedingly rare cases, the PMV is higher than 1. The PPD is almost always below 25%. It is only slightly increased at the end of June and the beginning of August.

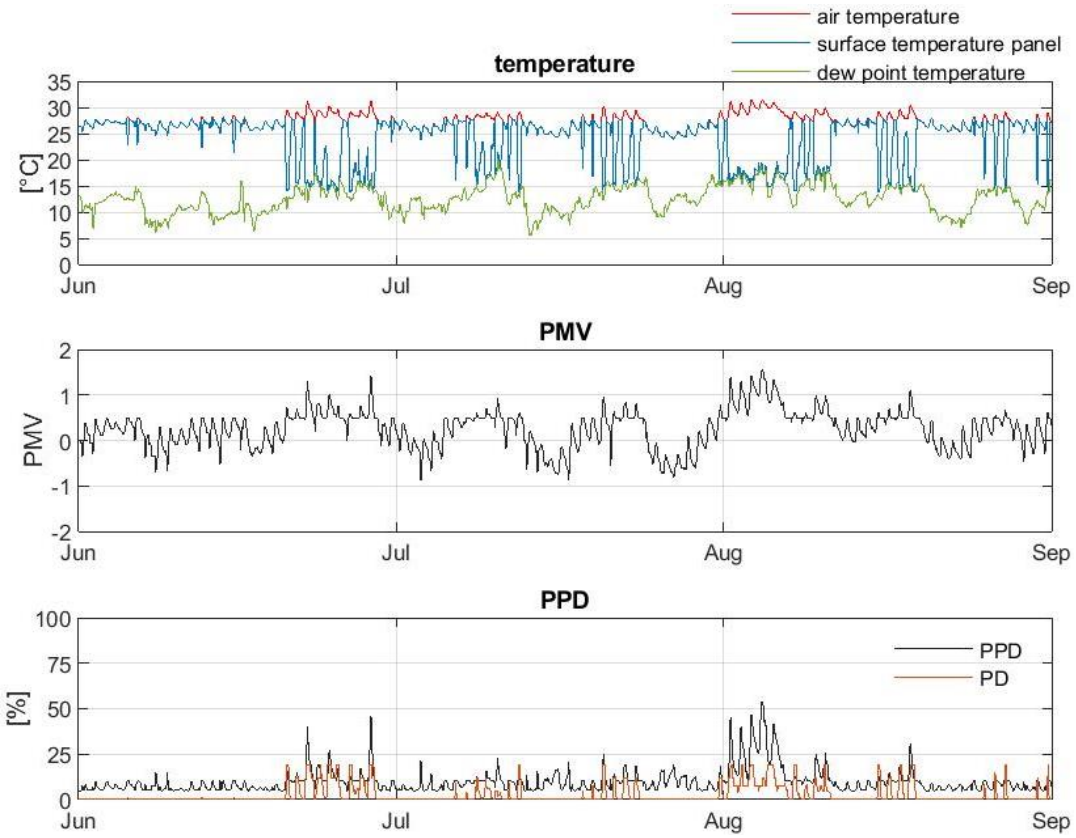

Figure 24 2017 - 1 radiant panel; vel= 0.2 m.s^{-1}; scenario without condensation

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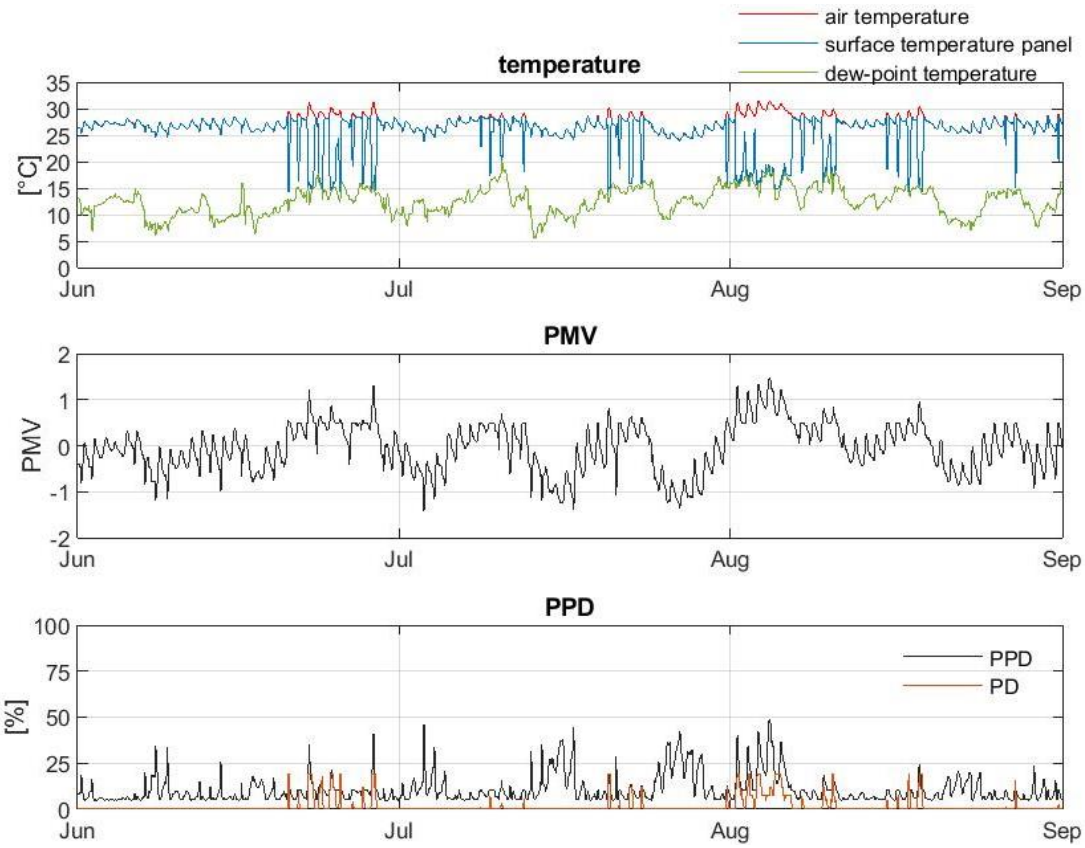

Figure 25 2017 - 1 radiant panel; vel= 0.5 m.s-1; scenario without condensation

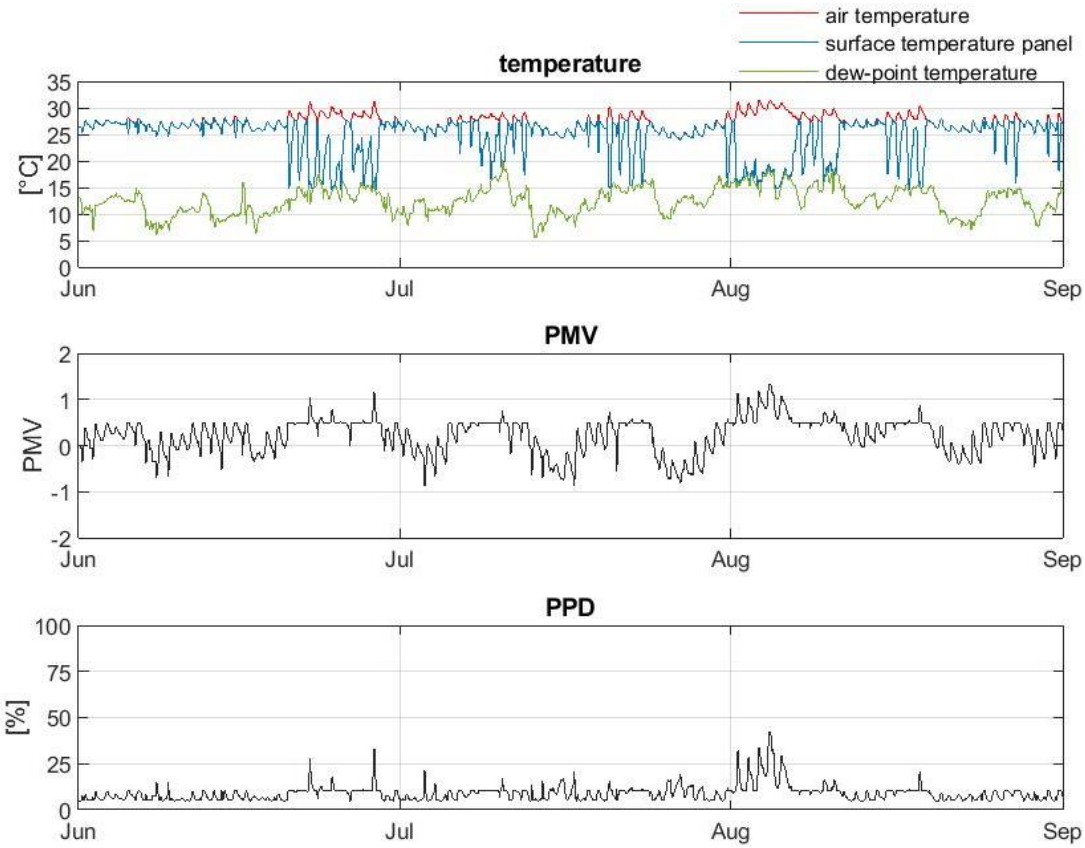

Figure 26 2017 - 2 radiant panels; vel= 0.2 m.s-1; scenario without condensation

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Figure 27 shows a cumulative distribution of the percentage of time in which PMV exceeds a specific value. This is presented for all cases of 2017. The graphs for the other two years are in the Appendix. The figure shows the thermal comfort improvement of radiant and convective cooling solutions. They are illustrated individually and both in combination.

Table 10 summarizes the results of all calculated cases and all three years. In particular, it shows the percentage of time in which the PMV exceeds +0.5 or +1.0 within the office hours (8:00 am to 6:00 pm).

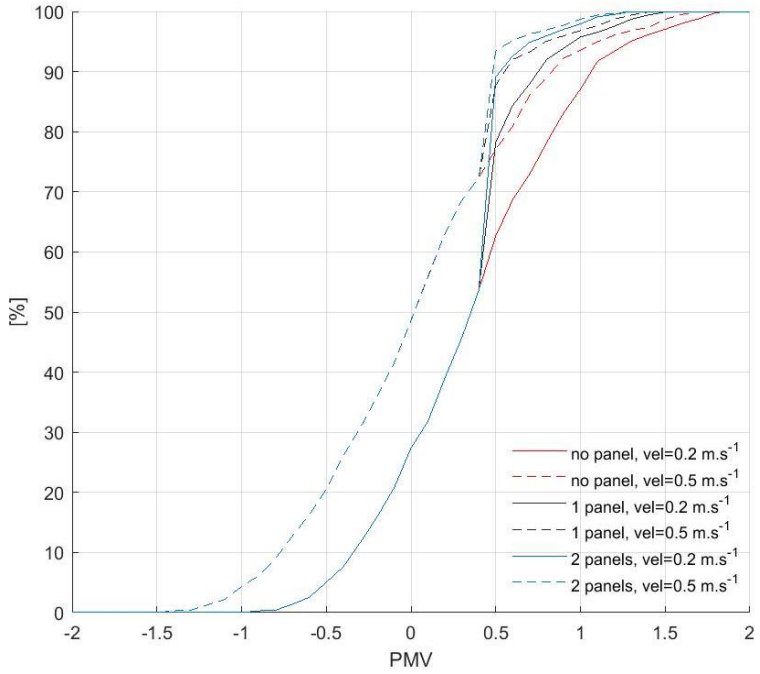

Figure 27 2017 - Cumulative distribution of the percentage of time when PMV exceeds a specific value (all scenarios without condensation)

Table 10 Percentage in which the PMV exceeds 0.5 or 1 within the working hours (8:00 AM – 6:00 PM); scenario with condensation

	No radiant cooling panel				**1 radiant cooling panel**				**2 radiant cooling panels**			
	PMV > 0.5		**PMV > 1.0**		**PMV > 0.5**		**PMV > 1.0**		**PMV > 0.5**		**PMV > 1.0**	
Air velocity [m.s^{-1}]	**0.2**	**0.5**	**0.2**	**0.5**	**0.2**	**0.5**	**0.2**	**0.5**	**0.2**	**0.5**	**0.2**	**0.5**
2019	49.9	36.6	20.9	7.0	34.2	19.5	4.3	2.5	18.4	6.8	2.4	2.1
2018	42.4	28.9	21.3	14.2	27.4	19.9	12.7	9.4	19.1	14.9	7.6	5.0
2017	41.2	25.2	14.1	7.2	22.9	13.1	5.1	3.5	12.5	7.3	2.6	1.7

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Scenario with surface condensation

Figures 28 - 30 show the results for some of the calculated cases of 2017. The outcome for the other examined years and cases is presented in more detail within the Appendix. Within the used calculation procedure, the surface temperature of the radiant panel was not hindered from falling below the dew point temperature. As a result, surface condensation is possible. The graphs show the PMV, PPD, and PD, which were calculated on an hourly basis. The dynamically adjusted surface temperature of the radiant cooling panel is illustrated as well.

Due to the fact that surface condensation is possible for this scenario, the surface temperature of the cooling panel is occasionally lower than the dew point temperature. This occurred at the beginning of August and sometimes at the end of June.

Figure 31 shows a cumulative distribution of the percentage of time in which PMV exceeds a specific value. This is presented for all cases of 2017. It illustrates the thermal comfort improvement of radiant and convective cooling solutions.

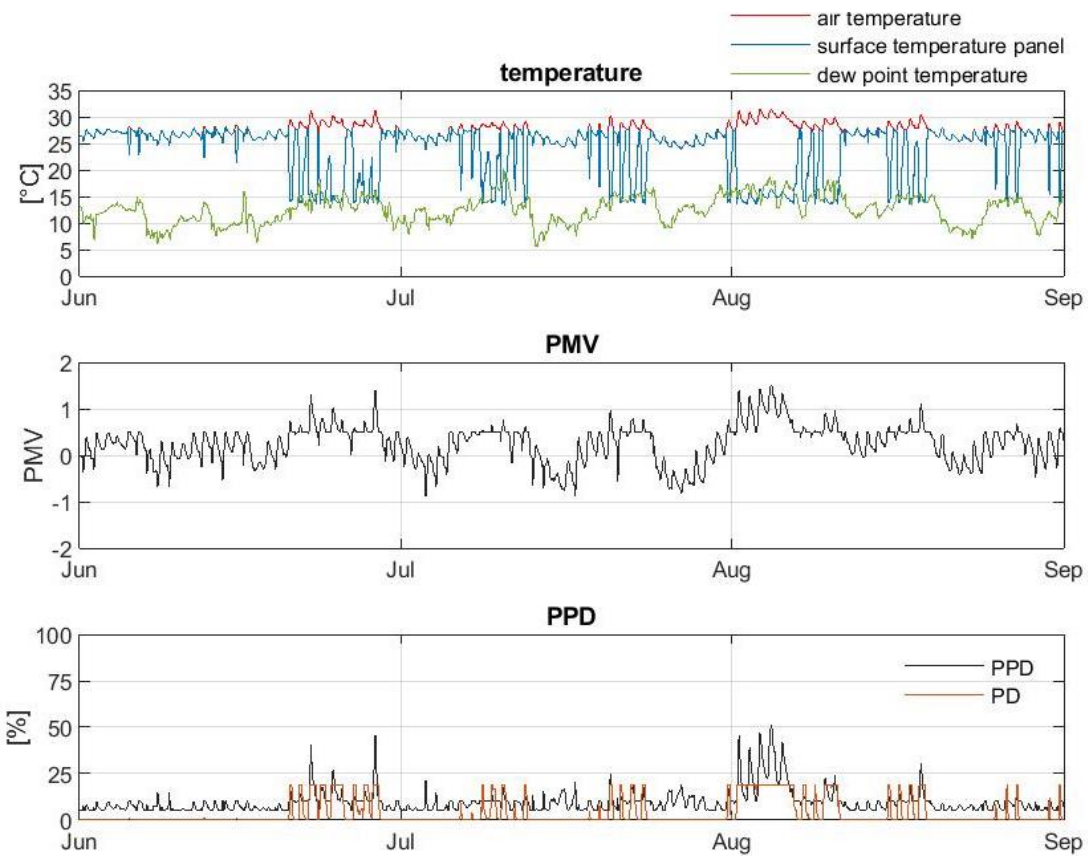

Figure 28 2017 - 1 radiant panel; vel= 0.2 m.s^{-1}; scenario with condensation

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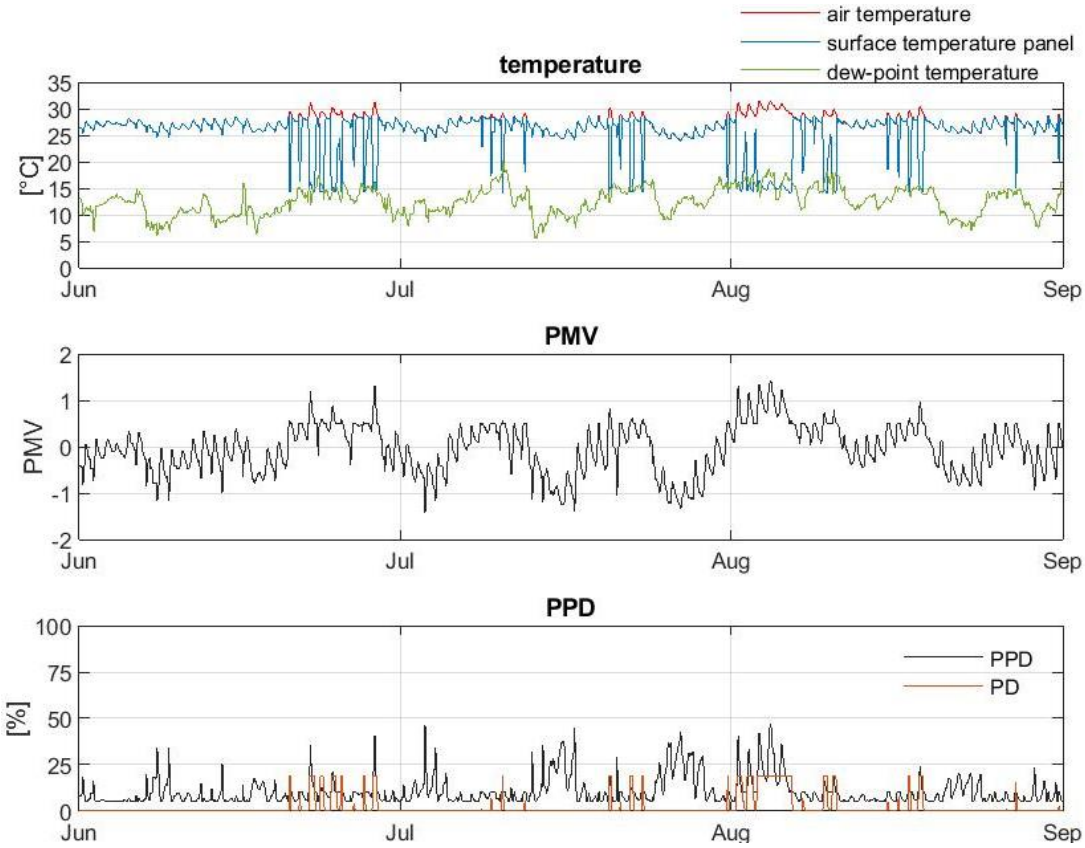

Figure 29 2017 - 1 radiant panel; vel= 0.5 m.s^{-1}; scenario with condensation

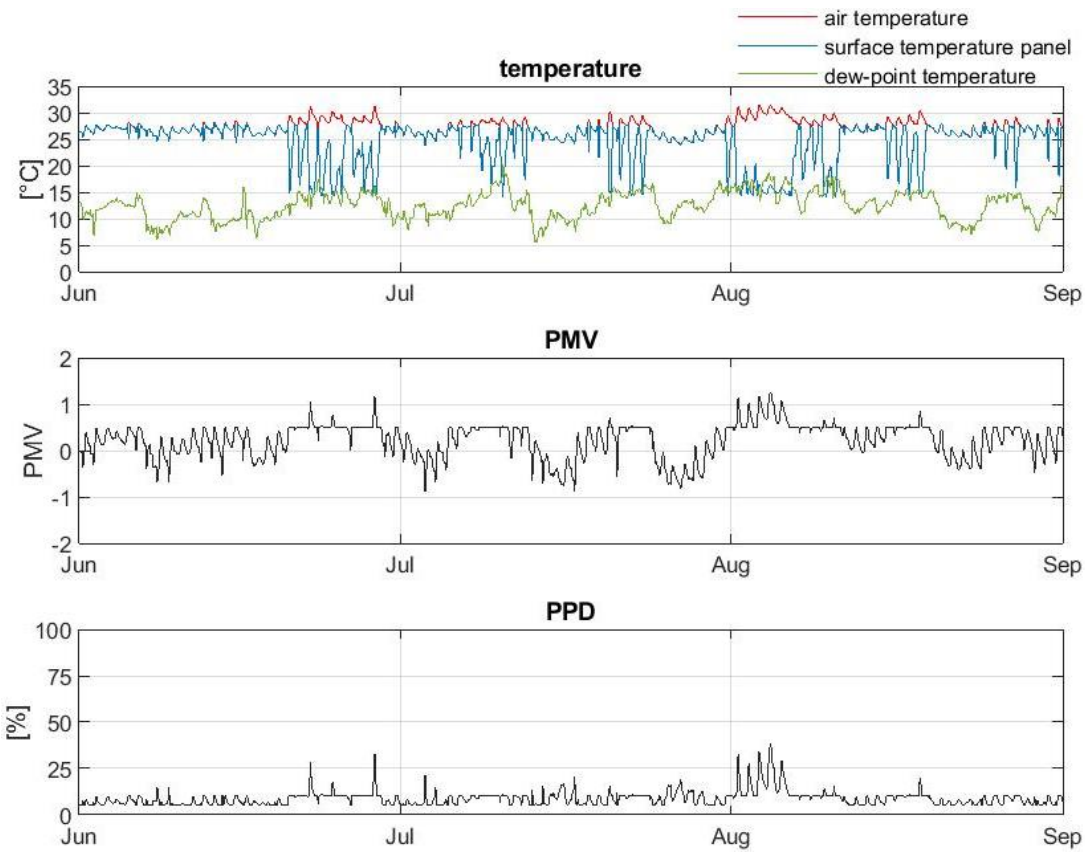

Figure 30 2017 - 2 radiant panels; vel= 0.2 m.s^{-1}; scenario with condensation

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Table 11 provides a summary of the results from all calculated cases with surface condensation and all three years. In more detail, it shows the percentage of time in which the PMV exceeds +0.5 or +1.0 within the office hours (8:00 am to 6:00 pm).

The percentage of time in which condensation occurs within the working hours is presented in Figure 32.

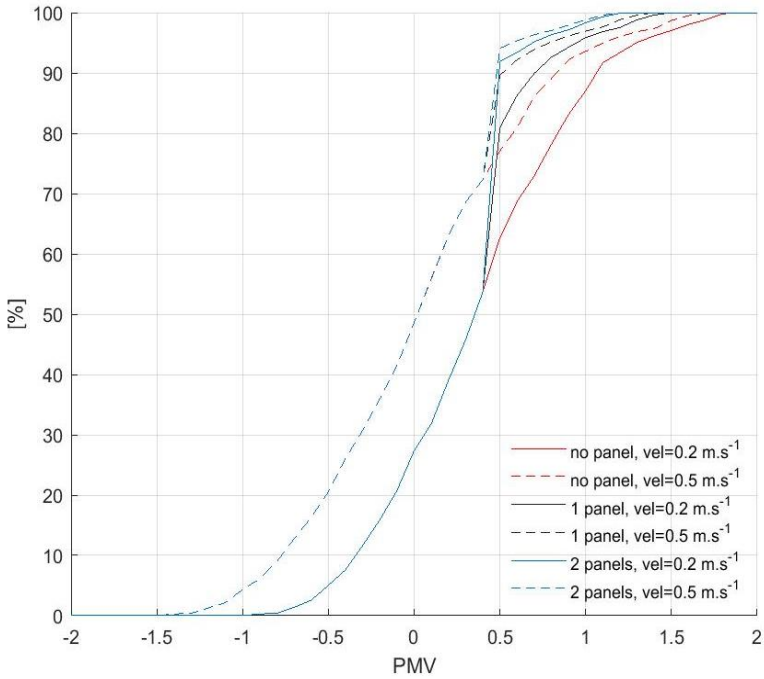

Figure 31 2017 - Cumulative distribution of the percentage of time when PMV exceeds a specific value (all scenarios with condensation)

Table 11 Percentage in which the PMV exceeds 0.5 or 1 within the working hours (8:00 AM – 6:00 PM); scenario with condensation

	No radiant cooling panel				**1 radiant cooling panel**				**2 radiant cooling panels**			
	PMV > 0.5		**PMV > 1.0**		**PMV > 0.5**		**PMV > 1.0**		**PMV > 0.5**		**PMV > 1.0**	
Air velocity [m.s^{-1}]	**0.2**	**0.5**	**0.2**	**0.5**	**0.2**	**0.5**	**0.2**	**0.5**	**0.2**	**0.5**	**0.2**	**0.5**
2019	49.9	36.6	20.9	7.0	31.4	17.2	3.9	2.5	12.8	5.8	2.1	1.9
2018	42.4	28.9	21.3	14.2	26.6	18.9	12.1	9.2	17.8	13.9	6.5	4.5
2017	41.2	25.2	14.1	7.2	21.6	12.5	4.8	3.3	10.3	6.7	2.5	1.6

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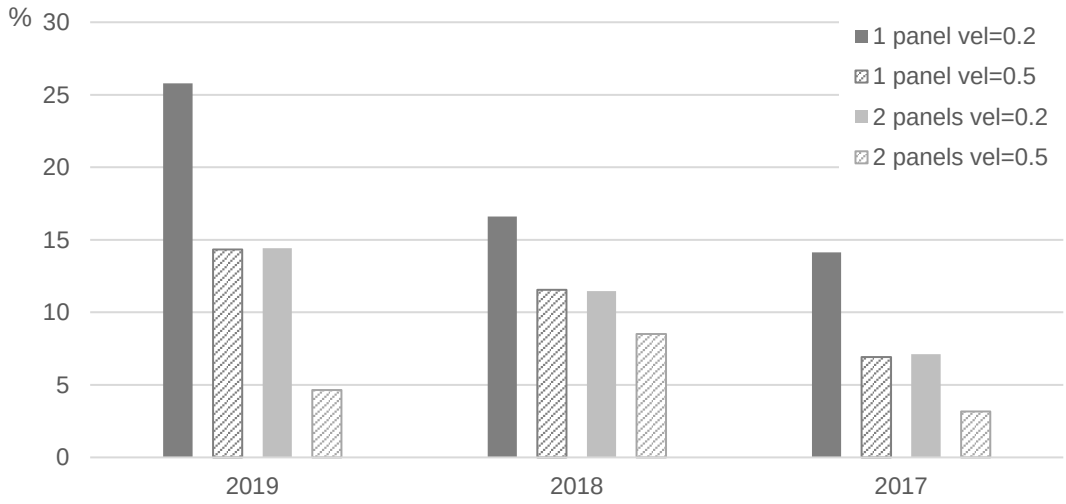

Figure 32 Percentage of time in which condensation occurs within the working hours (8:00 AM – 6:00 PM); velocity in m.s^{-1}

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5.3 Discussion

The results of the computational study are discussed based on the initial research questions from chapter 5.1.4:

Q1 What are the effects of one radiant cooling panel on occupants' thermal comfort?

In order to assess the impact of a radiant cooling element on occupants' thermal comfort, the results of two cases are compared. In this context, the calculated scenarios which are used for this comparison are the base case without a cooling system as well as the case that includes one radiant panel. Note that for both of these scenarios the calculations without condensation as well as without an increased air speed are used for this comparison.

Figures 23 and 24 illustrate the outcome for the entire cooling season of both cases. It is noticeable that by positioning a radiant element in close proximity to an occupant, the time in which the PMV exceeds the recommended limit is significantly lower. This is illustrated even more clearly in Figure 33. It compares both cases based on the percentage of time in which the PMV exceeds a specific limit within the occupied hours of the cooling season. The percentage is significantly reduced when an occupant-centric radiant panel is available. This applies to all calculated years. However, this reduction is especially noticeable for the time in which PMV exceeds a value of 1 in the year of 2019. The reason for this outcome is the fact that for the case without a cooling system, the calculated PMV is often slightly above 1 (see Figure 41). By using a radiant panel, many of those values were able to fall below 1.

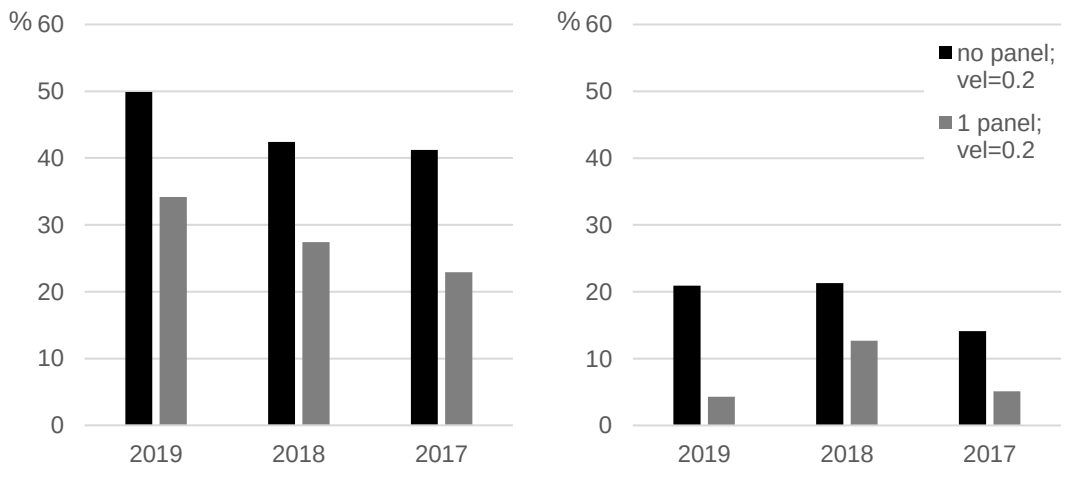

Figure 33 Percentage in which the PMV exceeds 0.5 (left) or 1 (right) within the working hours – comparison no cooling system to 1 radiant panel; velocity in m.s^{-1}

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As mentioned before, the study was conducted for the climatic conditions in Vienna. The results suggest that in such a location, occupants' thermal comfort can be significantly improved, if a user-centric radiant cooling panel is used. Even one of the proposed radiant elements can have a major impact on occupants' comfort within the summer months.

Q2 What are the effects of two radiant cooling panels on occupants' thermal comfort?

The impact of a larger surface area is also evaluated by comparing some of the scenarios. In this context, Figure 34 illustrates the percentage of time in which the PMV is higher than +0.5 or +1.0 within the specified period. This is shown for three cases: *i)* without a cooling system, *ii)* for one radiant panel, and *iii)* for two radiant panels. The presented values for this comparison are derived from the calculations without condensation and without an additional fan. It is clearly noticeable that with a larger radiant surface area, the increased part of the PMV is reduced even further. In 2019, for instance, the PMV is half the time above the recommended limit, if no cooling panel is used. After positioning two user-centric radiant cooling elements, this value reduces to 18.4%.

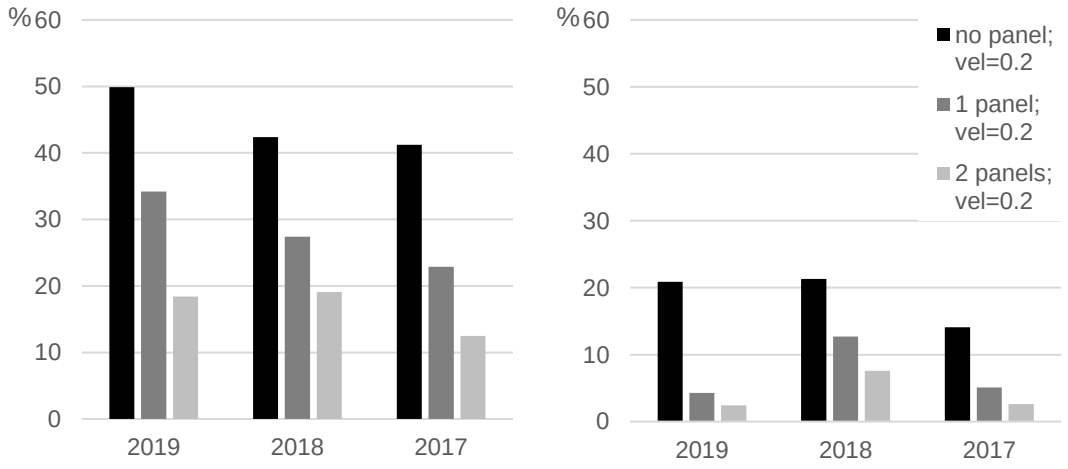

Figure 34 Percentage in which the PMV exceeds 0.5 (left) or 1 (right) within the working hours – comparison no cooling system to 1 and 2 radiant panels; velocity in m.s^{-1}

Q3 What are the effects of an elevated air flow speed on occupants' thermal comfort?

Figure 35 shows the percentage of time in which the PMV exceeds a specific limit for the year of 2017. The values are presented for multiple cases. The aim of this graph is to illustrate the outcome for the scenarios with an increased air flow speed next to

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the results of the radiant cooling strategies. By comparing the case which includes only a fan to the scenario with one radiant panel, it is noticeable that the radiant cooling option achieves slightly better results. Another advantage of this option is the fact that a radiant cooling element does not generate draft, which can be uncomfortable for some people.

Figure 35 also documents the effects if the radiant cooling elements are supported by a fan. It is noticeable that the additional air flow speed contributes to a further reduction of the time in which the PMV is above the recommended limit. The results suggest that with two radiant panels as well as an increased air speed, the percentage of time in which the PMV is above +0.5 is reduced to 7.3%. Furthermore, only 1.7% of the time, the PMV exceeds a value of 1.

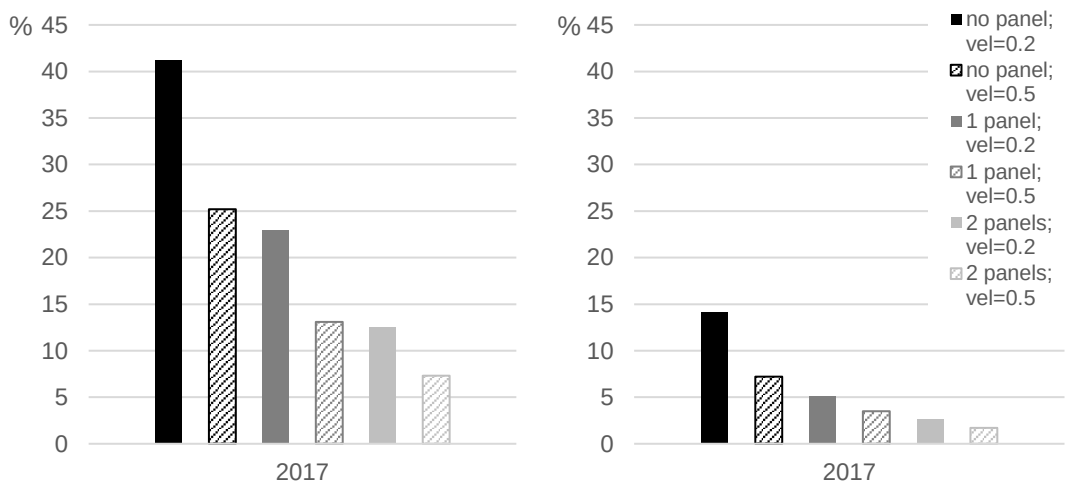

Figure 35 Percentage in which the PMV exceeds 0.5 (left) or 1 (right) within the working hours – comparison with/without elevated air speed; velocity in m.s^{-1}

Q4 To what extent can occupants' thermal comfort be improved by allowing surface condensation on the radiant panel?

Another aim of this research was to investigate the impact of lower radiant surfaces temperatures by allowing condensation to occur. In order to evaluate this effect, the results from all calculated cases without condensation are compared to the scenarios with surface condensation. Again, this is done by evaluating the percentage of time in which the PMV exceeds a specific limit within the occupied hours of the cooling season. Figure 36 shows the comparison for the exemplary year of 2017.

It is noticeable that by allowing condensation to occur, the percentage in which the PMV is above +0.5 is further reduced. This applies to all calculated cases. However, in some cases this improvement is rather small. A reason for the outcome is the fact

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that the reduction of the panels' surface temperature is sometimes also limited by the specified condition with regard to the radiant asymmetry.

Nonetheless, the results suggest that providing lower surface temperatures by allowing condensation further reduces the time in which the PMV is increased. For this reason, the approach can be an appropriate solution to improve occupants' thermal comfort during the summer months.

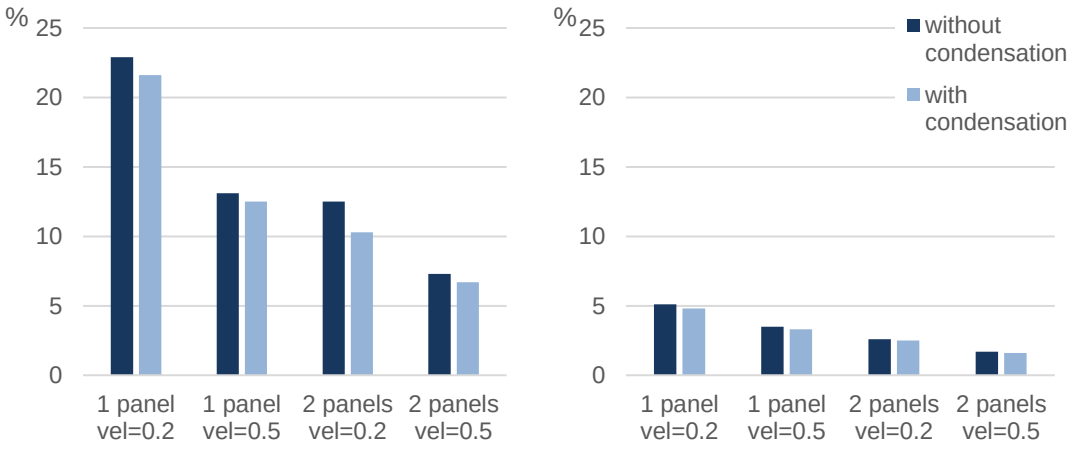

Figure 36 Percentage in which the PMV exceeds 0.5 (left) or 1 (right) within the working hours – comparison scenarios with/without condensation; velocity in m.s^{-1}

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6 CONCLUSION

6.1 Summary of contents

This master thesis explored the potential of a number of previously proposed user-centric radiant cooling solutions. These involve three main concepts. The first one aims at positioning the radiant cooling elements closer to occupants. This increases the energy efficiency and allows more personal control options. The second concept aims at designs that can accommodate surface condensation. For this purpose, the radiant elements must be designed as vertical panels. By incorporating drainage systems, the temperature of the radiant elements is not restricted to stay above the dew point temperature. As a result, it can be clearly lower in comparison to conventional radiant cooling solutions. The last concept aims at incorporating vegetation into the radiant panel designs. This can improve the indoor climate. Furthermore, the condensate can be used to water the plants.

A preliminary computational study explored the thermal comfort provision potential of the examined occupant-centric radiant cooling solutions. For this purpose, the PMV, as a common indicator of thermal comfort, was used (ISO 2006; ASHRAE 2017). Furthermore, specific assumptions were made for the calculation procedure. At specific ambient air temperatures, the activated radiant panel was able to keep the PMV below its recommended limit of +0.5. At higher air temperatures the cooling element had to be supported by an additional fan. For the used assumptions and with an increased air flow speed by a fan, the PMV did not exceed +0.5 until an ambient air temperature of 30 °C.

A further computational case study assessed occupants' thermal comfort for the climatic conditions within an office area in Vienna, Austria. The results suggest that thermal comfort can be significantly improved if a radiant cooling panel is positioned in close proximity to a user. Consequently, the calculated percentage of time in which PMV exceeds the recommended limit of +0.5 is lower for the cases with a radiant element. Furthermore, the outcome suggests that occupants' thermal comfort is further improved if lower panel surface temperatures are possible by allowing condensation. The same applies for a second radiant element, or an increased air flow speed by additional fan.

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6.2 Future research

A number of occupant-centric radiant cooling solutions were examined within this contribution. In future, it would be desirable to further these solutions in more detail. Moreover, the computational case studies could be conducted for different locations. Thus, one could examine the extent to which user-centric radiant cooling elements could improve occupants' thermal comfort in other climatic regions. Especially buildings in a hot and humid climate could be the focus of future assessments.

Furthermore, the energy efficiency of the user-centric radiant cooling elements needs to be systematically examined. For this purpose, radiant cooling panels can be compared to conventional air-conditioning systems.

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Table 10 Percentage in which the PMV exceeds 0.5 or 1 within the working hours (8:00 AM – 6:00 PM); scenario with condensation

Table 11 Percentage in which the PMV exceeds 0.5 or 1 within the working hours

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8 LITERATURE

Ali Ahmed, A.A.E.-M.M., 2012. *Using simulation for studying the influence of vertical shading devices on the thermal performance of residential buildings (Case study: New Assiut City).* Ain Shams Engineering Journal 3 (2), pp. 163–174. DOI: 10.1016/j.asej.2012.02.001.

Allouhi, A., Kousksou, T., Jamil, A., Bruel, P., Mourad, Y., Zeraouli, Y. 2015. *Solar driven cooling systems: An updated review.* Renewable and Sustainable Energy Reviews 44, pp. 159–181. DOI: 10.1016/j.rser.2014.12.014.

ASHRAE, 2012. *ASHRAE Handbook. Heating, Ventilating, and Air-Conditioning SYSTEMS AND EQUIPMENT*. Atlanta, GA: ASHRAE.

ASHRAE, 2017. *ASHRAE 55 - Thermal Environmental Thermal Conditions for Human Occupancy.*

ASTM, 2019. ASTM E1980-11. Standard Practice for Calculating Solar Reflectance Index of Horizontal and Low-Sloped Opaque Surfaces.

Bhamare, D.K., Rathod, M.K., Banerjee, J., 2019. *Passive cooling techniques for building and their applicability in different climatic zones—The state of art.* Energy and Buildings 198, pp. 467–490. DOI: 10.1016/j.enbuild.2019.06.023.

Cabrera, F. J., Fernández-García, A., Silva, R.M.P., Pérez-García, M., 2013. *Use of parabolic trough solar collectors for solar refrigeration and air-conditioning applications.* Renewable and Sustainable Energy Reviews 20, pp. 103–118. DOI: 10.1016/j.rser.2012.11.081.

Cetin, M., Sevik, H., 2016. *Measuring the Impact of Selected Plants on Indoor CO2 Concentrations.* Pol. J. Environ. Stud. 25 (3), pp. 973–979. DOI: 10.15244/pjoes/61744.

Chiang, W.-H., Wang, C.-Y., Huang, J.-S., 2012. *Evaluation of cooling ceiling and mechanical ventilation systems on thermal comfort using CFD study in an office for subtropical region.* Building and Environment 48, pp. 113–127. DOI: 10.1016/j.buildenv.2011.09.002.

Cubick, R., 2017. Radiant Cooling System Components. *https://web.uponor.hk/radiant-cooling-blog/radiant-cooling-system-components/.* Accessed 02.05.2020.

Daviran, S., Kasaeian, A., Golzari, S., Mahian, O., Nasirivatan, S., Wongwises, S., 2017. *A comparative study on the performance of HFO-1234yf and HFC-134a as an*

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alternative in automotive air conditioning systems. Applied Thermal Engineering 110, pp. 1091–1100. DOI: 10.1016/j.applthermaleng.2016.09.034.

Davis, M.M., Hirmer, S., 2015. *The potential for vertical gardens as evaporative coolers: An adaptation of the 'Penman Monteith Equation*. Building and Environment 92, pp. 135–141. DOI: 10.1016/j.buildenv.2015.03.033.

DelPrince, J.M., 2013. *Interior plantscaping. Principles and practices.* Clifton Park: Delmar Cengage Learning.

Eicker, U., Pietruschka, D., Schmitt, A., Haag, M., 2015. *Comparison of photovoltaic and solar thermal cooling systems for office buildings in different climates.* Solar Energy 118, pp. 243–255. DOI: 10.1016/j.solener.2015.05.018.

Evans, P., 2017. Absorption Chiller. *https://theengineeringmindset.com/absorption-chiller-works/.* Accessed 02.05.2020.

Fanger, P. O., 1970. *Thermal comfort.* Copenhagen: Danish Press.

Feng, J., Chuang, F., Borrelli, F., Bauman, F., 2015. *Model predictive control of radiant slab systems with evaporative cooling sources.* Energy and Buildings 87, pp. 199–210. DOI: 10.1016/j.enbuild.2014.11.037.

Fong, K. F., Chow, T. T., Lee, C. K., Lin, Z.; Chan, L. S., 2010. *Comparative study of different solar cooling systems for buildings in subtropical city.* Solar Energy 84 (2), pp. 227–244. DOI: 10.1016/j.solener.2009.11.002.

Gartenlexikon, 2020. Zimmerpflanzen für dunkle Standorte und kühle Räume. *https://www.gartenlexikon.de/zimmerpflanzen-dunkle-standorte/.* Accessed 26.04.2020.

Gau, U., 2005. *Eine mobile Kühlwand für Büroräume*. Master Thesis: TU Wien.

Greiner, K., Weber, A., 2016. *Zimmerpflanzen.* München: Gräfe und Unzer Verlag GmbH.

Hartmann, N., Glueck, C., Schmidt, F. P., 2011. *Solar cooling for small office buildings: Comparison of solar thermal and photovoltaic options for two different European climates.* Renewable Energy 36 (5), pp. 1329–1338. DOI: 10.1016/j.renene.2010.11.006.

He, Y., Li, N., He, M., He, D., 2017. *Using radiant cooling desk for maintaining comfort in hot environment.* Energy and Buildings 145, pp. 144–154. DOI: 10.1016/j.enbuild.2017.04.013.

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The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU WIEN Bibliothek Your knowledge hub

Hernández-Pérez, I., Álvarez, G., Xamán, J., Zavala-Guillén, I., Arce, J., Simá, E., 2014. *Thermal performance of reflective materials applied to exterior building components—A review.* Energy and Buildings 80, pp. 81–105. DOI: 10.1016/j.enbuild.2014.05.008.

Hestermann, U., Rongen, L., 2015. *Frick/Knöll Baukonstruktionslehre 1*. Wiesbaden: Springer Fachmedien Wiesbaden.

IEA, 2018a. The future of Cooling. Opportunities for energy-efficient air conditioning. *https://www.iea.org/reports/the-future-of-cooling*. Accsessed 26.04.2020.

IEA, 2018b. Air conditioning use emerges as one of the key drivers of global electricity-demand growth. *https://www.iea.org/news/air-conditioning-use-emerges-as-one-of-the-key-drivers-of-global-electricity-demand-growth*. Accsessed 26.04.2020.

Imanari, T., Omori, T., Bogaki, K., 1999. *Thermal comfort and energy consumption of the radiant ceiling panel system*. Energy and Buildings 30 (2), pp. 167–175. DOI: 10.1016/S0378-7788(98)00084-X.

ISO, 2006. *ISO 7730 - Ergonomics of the thermal environment - Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria criteria.*

Kalogirou, S. A., 2014. *Solar Energy Collectors*. Solar Energy Engineering: Elsevier, pp. 125–220.

Kim, T., Kato, S., Murakami, S., Rho, J., 2005. *Study on indoor thermal environment of office space controlled by cooling panel system using field measurement and the numerical simulation*. Building and Environment 40 (3), pp. 301–310. DOI: 10.1016/j.buildenv.2004.04.010.

Kirimtat, A., Koyunbaba, B.K., Chatzikonstantinou, I., Sariyildiz, S., 2016. *Review of simulation modeling for shading devices in buildings.* Renewable and Sustainable Energy Reviews 53, pp. 23–49. DOI: 10.1016/j.rser.2015.08.020.

Kuhn, T.E., 2017. *State of the art of advanced solar control devices for buildings*. Solar Energy 154, pp. 112–133. DOI: 10.1016/j.solener.2016.12.044.

Lazzarin, R. M., Noro, M., 2018. *Past, present, future of solar cooling: Technical and economical considerations.* Solar Energy 172, pp. 2–13. DOI: 10.1016/j.solener.2017.12.055.

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar.
The approved original version of this thesis is available in print at TU Wien Bibliothek.
TU WIEN Bibliothek Your knowledge hub

Levinson, R., Akbari, H., Konopacki, S., Bretz, S., 2005a *Inclusion of cool roofs in nonresidential Title 24 prescriptive requirements.* Energy Policy 33 (2), pp. 151–170. DOI: 10.1016/S0301-4215(03)00206-4.

Levinson, R., Berdahl, P., Asefawberhe, A., Akbari, H., 2005b. *Effects of soiling and cleaning on the reflectance and solar heat gain of a light-colored roofing membrane.* Atmospheric Environment 39 (40), pp. 7807–7824. DOI: 10.1016/j.atmosenv.2005.08.037.

Lohr, V., 1995. *Interior plants may improve worker productivity and reduce stress in a windowless environment.* Environ. Hort. 14.

Lun, Y. H. Venus, Tung, S. L. D., 2020. *Heat Pumps for Sustainable Heating and Cooling.* Cham: Springer International Publishing.

Mahdavi, A., Teufl, H., 2020. *Occupant-centric radiant cooling solutions. Requirements, designs, assessment.* In PLEA 2020 (Ed.): Proceedings of the PLEA 2020 Conference – to appear.

Memon, R.A., Chirarattananon, S., Vangtook, P., 2008. *Thermal comfort assessment and application of radiant cooling: A case study.* Building and Environment 43 (7), pp. 1185–1196. DOI: 10.1016/j.buildenv.2006.04.025.

Moya, T.A., van den Dobbelsteen, A., Ottelé, M., Bluyssen, P.M., 2019. *A review of green systems within the indoor environment.* Indoor and Built Environment 28 (3), pp. 298–309. DOI: 10.1177/1420326X18783042.

Mugnier, D., Neyer, D., White, S.D. (Eds.), 2017. *The solar cooling design guide. Case studies of successful solar air conditioning design.* Weinheim, Germany: Ernst & Sohn.

Niu, J. L., Zhang, L. Z., Zuo, H. G., 2002. *Energy savings potential of chilled-ceiling combined with desiccant cooling in hot and humid climates.* Energy and Buildings 34 (5), pp. 487–495. DOI: 10.1016/S0378-7788(01)00132-3.

Olesen, B. W., 2014. *Radiant heating and cooling by embedded water-based systems.* Solar Energy Engineering: Elsevier.

Olesen, B. W., Mattarolo, L., 2009. *Thermal comfort and energy performance of hydronic radiant cooling systems compared to convective systems.* In: Proceedings of Healthy Buildings.

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar.
The approved original version of this thesis is available in print at TU Wien Bibliothek.
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Palmero-Marrero, A.I., Oliveira, A.C., 2010. *Effect of louver shading devices on building energy requirements.* Applied Energy 87 (6), pp. 2040–2049. DOI: 10.1016/j.apenergy.2009.11.020.

Pérez-Urrestarazu, L., Fernández-Cañero, R., Franco, A., Egea, G., 2016. *Influence of an active living wall on indoor temperature and humidity conditions.* Ecological Engineering 90, pp. 120–124. DOI: 10.1016/j.ecoleng.2016.01.050.

Pisello, A.L., 2017. *State of the art on the development of cool coatings for buildings and cities.* Solar Energy 144, pp. 660–680. DOI: 10.1016/j.solener.2017.01.068.

Qin, J., Sun, C., Zhou, X., Leng, H., Lian, Z., 2014. *The effect of indoor plants on human comfort.* Indoor and Built Environment 23 (5), pp. 709–723. DOI: 10.1177/1420326X13481372.

Revel, G.M., Martarelli, M., Emiliani, M., Celotti, L., Nadalini, R., Ferrari, A. et al., 2014a. *Cool products for building envelope – Part II: Experimental and numerical evaluation of thermal performances.* Solar Energy 105, pp. 780–791. DOI: 10.1016/j.solener.2014.02.035.

Revel, G.M., Martarelli, M., Emiliani, M., Gozalbo, A., Orts, M.J., Bengochea, M.A. et al., 2014b. *Cool products for building envelope – Part I: Development and lab scale testing.* Solar Energy 105, pp. 770–779. DOI: 10.1016/j.solener.2014.03.029.

Rhee, K.N., Kim, K.W., 2015. *A 50 year review of basic and applied research in radiant heating and cooling systems for the built environment.* Building and Environment 91, pp. 166–190. DOI: 10.1016/j.buildenv.2015.03.040.

Rhee, K.N., Olesen, B.W., Kim, K.W., 2017. *Ten questions about radiant heating and cooling systems.* Building and Environment 112, pp. 367–381. DOI: 10.1016/j.buildenv.2016.11.030.

Santamouris, M., Synnefa, A., Karlessi, T., 2011. *Using advanced cool materials in the urban built environment to mitigate heat islands and improve thermal comfort conditions.* Solar Energy 85 (12), pp. 3085–3102. DOI: 10.1016/j.solener.2010.12.023.

Santamouris, M., Kolokotsa, D.,2013. *Passive cooling dissipation techniques for buildings and other structures: The state of the art*. Energy and Buildings 57, pp. 74–94. DOI: 10.1016/j.enbuild.2012.11.002.

Sastry, G., Rumsey, P., 2014. *VAV vs. Radiant. Side-by-Side Comparison.* ASHRAE Journal May 2014.

Die approbierte gedruckte Originalversion dieser Diplomarbeit ist an der TU Wien Bibliothek verfügbar.
The approved original version of this thesis is available in print at TU Wien Bibliothek.
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Steinkopf, L.E., 2017. *Houseplants. The complete guide to choosing, growing, and caring for indoor plants.* Minneapolis, MN: Cool Springs Press.

Stetiu, C., 1999. *Energy and peak power savings potential of radiant cooling systems in US commercial buildings.* Energy and Buildings 30 (2), pp. 127–138. DOI: 10.1016/S0378-7788(98)00080-2.

Synnefa, A., Dandou, A., Santamouris, M., Tombrou, M., Soulakellis, N., 2008. *On the Use of Cool Materials as a Heat Island Mitigation Strategy.* J. Appl. Meteor. Climatol. 47 (11), pp. 2846–2856. DOI: 10.1175/2008JAMC1830.1.

Synnefa, A., Santamouris, M., Apostolakis, K., 2007. *On the development, optical properties and thermal performance of cool colored coatings for the urban environment.* Solar Energy 81 (4), pp. 488–497. DOI: 10.1016/j.solener.2006.08.005.

Testa, J., Krarti, M., 2017. *A review of benefits and limitations of static and switchable cool roof systems.* Renewable and Sustainable Energy Reviews 77, pp. 451–460. DOI: 10.1016/j.rser.2017.04.030.

Tian, Z., Love, J.A., 2009. *Energy performance optimization of radiant slab cooling using building simulation and field measurements.* Energy and Buildings 41 (3), pp. 320–330. DOI: 10.1016/j.enbuild.2008.10.002.

Vangtook, P., Chirarattananon, S., 2007. *Application of radiant cooling as a passive cooling option in hot humid climate.* Building and Environment 42 (2), pp. 543–556. DOI: 10.1016/j.buildenv.2005.09.014.

Wolverton, B., Douglas, W., Bounds, K., 1989. *A study of Interior Landscape Plants for Indoor Air Pollution Abatement*. NASA.

World Health Organization, 2010. *WHO Guidelines for indoor air quality: selected pollutants*. Geneva: WHO.

Xu, Y. F., Li, M., Wang, Y. F., Wang, R., 2018. *Solar Cooling Systems*. In: Ruzhu Wang, Xiaoqiang Zhai (Eds.). Handbook of Energy Systems in Green Buildings, vol. 44. Berlin, Heidelberg: Springer Berlin Heidelberg, pp. 195–255.

Zhang, W., Lu, L., Peng, J., 2017. *Evaluation of potential benefits of solar photovoltaic shadings in Hong Kong*. Energy 137, pp. 1152–1158. DOI: 10.1016/j.energy.2017.04.166.

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9 APPENDIX

9.1 Annotated Bibliography

A selection of studies with regard to radiant cooling are presented in the following paragraphs.

Stetiu, C. (1999). Energy and peak power savings potential of radiant cooling systems in US commercial buildings. Energy and Buildings, 30(2), 127–138. https://doi.org/10.1016/S0378-7788(98)00080-2

> The contribution explores the energy and peak power savings potential of radiant cooling systems. It was conducted for commercial buildings in the US. Radiant cooling systems are compared to conventional all-air conditioning systems. The outcome showed that the energy consumption can be reduced by 30% if the radiant cooling system was used. Moreover, it can save 27% of the peak power demand.

Hao, X., Zhang, G., Chen, Y., Zou, S., & Moschandreas, D. J. (2007). A combined system of chilled ceiling, displacement ventilation and desiccant dehumidification. Building and Environment, 42(9), 3298–3308. https://doi.org/10.1016/j.buildenv.2006.08.020

> The influence of a chilled ceiling that is combined with a ventilation system on a buildings' energy consumption is analyzed. The results are compared to a conventional all-air cooling system. The study is conducted for an office area in a hot and humid climate. To control the indoor humidity, a desiccant dehumidification system is used. The aim is to avoid surface condensation. The results suggest that the energy savings by the chilled ceiling with displacement ventilation are 8.2% in comparison to the conventional all-air cooling system. Furthermore, it was discussed that a better indoor air quality and thermal comfort can be achieved by using the chilled ceiling.

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Baharun, A., Imran, M. S., Ibrahim, S. H., & Wan Zainal Abidin, W. A. (2018). Night Cooled Radiant Cooling Panel for Sustainable Building Cooling Mode in Malaysia. Journal of Construction in Developing Countries, 23(1), 61–79. https://doi.org/10.21315/jcdc2018.23.1.4

This study explored the effects of a night cooled radiant cooling panel in Malaysia. The general night-time temperature there is about 23°C. For this reason, a pitched roof was used to cool water for the radiant system. At daytime, at an outdoor temperature of over 30°C, it was possible for the radiant cooling system to maintain the indoor temperature under 28°C. Nonetheless, a wall as well as a ceiling radiant cooling system had to be used to improve the operative temperature as well as the PMV in a satisfied way.

Vangtook, P., & Chirarattananon, S. (2007). Application of radiant cooling as a passive cooling option in hot humid climate. Building and Environment, 42(2), 543–556. https://doi.org/10.1016/j.buildenv.2005.09.014

This study analyzed a radiant cooling systems in a hot and humid climate. Vangtook and Chirarattananon conducted a whole-year simulation study. This was done for a residential building in Thailand. A radiant cooling ceiling was used. The Predicated mean vote (PMV) was selected to evaluate occupants' thermal comfort. The outcome suggests that a cooling tower can be an option to provide chilled water for the radiant cheiling as well as pre-cool the ventilation air to improve users' thermal comfort.

Nutprasert, N., & Chaiwiwatworakul, P. (2014). Radiant Cooling with Dehumidified Air Ventilation for Thermal Comfort in Buildings in Tropical Climate. Energy Procedia, 52, 250–259. https://doi.org/10.1016/j.egypro.2014.07.076

Nutprasert and Chaiwiwatworakul analysed a radiant cooling system in Thailand. In such a hot and humid climate, radiant cooling can be a challenging due to a high relative humidity. The study was conducted in a lab. Simulations with TRNSYS were conducted as well. The results showed that radiant cooling systems could be used to provide thermal comfort in tropical buildings. Nonetheless, dehumidification of the ventilation air is definitely necessary.

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Kim, T., Kato, S., Murakami, S., & Rho, J.-W. (2005). Study on indoor thermal environment of office space controlled by cooling panel system using field measurement and the numerical simulation. Building and Environment, 40(3), 301–310. https://doi.org/10.1016/j.buildenv.2004.04.010

A vertical cooling panel system was evaluated by field measurements and CFD simulations. It was applied in an office area in Japan. The authors conclude that the cooling element used in this study was found to be quit energy efficient. The outcome suggests that it removed more heat (by radiation) than the conventional all-air system.

He, Y., Li, N., He, M., & He, D. (2017). Using radiant cooling desk for maintaining comfort in hot environment. Energy and Buildings, 145, 144–154. https://doi.org/10.1016/ j.enbuild.2017.04.013

A recent pilot study presented another novel type of application. It refers to a radiant cooling desk (He et al. 2017). Water-cooled panels are mounted to the back of the table and used as the tabletop. In the course of the study, the surface temperature of the panel was set in a way to avoid surface condensation. The results suggested that participants' thermal comfort was increased. However, the cooling effect mainly influenced the upper body parts

Rhee, K.-N., & Kim, K. W. (2015). A 50 year review of basic and applied research in radiant heating and cooling systems for the built environment. Building and Environment, 91, 166–190. https://doi.org/10.1016/j.buildenv.2015.03.040

Hee and Kim conducted a literature review. This involved research efforts about radiant heating and cooling systems within 50 year. They present information about the heating and cooling capacity, CFD analysis, energy simulation, system configuration and control strategies, etc. Furthermore, they offer a tables with detailed summaries of research studies pertaining to comfort issues and one about energy simulations.

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Rhee, K.-N., Olesen, B. W., & Kim, K. W. (2017). Ten questions about radiant heating and cooling systems. Building and Environment, 112, 367–381. https://doi.org/10.1016/ j.buildenv.2016.11.030

This contribution summarizes important aspects about to radiant heating and cooling systems. It involves information about thermal comfort, the energy performance of the systems, control strategies, condensation issues. A comprehensive table with studies on radiant cooling in hot and humid climates is provided as well.

Saber, E. M., Tham, K. W., & Leibundgut, H. (2016). A review of high temperature cooling systems in tropical buildings. Building and Environment, 96, 237–249. https://doi.org/10.1016/j.buildenv.2015.11.029

This publication explored different high temperature cooling systems in tropical climates. A radiant cooling panel, radiant slab cooling, and passive as well as active chilled beams are analyzed. Moreover, Saber et al. provided a detailed list of studies with regard to this topic.

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9.2 Thermal comfort evaluation

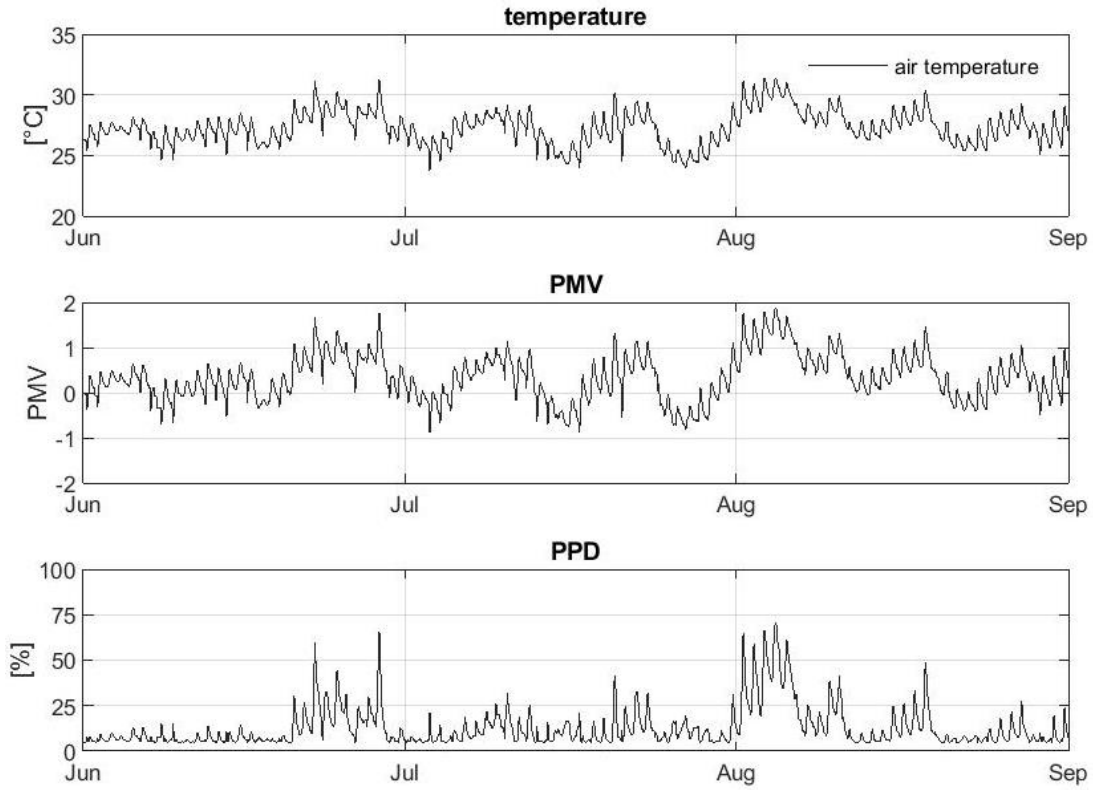

Figure 37 2017 - no radiant panel; vel= 0.2 m.s^{-1}

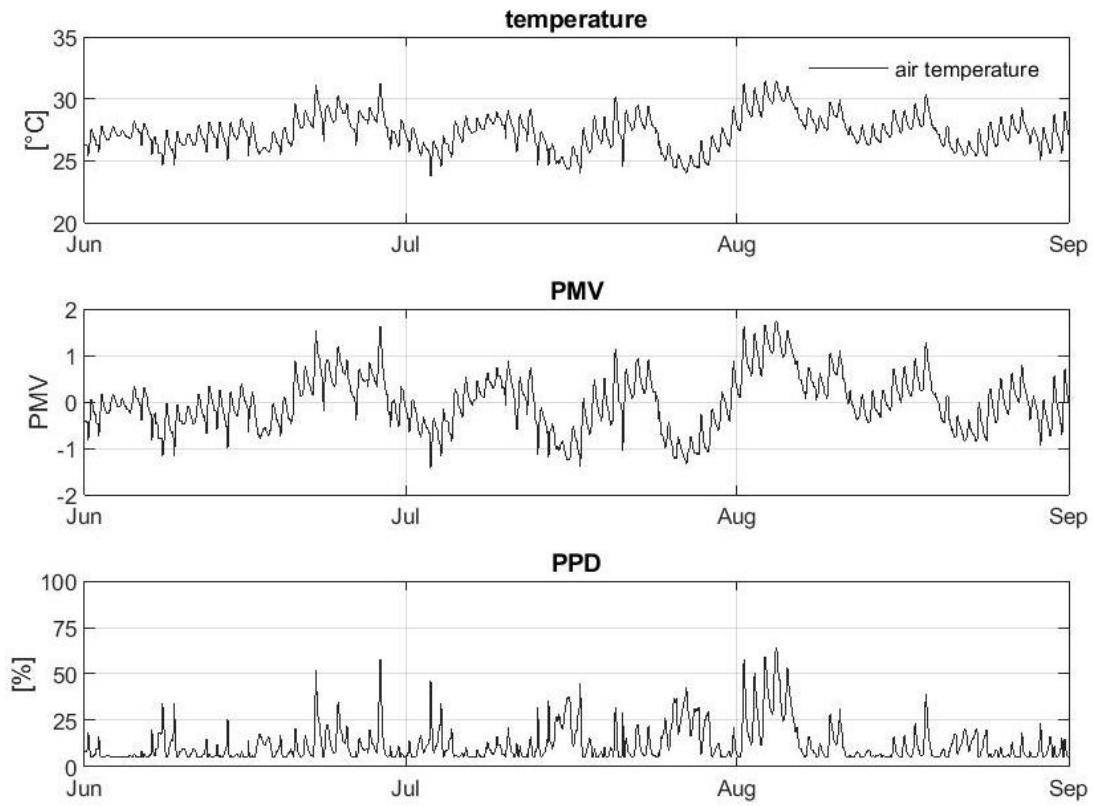

Figure 38 2017 - no radiant panel; vel= 0.5 m.s^{-1}

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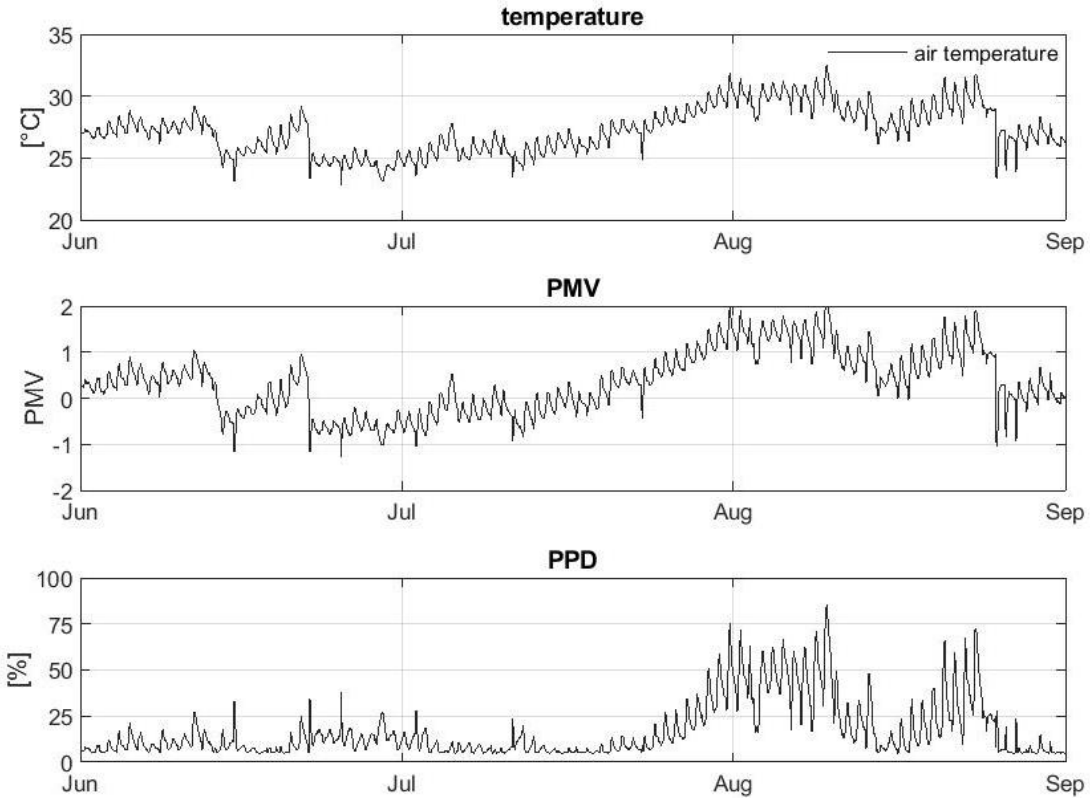

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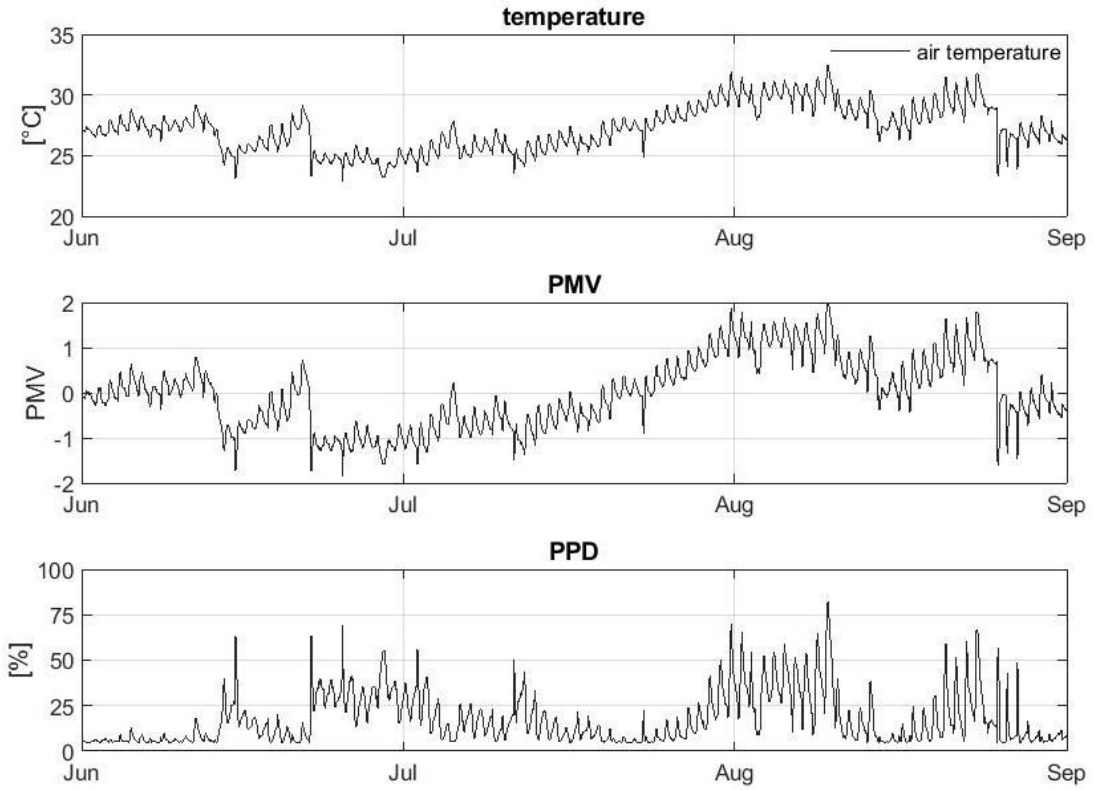

Figure 40 2018 - no radiant panel; vel= 0.5 m.s^{-1}

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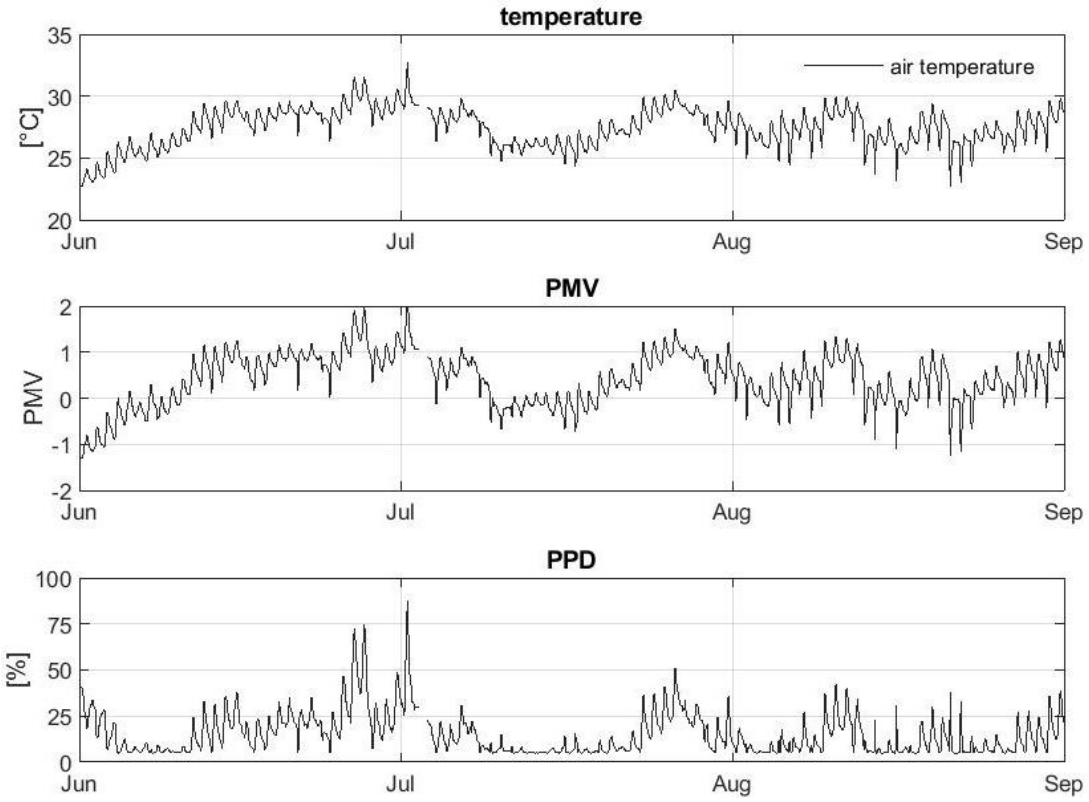

Figure 41 2019 - no radiant panel; vel= 0.2 m.s^{-1}

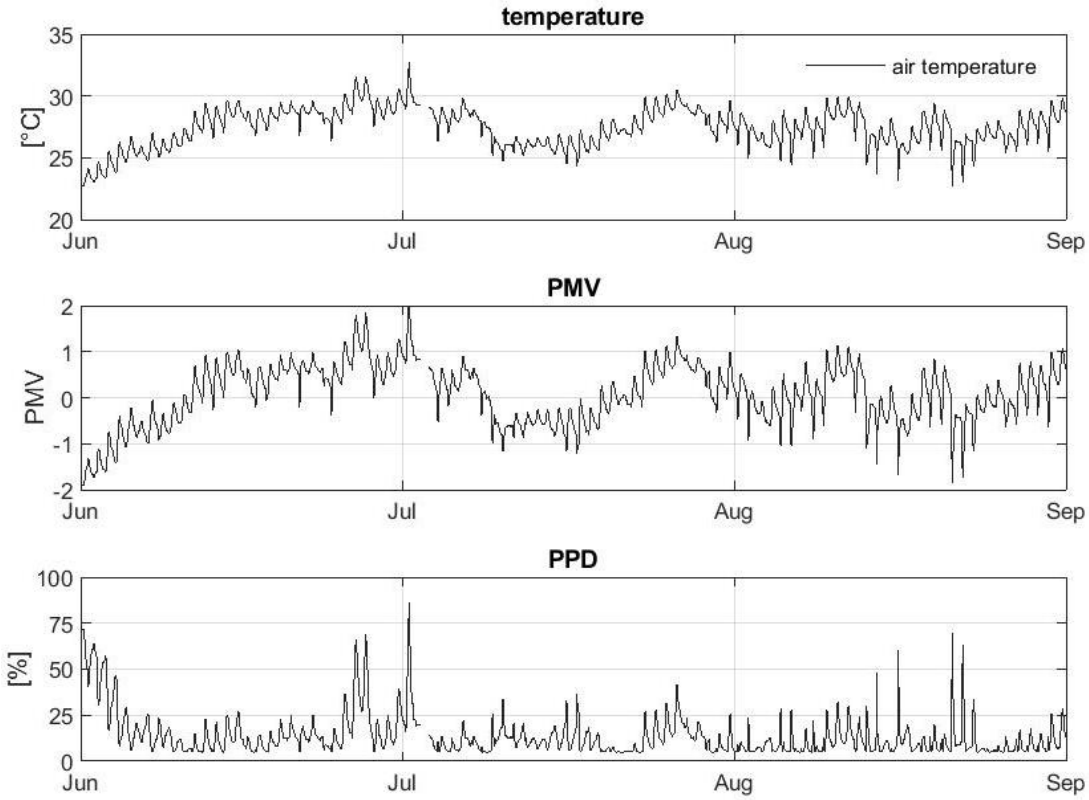

Figure 42 2019 - no radiant panel; vel= 0.5 m.s^{-1}

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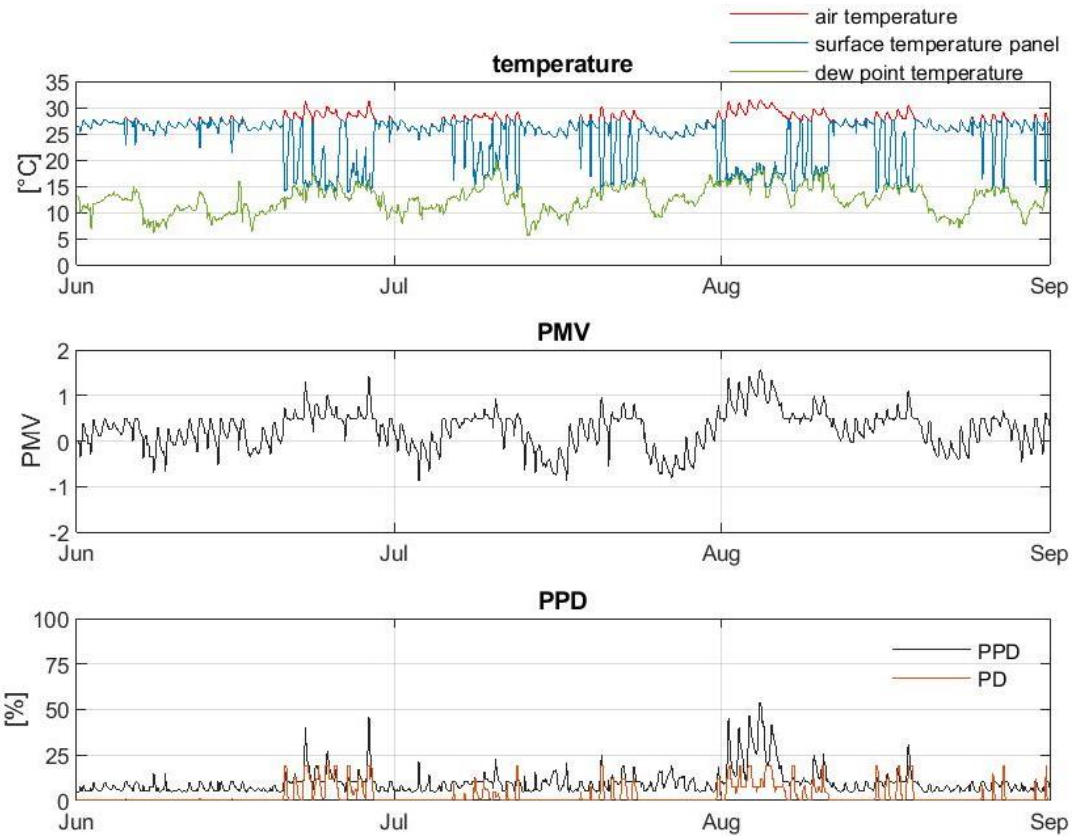

Figure 43 2017 - 1 radiant panel; vel= 0.2 m.s^{-1}; scenario without condensation

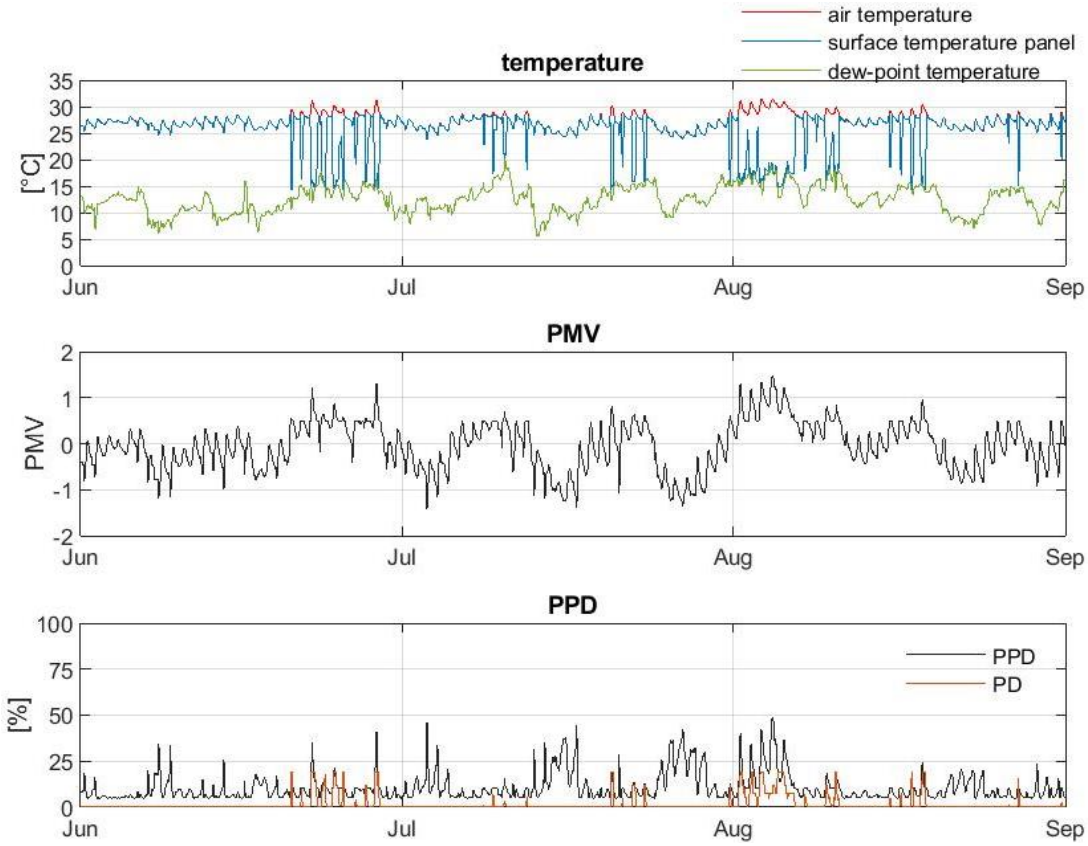

Figure 44 2017 - 1 radiant panel; vel= 0.5 m.s^{-1}; scenario without condensation

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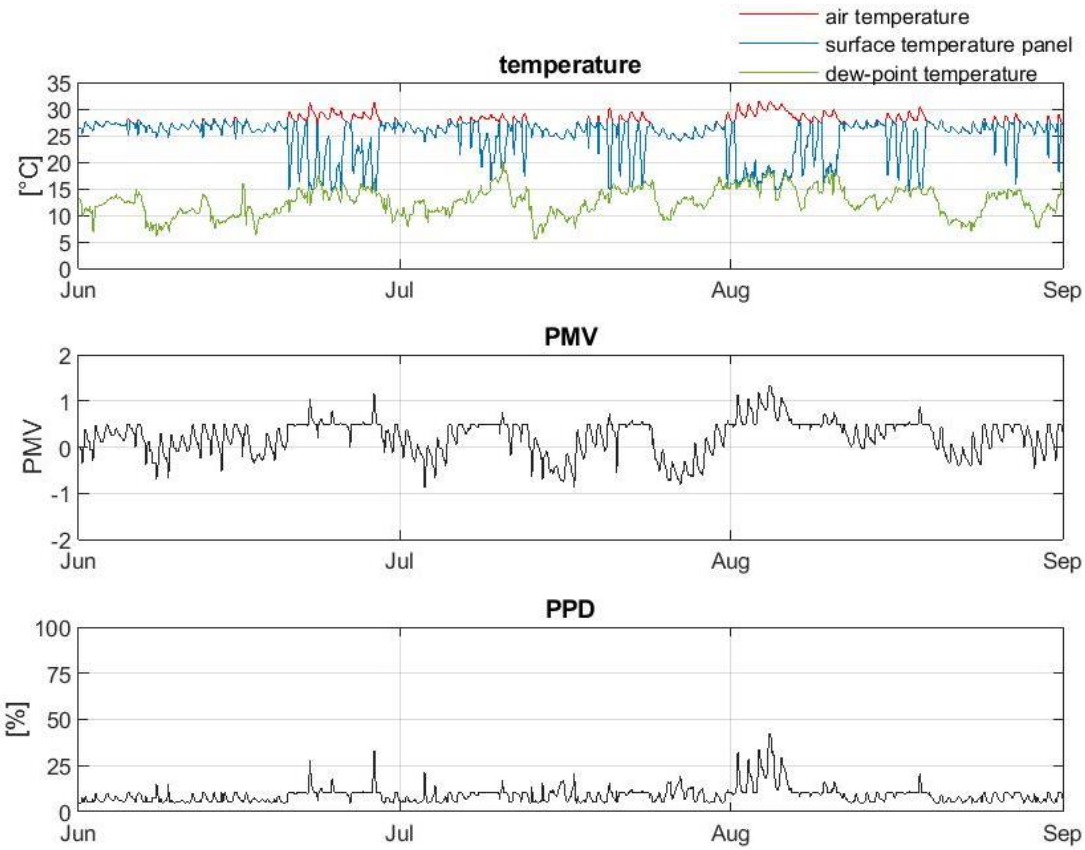

Figure 45 2017 - 2 radiant panels; vel= 0.2 m.s^{-1}; scenario without condensation

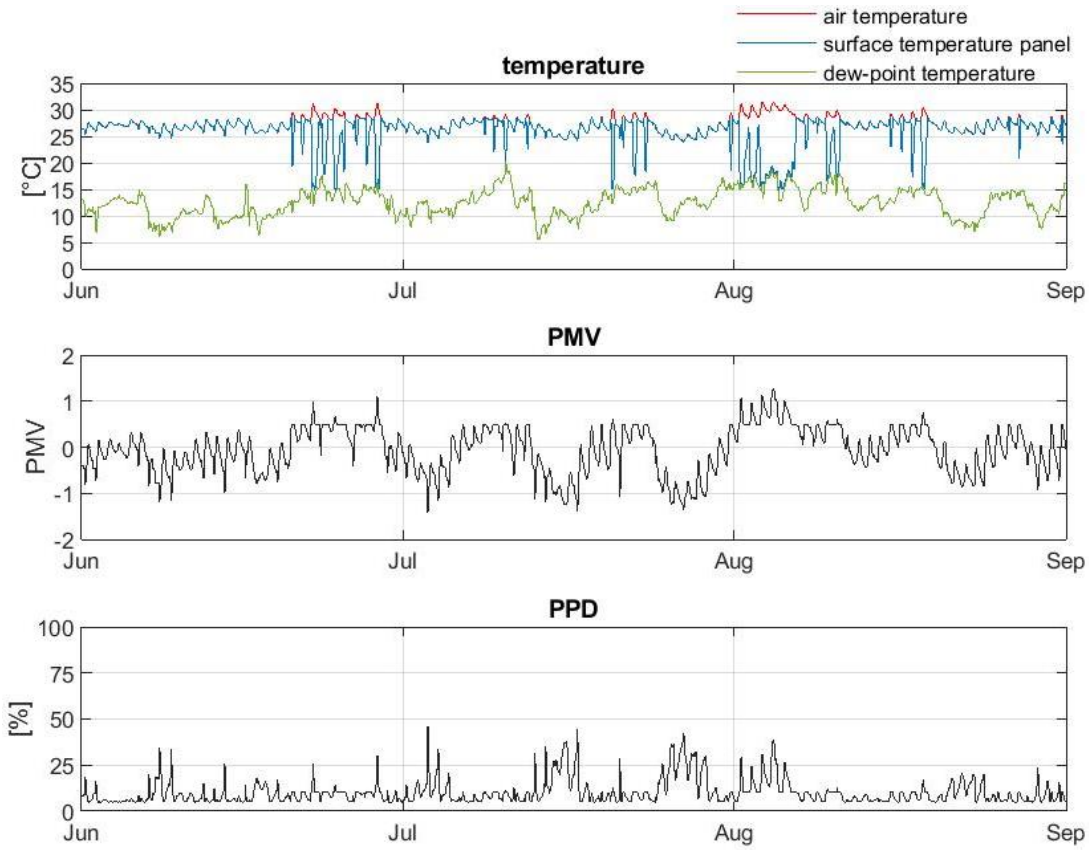

Figure 46 2017 - 2 radiant panels; vel= 0.5 m.s^{-1}; scenario without condensation

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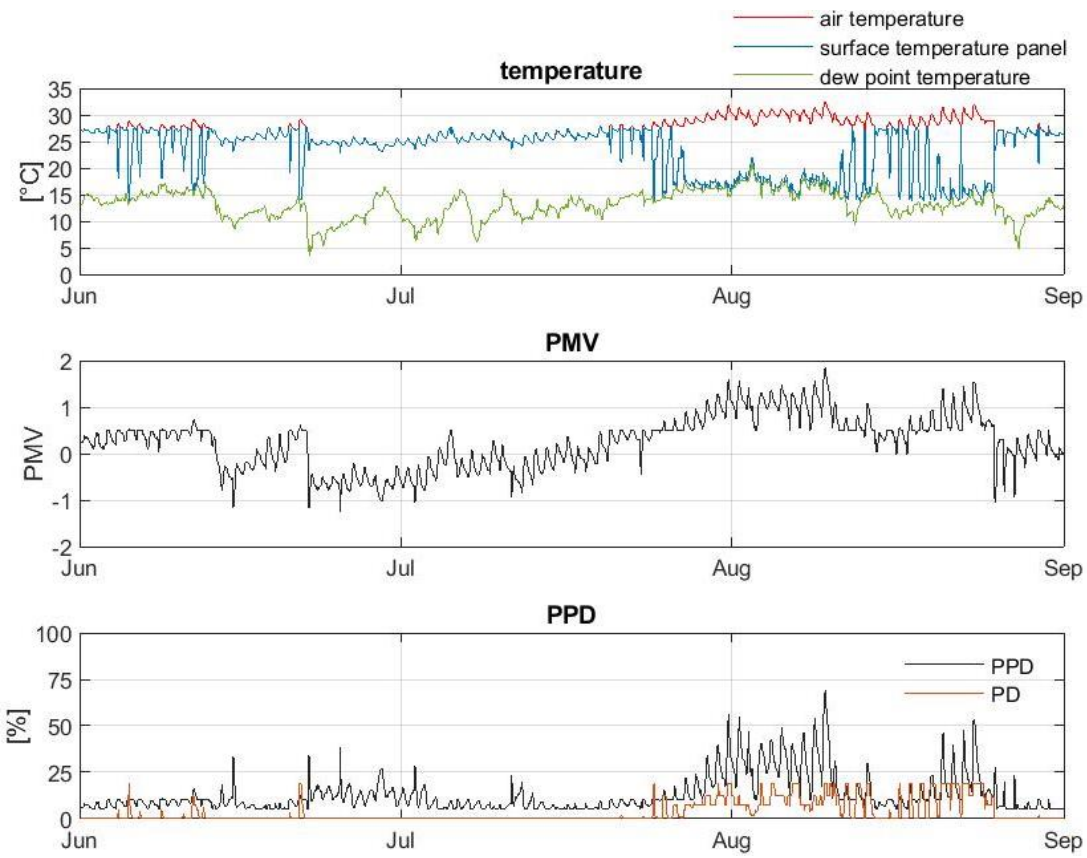

Figure 47 2018 - 1 radiant panel; vel= 0.2 m.s^{-1}; scenario without condensation

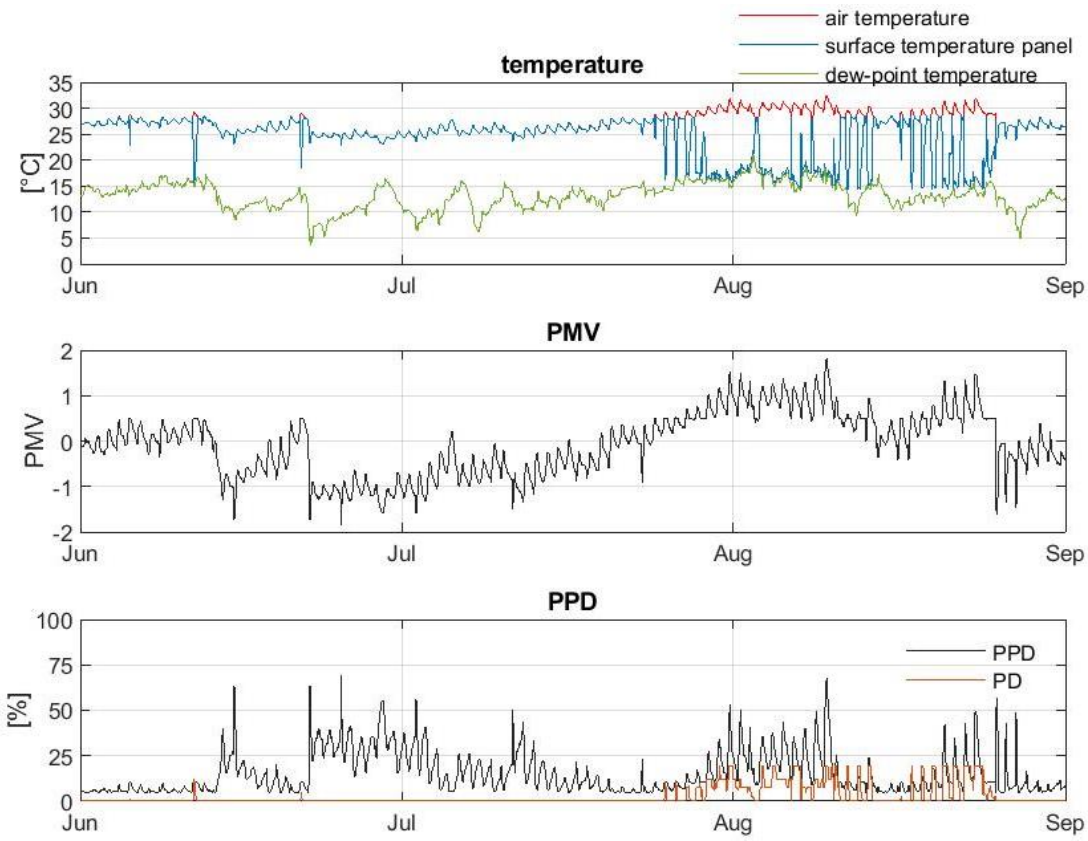

Figure 48 2018 - 1 radiant panel; vel= 0.5 m.s^{-1}; scenario without condensation

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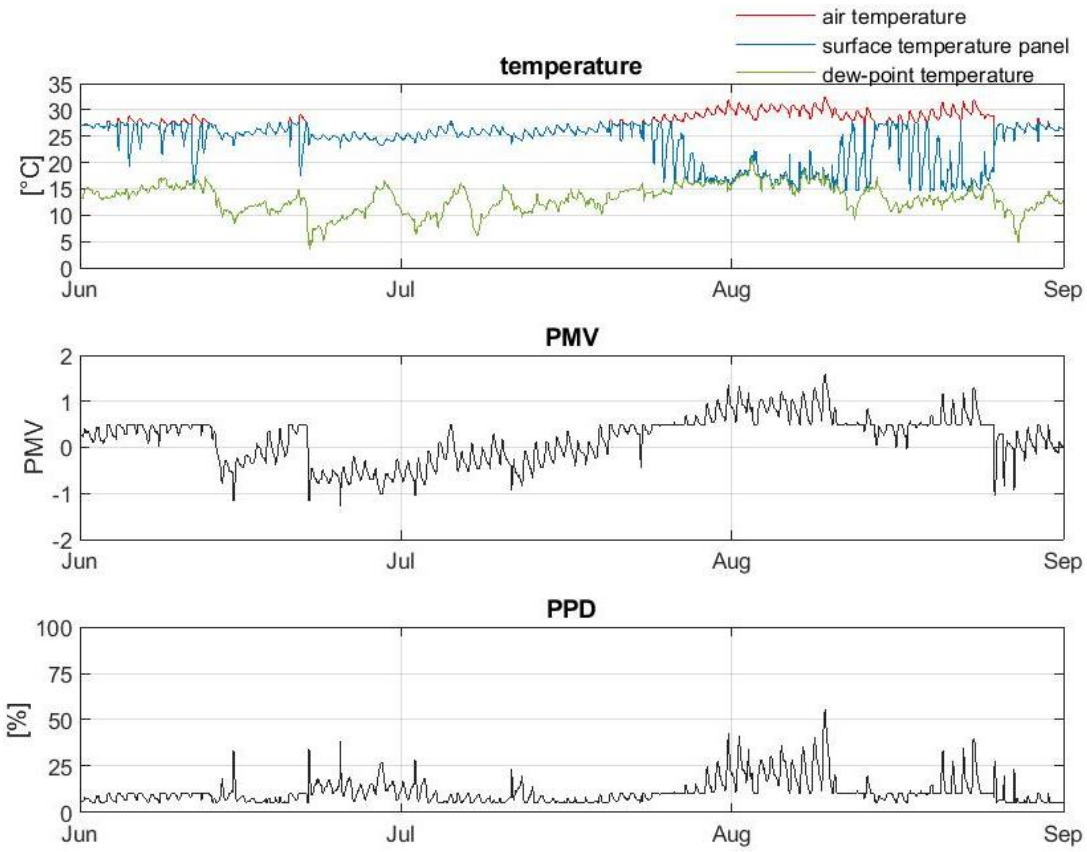

Figure 49 2018 - 2 radiant panels; vel= 0.2 m.s^{-1}; scenario without condensation

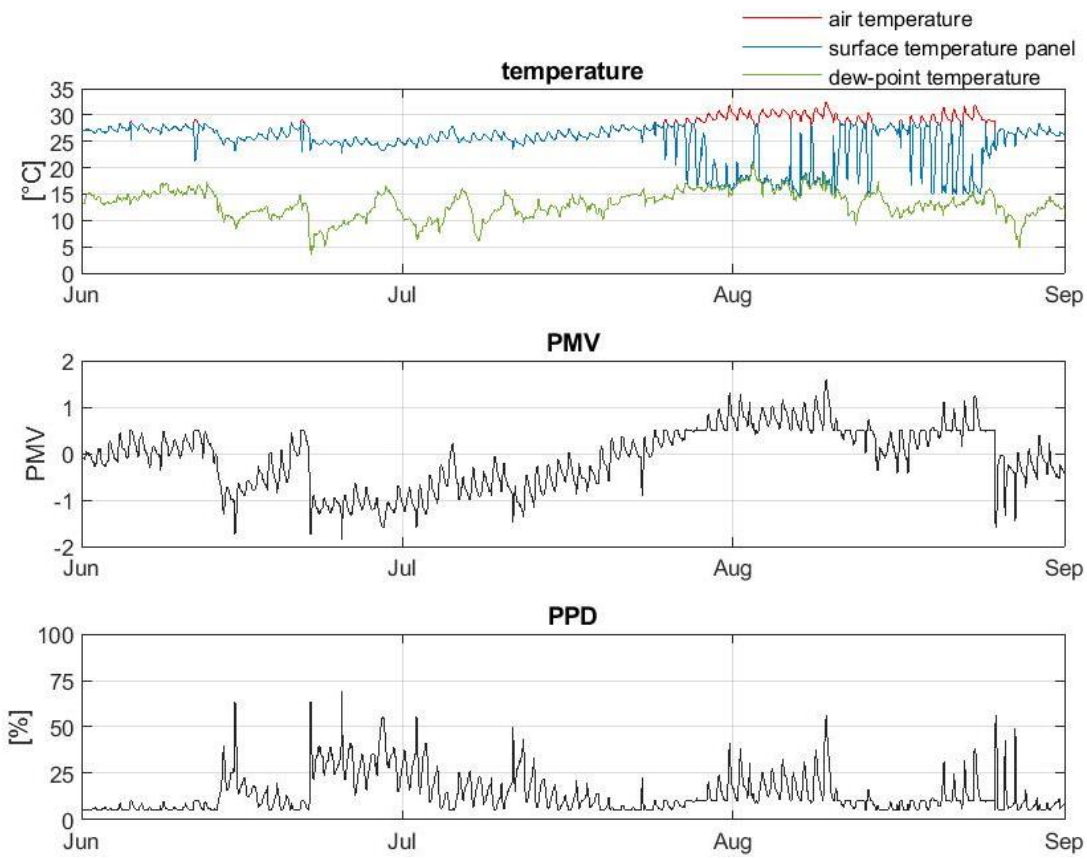

Figure 50 2018 - 2 radiant panels; vel= 0.5 m.s^{-1}; scenario without condensation

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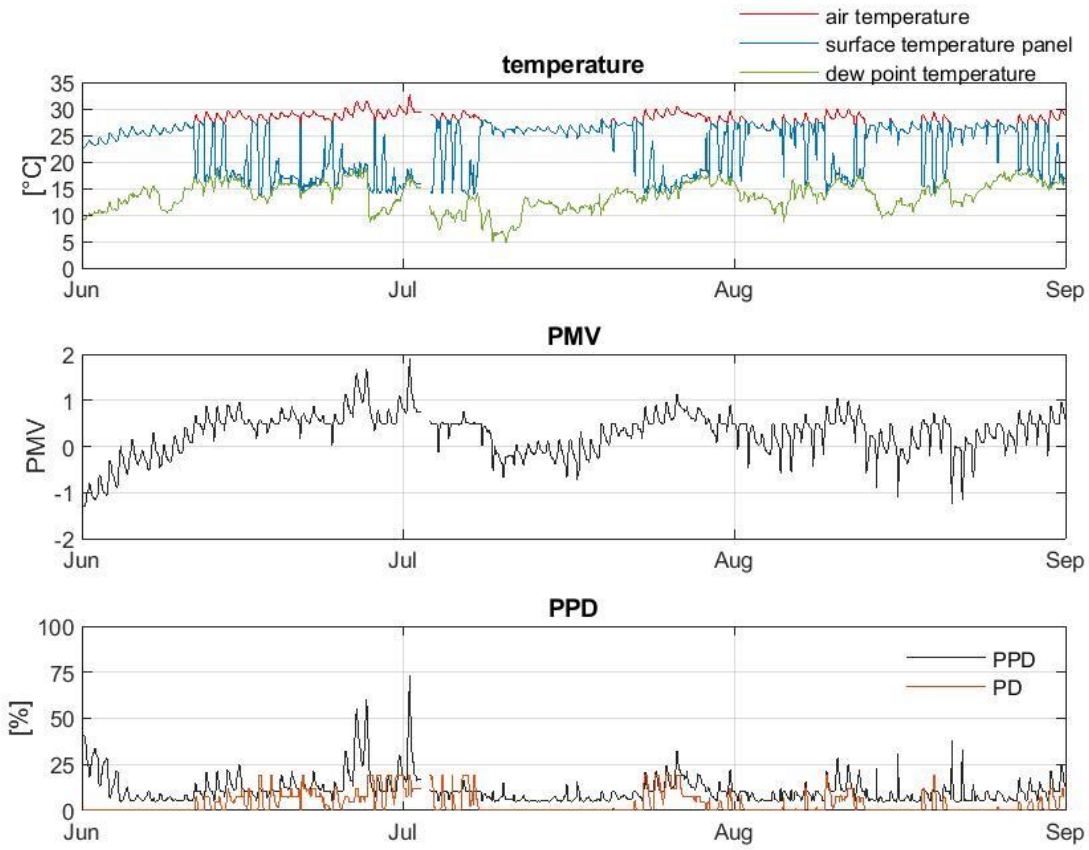

Figure 51 2019 - 1 radiant panel; vel= 0.2 m.s^{-1}; scenario without condensation

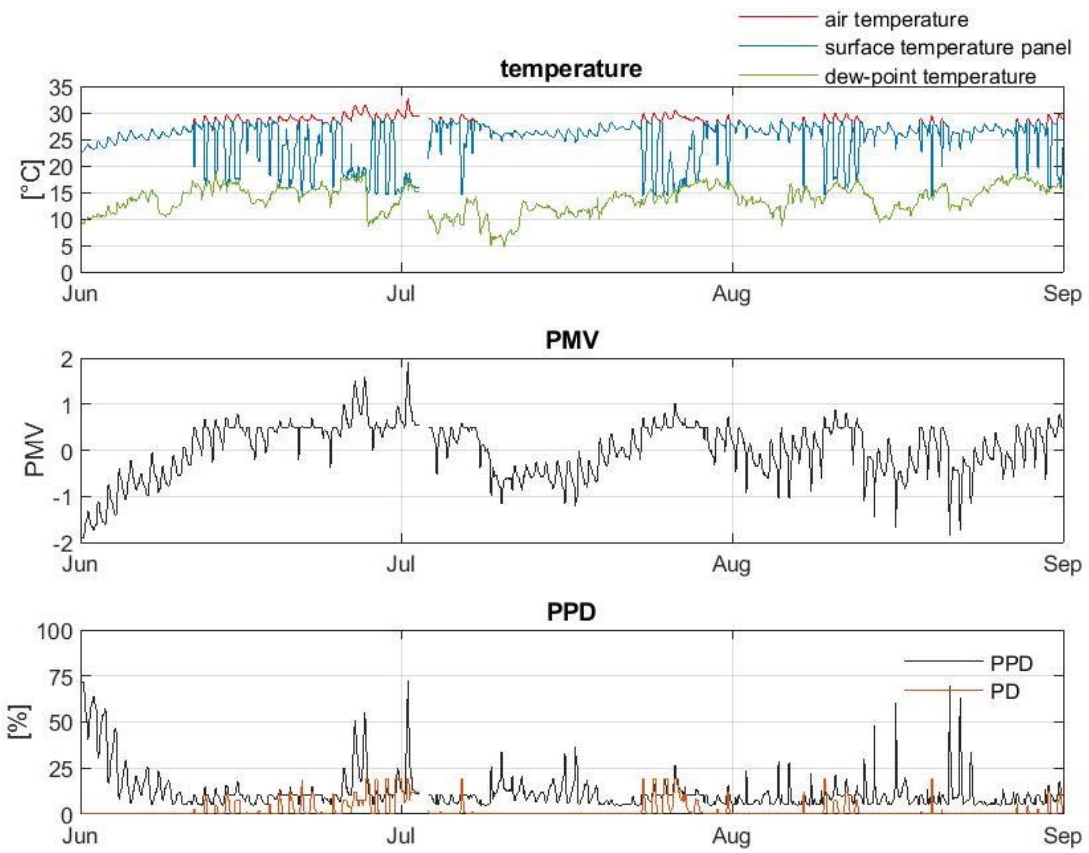

Figure 52 2019 - 1 radiant panel; vel= 0.5 m.s^{-1}; scenario without condensation

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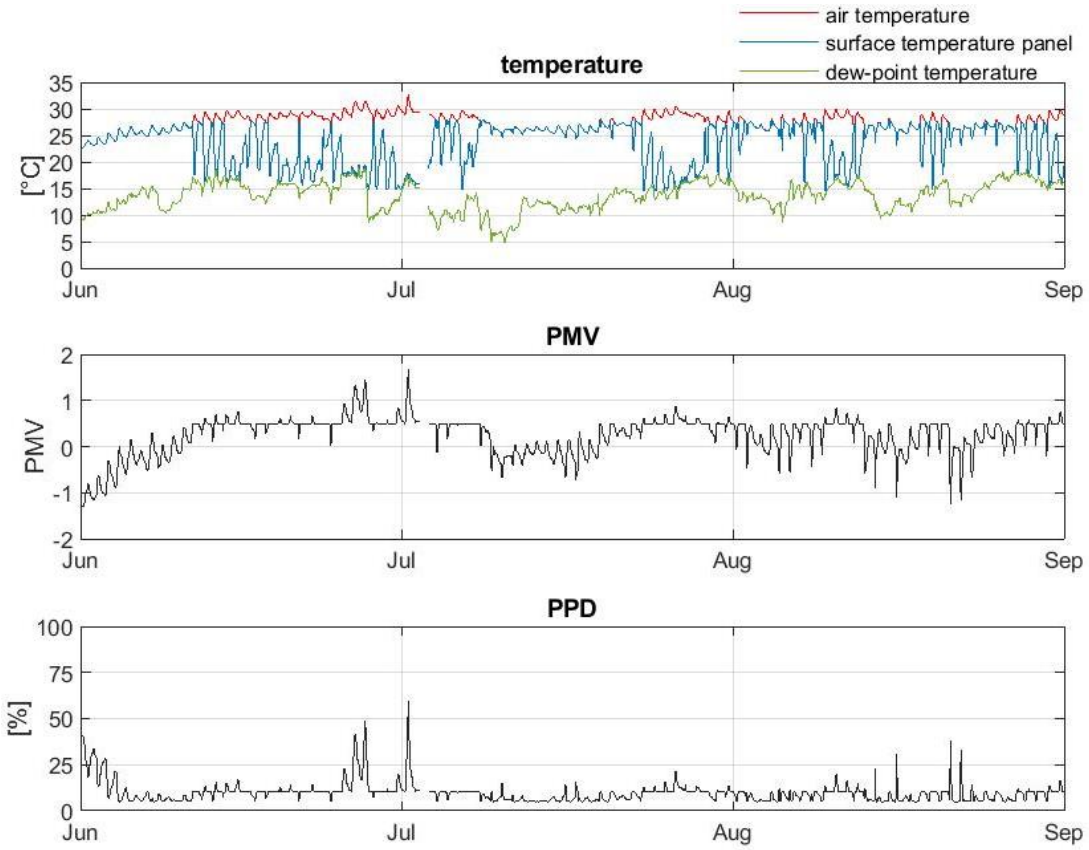

Figure 53 2019 - 2 radiant panels; vel= 0.2 m.s^{-1}; scenario without condensation

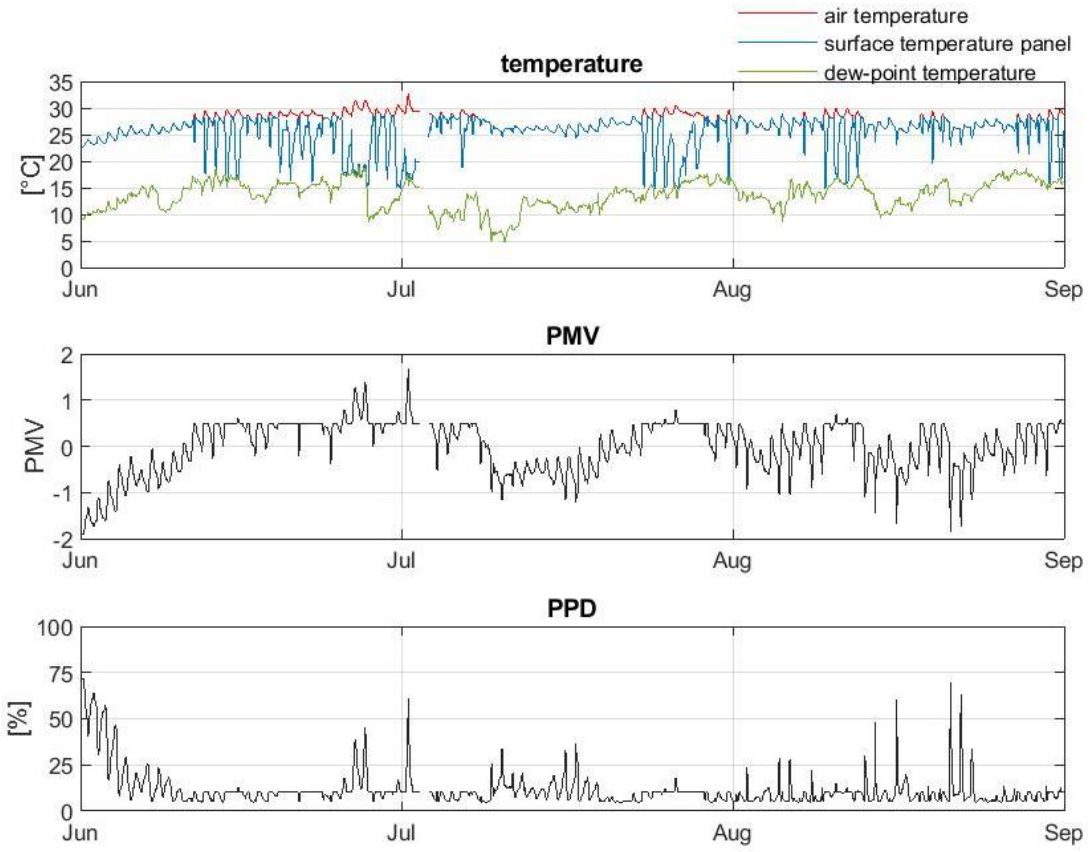

Figure 54 2019 - 2 radiant panels; vel= 0.5 m.s^{-1}; scenario without condensation

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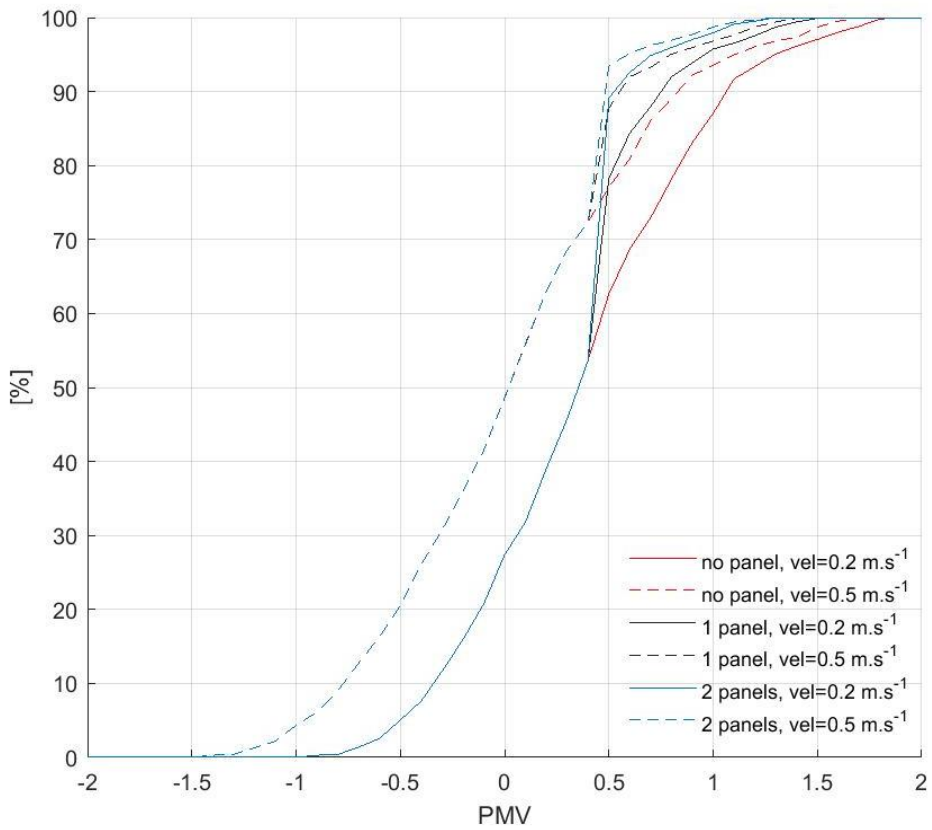

Figure 55 2017 - Cumulative distribution of the percentage of time when PMV exceeds a specific value (all scenarios without condensation)

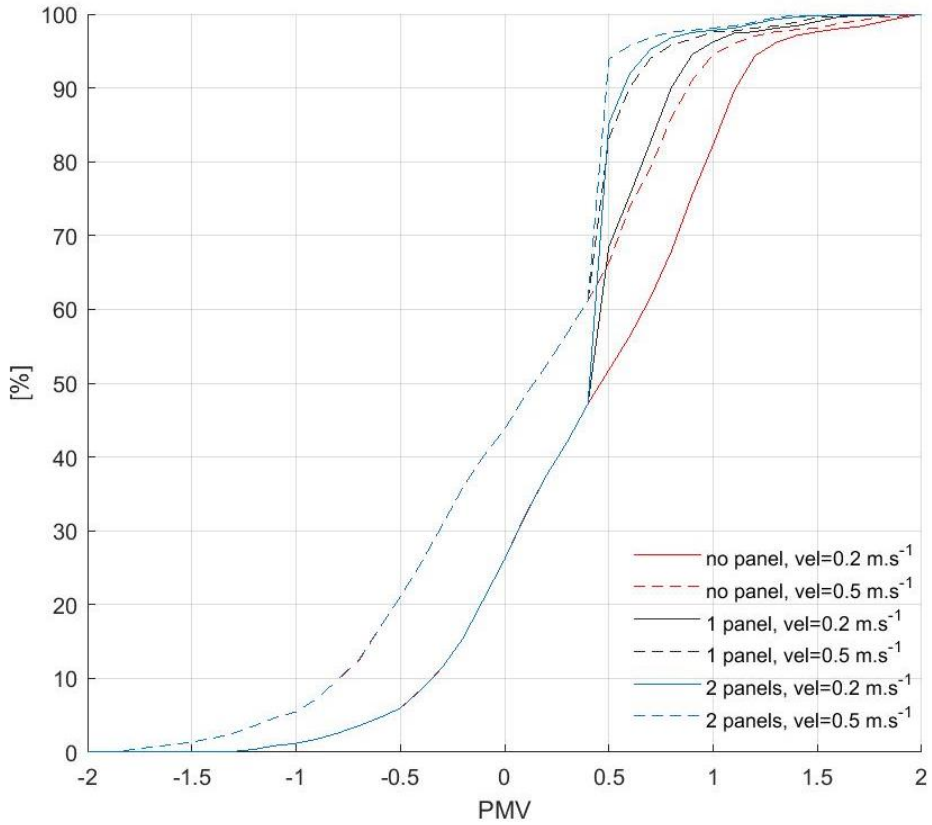

Figure 56 2018 - Cumulative distribution of the percentage of time when PMV exceeds a specific value (all scenarios without condensation)

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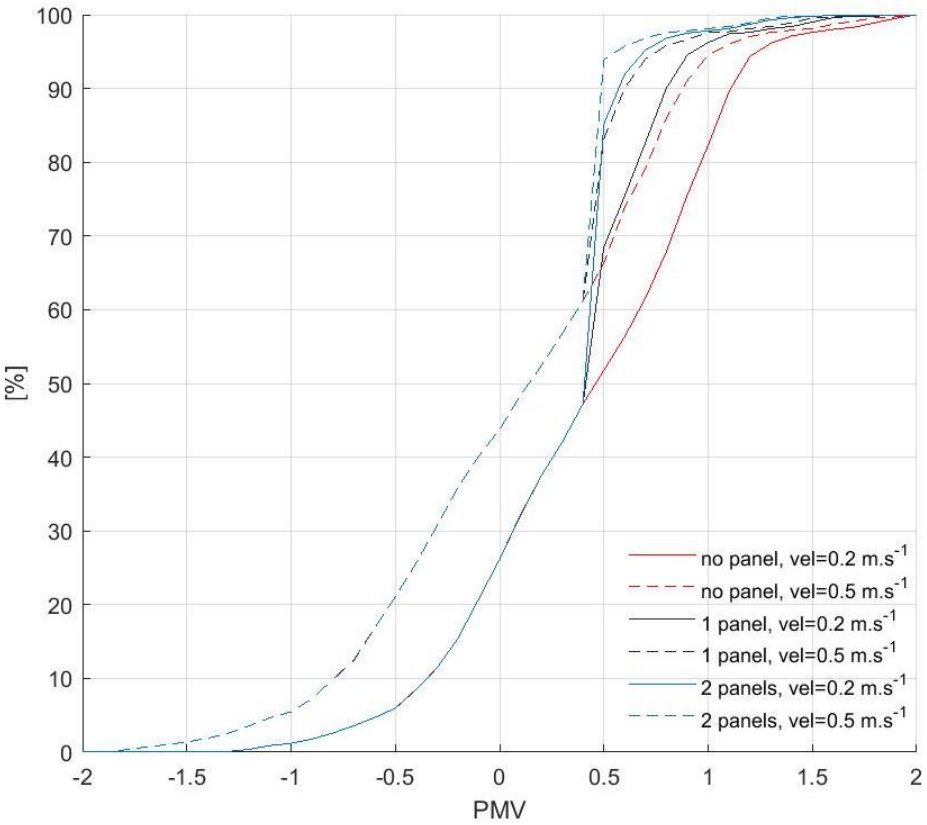

Figure 57 2019 - Cumulative distribution of the percentage of time when PMV exceeds a specific value (all scenarios without condensation)

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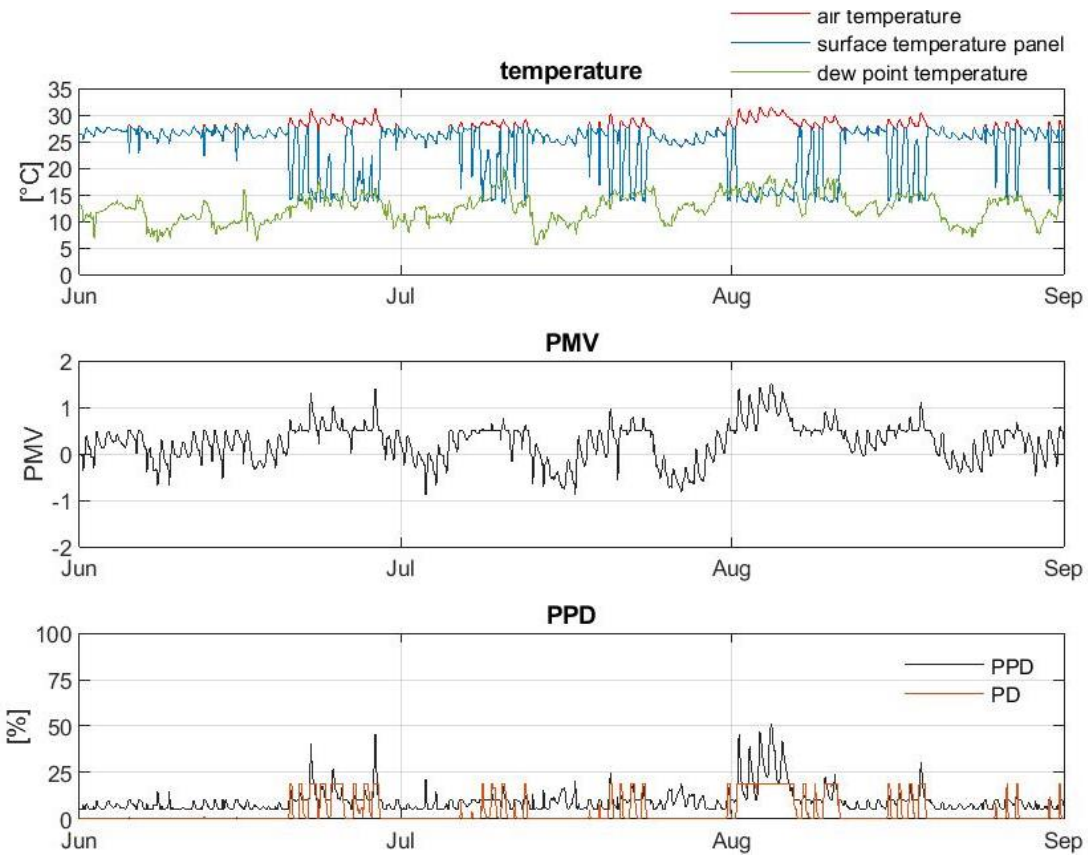

Figure 58 2017 - 1 radiant panel; vel= 0.2 m.s^{-1}; scenario with condensation

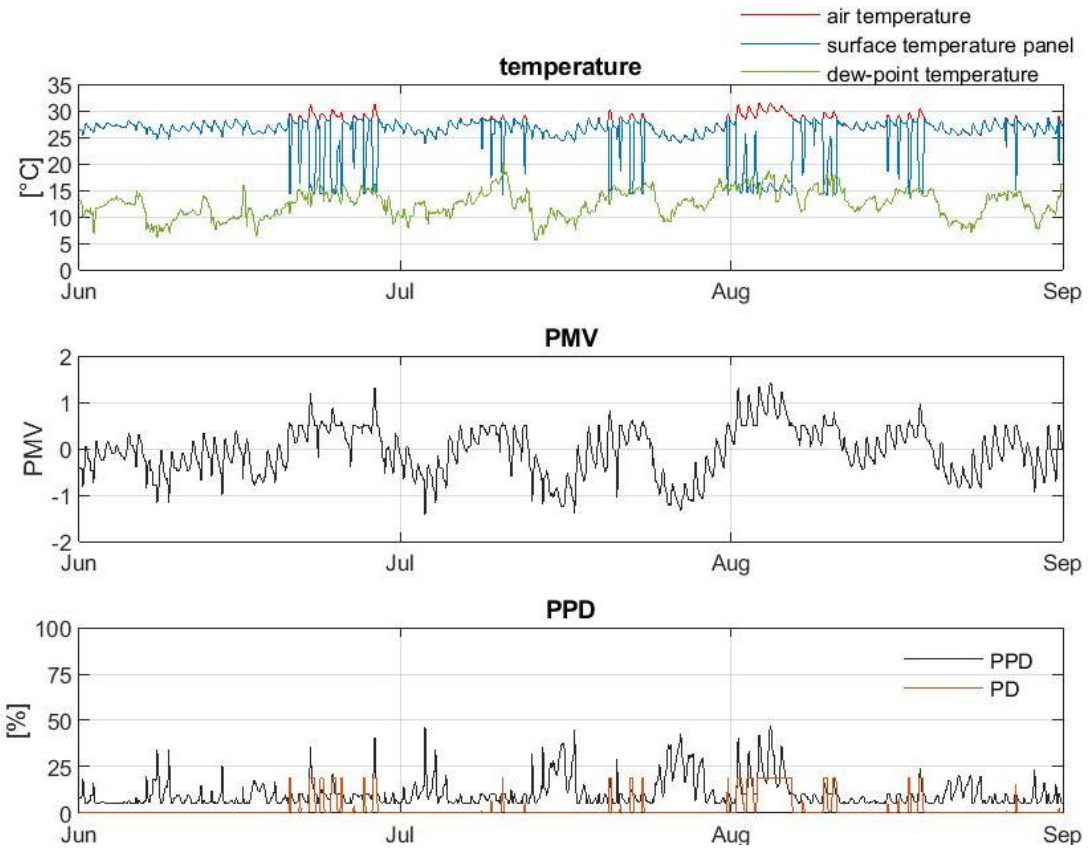

Figure 59 2017 - 1 radiant panel; vel= 0.5 m.s^{-1}; scenario with condensation

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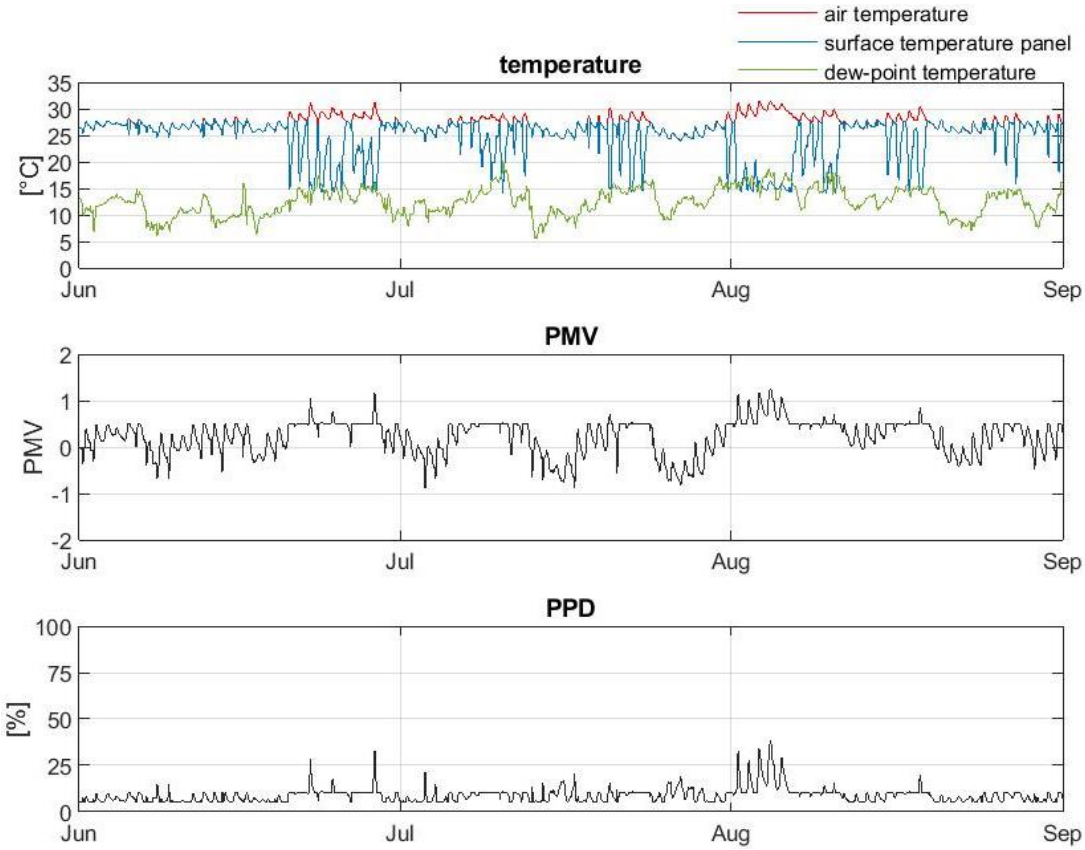

Figure 60 2017 - 2 radiant panels; vel= 0.2 m.s^{-1}; scenario with condensation

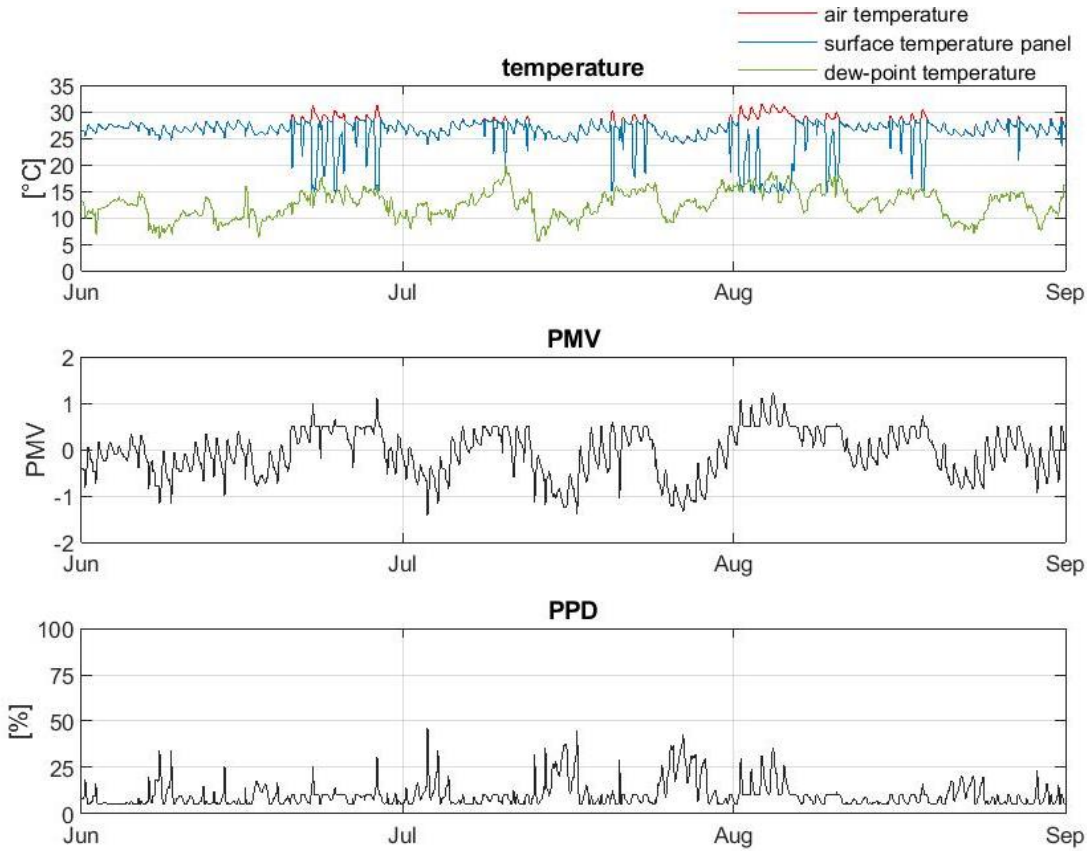

Figure 61 2017 - 2 radiant panels; vel= 0.5 m.s^{-1}; scenario with condensation

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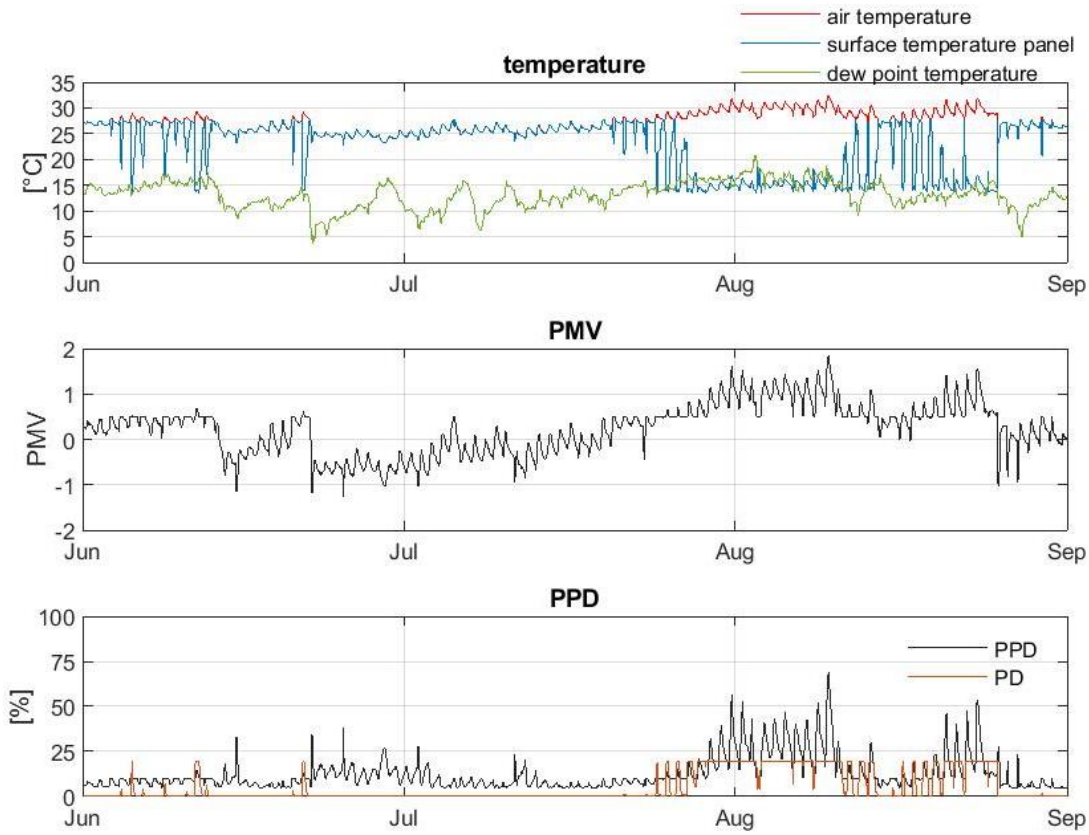

Figure 62 2018 - 1 radiant panel; vel= 0.2 m.s^{-1}; scenario with condensation

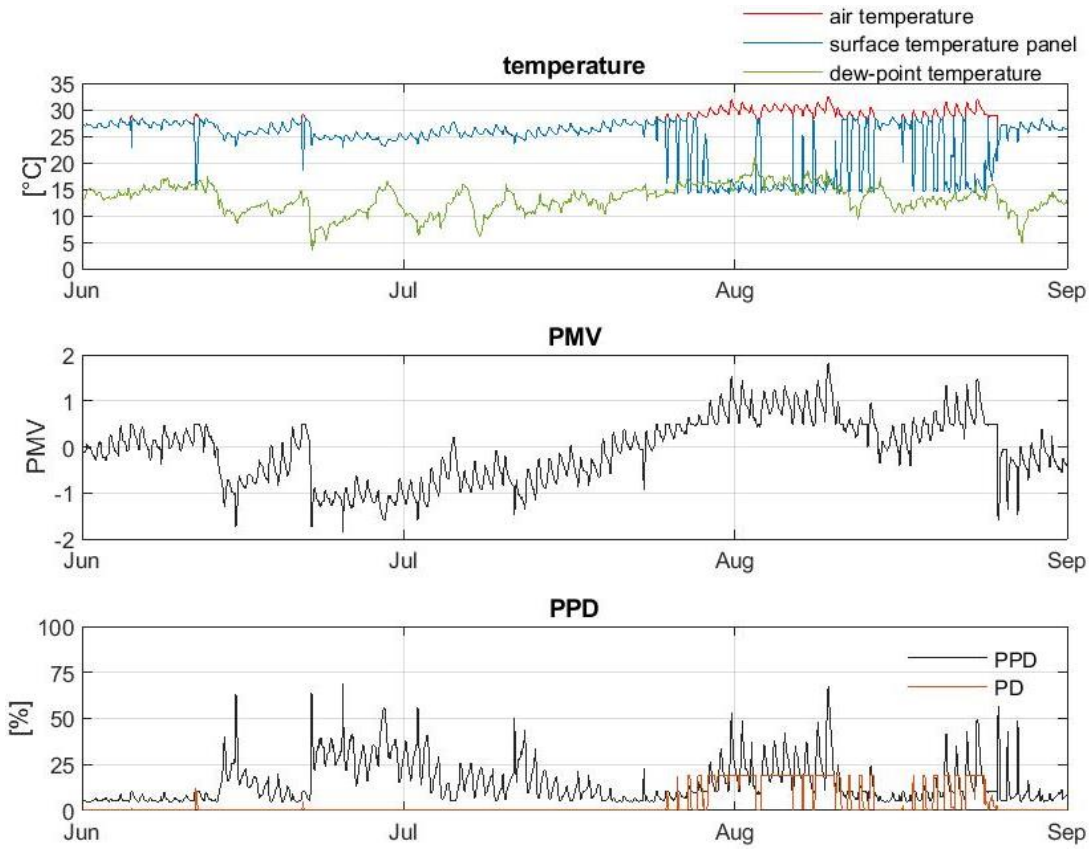

Figure 63 2018 - 1 radiant panel; vel= 0.5 m.s^{-1}; scenario with condensation

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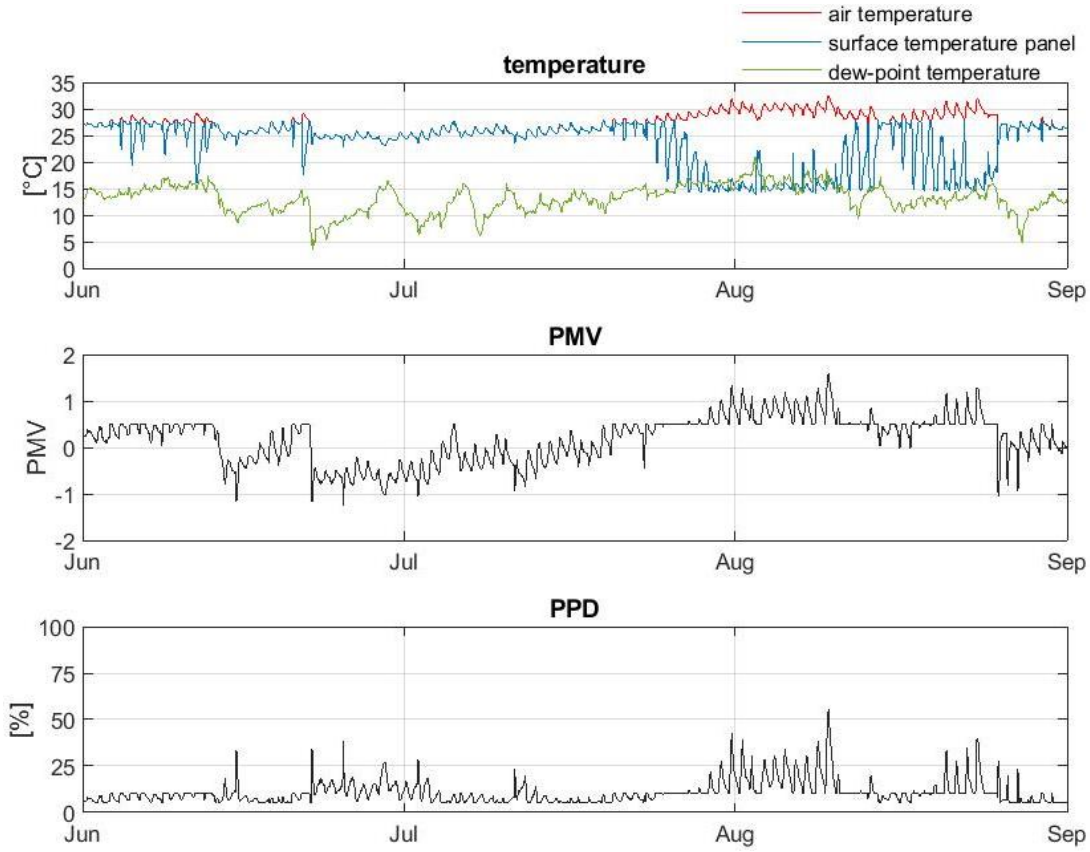

Figure 64 2018 - 2 radiant panels; vel= 0.2 m.s^{-1}; scenario with condensation

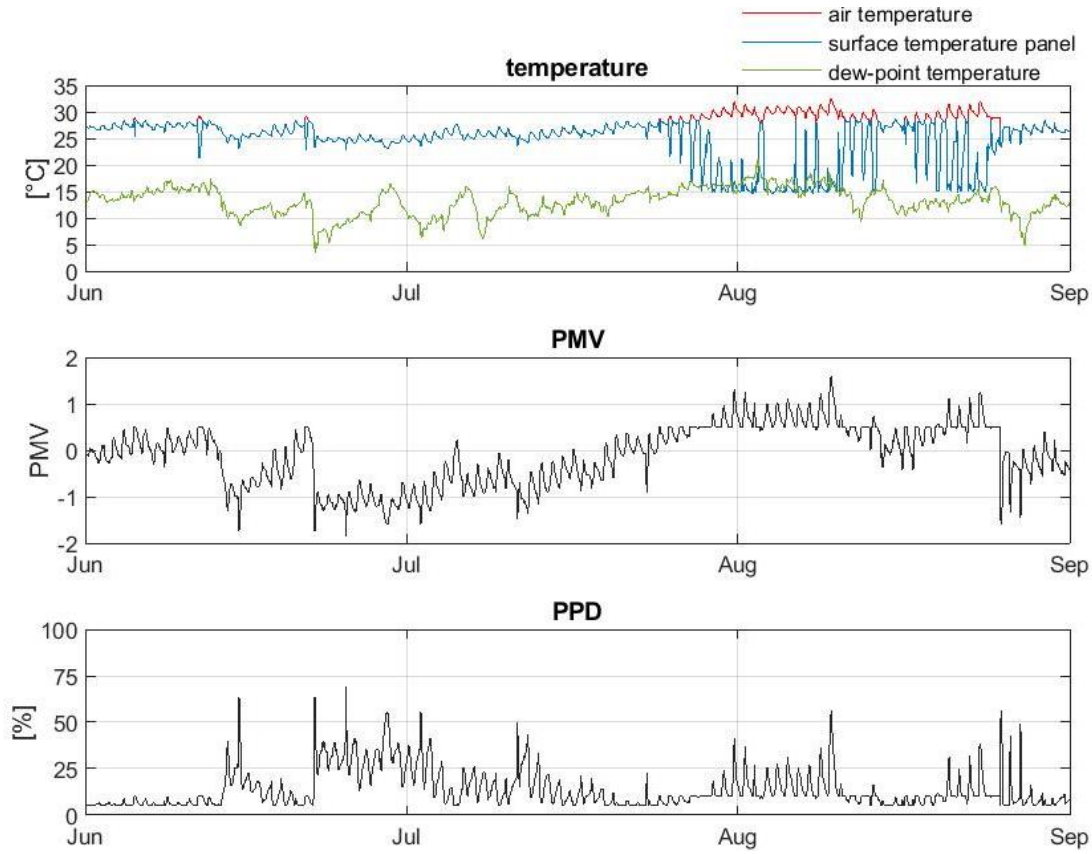

Figure 65 2018 - 2 radiant panels; vel= 0.5 m.s^{-1}; scenario with condensation

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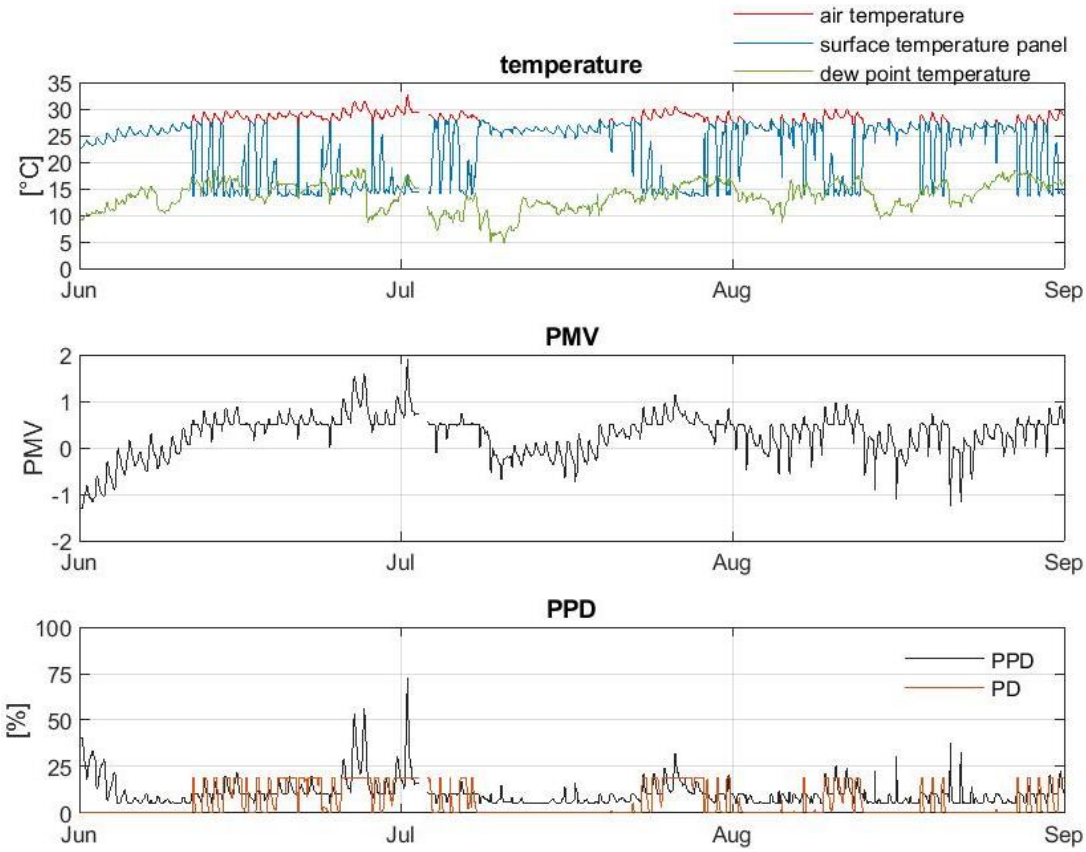

Figure 66 2019 - 1 radiant panel; vel= 0.2 m.s^{-1}; scenario with condensation

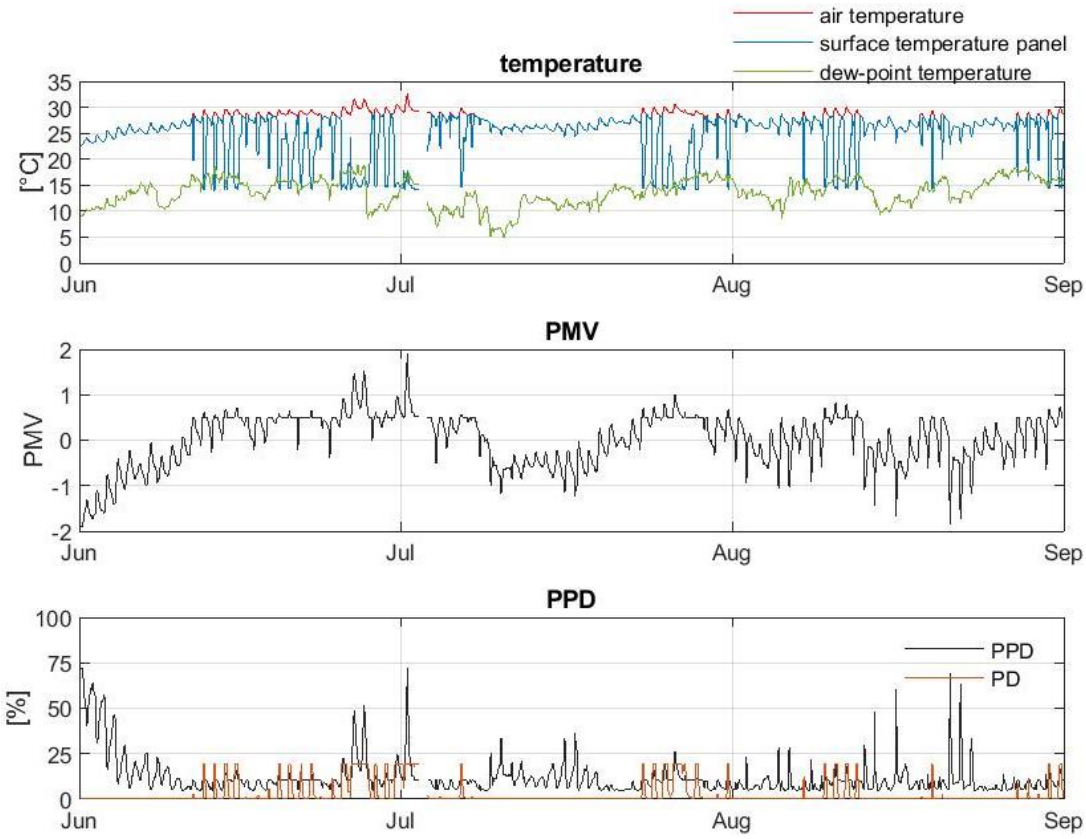

Figure 67 2019 - 1 radiant panel; vel= 0.5 m.s^{-1}; scenario with condensation

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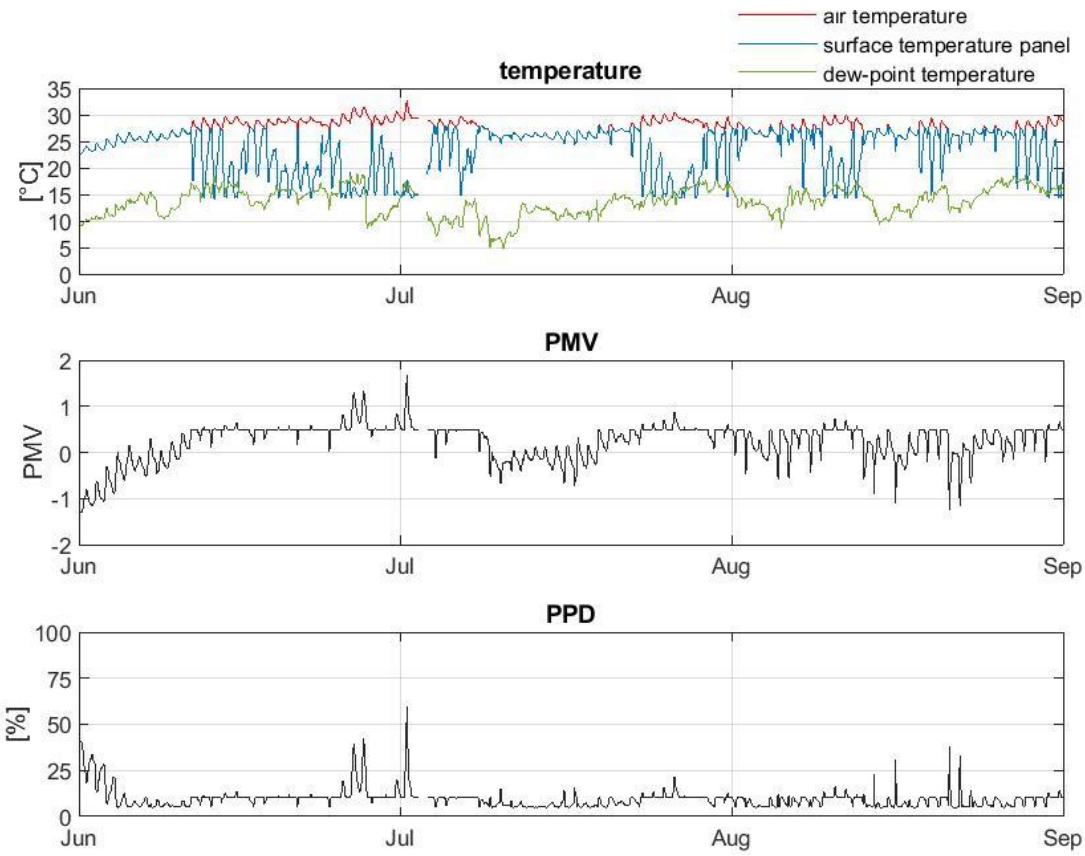

Figure 68 2019 - 2 radiant panels; vel= 0.2 m.s^{-1}; scenario with condensation

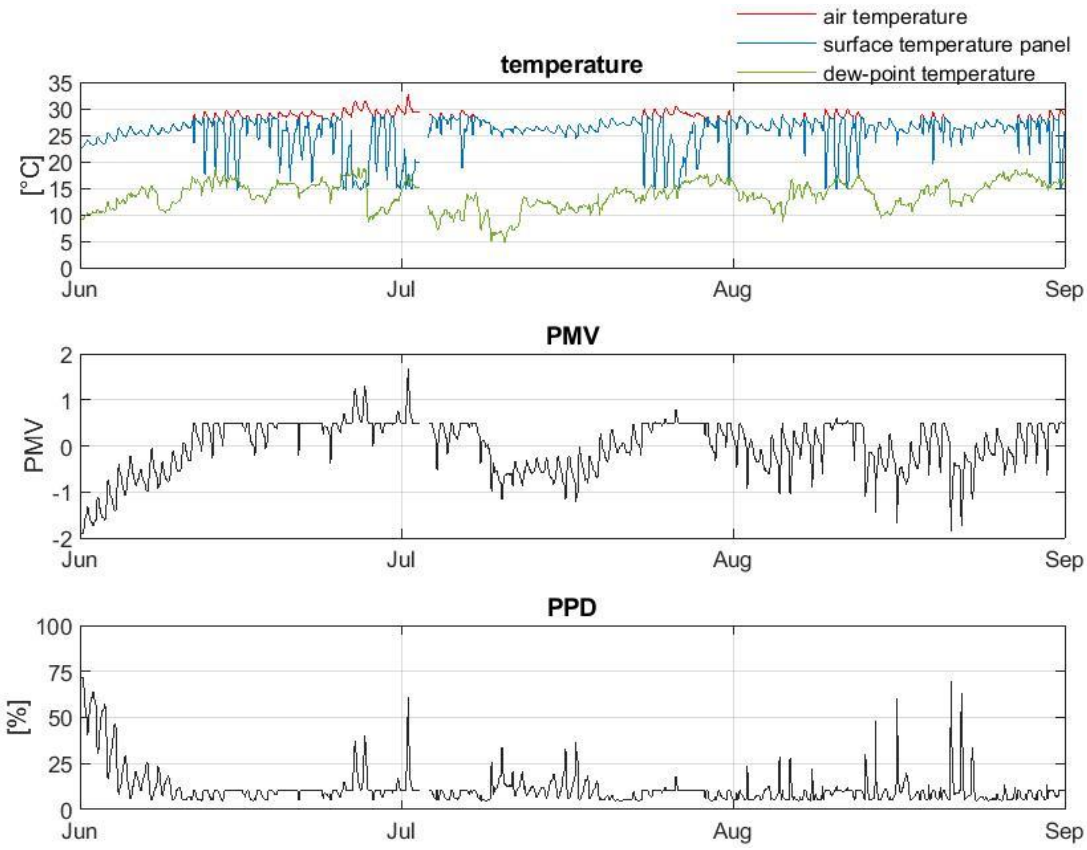

Figure 69 2019 - 2 radiant panels; vel= 0.5 m.s^{-1}; scenario with condensation

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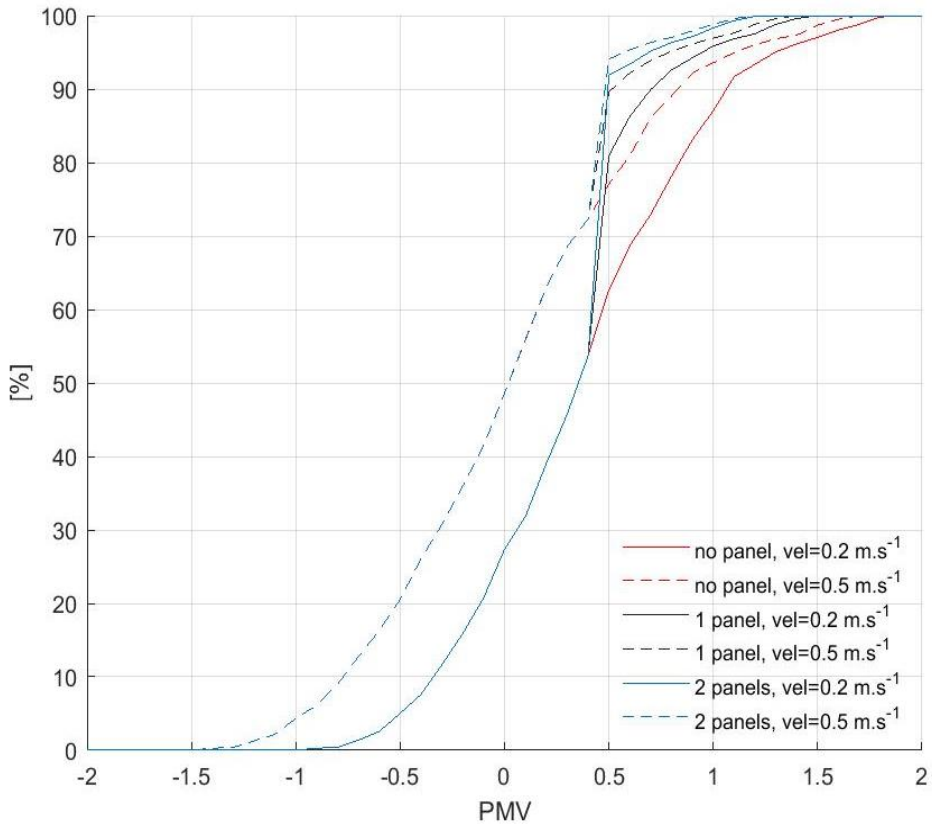

Figure 70 2017 - Cumulative distribution of the percentage of time when PMV exceeds a specific value (all scenarios with condensation)

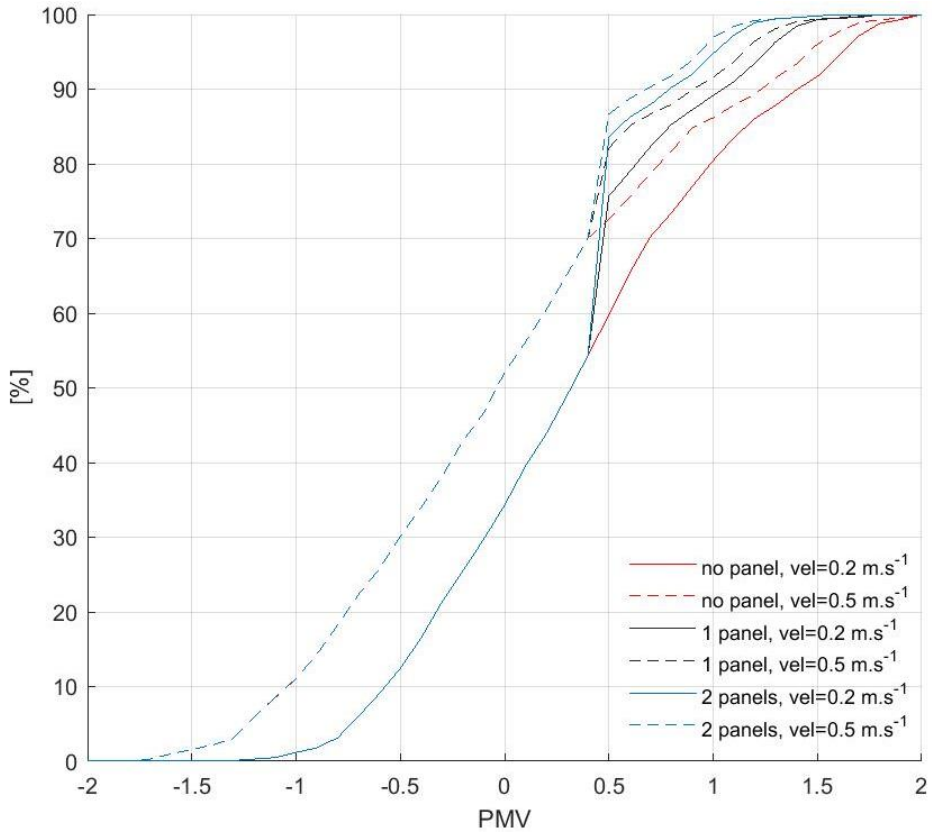

Figure 71 2018 - Cumulative distribution of the percentage of time when PMV exceeds a specific value (all scenarios with condensation)

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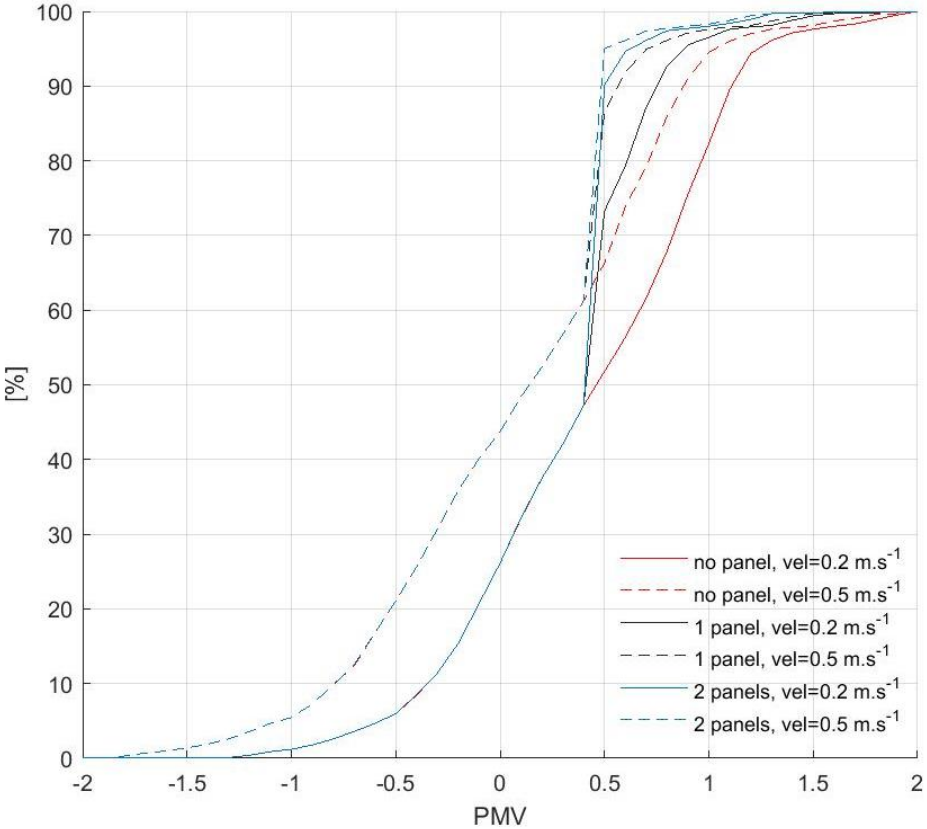

Figure 72 2019 - Cumulative distribution of the percentage of time when PMV exceeds a specific value (all scenarios with condensation)

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