Article

Investigating Optimum Cooling Set Point Temperature and Air Velocity for Thermal Comfort and Energy Conservation in Mixed-Mode Buildings in India

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Abstract: In warm and hot climates, ceiling fans and/or air conditioners (ACs) are used to maintain thermal comfort. Ceiling fans provide air movement near the skin, which enhances the evaporation of sweat, reduces heat stress, and enhances thermal comfort. This is also called the cooling effect. However, AC usage behaviour and the effects of elevated air speed through the use of ceiling fans on indoor operative temperature during AC usage are not widely studied. This study investigated the optimum AC (cooling) set point temperature and air velocity necessary for maintaining thermal comfort while achieving energy conservation, in mixed-mode buildings in India, through field studies by using used custom-built Internet of Things (IOT) devices. In the current study, the results indicate a 79% probability that comfort conditions can be maintained by achieving a temperature drop of 3K. If this drop can be achieved, as much as possible, through passive measures, the duration of AC operation and its energy consumption are reduced, at least by 67.5 and 58.4%, respectively. During the air-conditioned period, there is a possibility that the cooing effect is reduced because of increase in operative temperature due to ceiling fan operation. Therefore, the optimum solution is to maintain the highest AC set point and minimum fan speed setting that are acceptable.

Keywords: elevated air speed; thermal comfort; mixed-mode buildings; set point temperature; energy consumption in buildings

1. Introduction

Most small-to-medium office buildings and residential buildings in India use ceiling fans and/or room air conditioners (RACs), such as split and variable-refrigerant-volume air conditioners to maintain thermal comfort (satisfaction) [1,2]. Such buildings are usually called mixed-mode buildings, where a distinct period for natural ventilation and air-conditioning exists. Often, simple occupant controls are used, such as opening and closing the windows and adjusting the AC (cooling) set point temperature and ceiling fan speed [3–5]. The use of RACs results in significant energy consumption for space cooling and is expected to increase manifold in the coming decade due to factors such as the huge potential for RAC sales, increasing income levels and expectations of thermal comfort, and increasing outdoor temperatures [1,6,7].

To reduce space cooling energy consumption in buildings, key policy instruments in India include energy codes for commercial buildings (Energy Conservation Building Code—ECBC) and residential buildings (ECO NIWAS SAMHITA), which specify minimum performance requirements for building envelope and technical systems [8,9]; minimum energy performance standards (MEPS) for RACs and ceiling fans, which are regulated by

the mandatory and voluntary Bureau of Energy Efficiency (BEE) (energy) star labelling scheme, respectively [10,11]; the Super-Efficient Equipment Programme (SEEP), which aims to introduce and deploy super-efficient 35W ceiling fans against a market average of 70 W ceiling fans [12,13]; and Energy Efficiency Services Limited's (EESL) EESL Super-Efficient Air-conditioner Program (ESEAP), which has sold over 1300 Super-Efficient 1.5 TR (approximately 5.3 kW) capacity air conditioners (ACs) that are at least 15% more efficient than the BEE's five-star labelled ACs.

In addition to energy efficiency, appliance usage (i.e., user behaviour) plays a vital role in energy consumption [14–16]. For example, behavioural aspects, such as AC (cooling) set point temperature and its operating duration, influence energy consumption [17,18]. In addition, simulation studies indicate that the simultaneous use of ACs with elevated air speed results in energy savings [19] because similar levels of thermal comfort satisfaction can be felt at a higher AC set point temperature in the former case compared with the latter case. However, in Indian buildings, the effect of AC usage behaviour on space cooling energy consumption, and the effect of elevated air speed through the use of ceiling fans on indoor operative temperature (a critical parameter for determining thermal comfort) during AC usage are not widely studied, especially through field studies (see Section 1.3).

To comprehend the objectives of the study, it is important to understand the methods used to define thermal comfort in mixed-mode buildings, how to enhance thermal comfort and achieve energy savings with elevated air speed, and key gaps in the current research. Therefore, in the following sub-sections of this introduction, thermal comfort models in mixed-mode buildings, the enhancement of thermal comfort and energy savings with elevated air speed, gaps in the current research, the objectives of the study and the structure of the paper are presented.

1.1. Thermal Comfort Satisfaction in Mixed-Mode Buildings

Thermal comfort satisfaction is crucial for the wellbeing and productivity of occupants. Establishing 'thermal comfort for all' through sustainable and smart space cooling technologies, aligned with the greenhouse gas reduction goals, is a priority for the Government of India [20]. Thermal comfort in buildings is usually defined by using static models, such as Fanger's predicted mean vote-predicted people dissatisfied (PMV-PPD) model, and variable models, such as the adaptive thermal comfort (ATC) model [21–23]. Because of their wider acceptance, e.g., in international thermal comfort standards and national building energy codes and their fundamental differences, both the PMV-PPD model and an ATC model for India are considered in this study.

PMV is expressed in relation to the various thermal loads in the space by considering four environmental variables: air temperature (T_a), mean radiant temperature (T_{mrt}), air velocity (v), and relative humidity (rh), as well as two occupant variables: clothing resistance (clo) and the activity level of the occupants (met). PMV is then expressed as an index that predicts the mean value of thermal sensation votes on a sensation scale between -3 and $+3$, which correspond to cold and hot, respectively. PPD is an index that estimates the percentage of thermally dissatisfied people and is expressed as a function of the PMV based on an empirical relation [24].

The ATC model assumes that the occupants' thermal comfort preferences are shaped by their past and present experiences in relation to the outdoor environmental conditions and behavioural adaptations. Furthermore, it assumes that thermal discomfort is mitigated through appropriate actions, such as opening the windows, adjusting ambient air velocity and AC set point temperature, and wearing appropriate clothing. Adaptive models are developed based on thermal comfort field surveys and are usually specific to climate, region, and building typology and operating mode (i.e., naturally ventilated, mixed-mode or air-conditioned). Indoor operative temperature, T_o, is a key parameter for expressing thermal comfort satisfaction using ATC models. It is defined as the weighted average of

the air temperature and mean radiant temperature, and weighed by their respective heat transfer coefficients, W *and* $1 - W$ (see Equation (1)) [25].

$$T_o = WT_a + (1 - W)T_{mrt} \qquad (1)$$

Usually, W is taken as 0.5 for practical purposes; however, technically, this is only valid when $T_{mrt} = T_a$. The ATC model expresses thermal comfort satisfaction in categories of acceptability bands around a neutral operative temperature, T_n. T_n is a function of the chosen outdoor environmental parameter, such as the mean monthly outdoor air temperature, which is given by the following [26]:

$$T_n = x * (y) + z \qquad (2)$$

where T_n is the indoor neutral operative temperature, x and z are constants that are specific to the ATC model and y is the chosen outdoor environmental parameter, which is usually valid for a limited range of y. Thermal comfort satisfaction is expressed in bands of acceptability between which 90, 85, and 80% of the occupants are satisfied. The bands are given by $T_n \pm \varepsilon_{90/85/80}$, where ε_{90}, $\varepsilon_{85,}$, $\varepsilon_{,80}$ are the bands of acceptability between which 90, 85, and 80% of the occupants are satisfied, respectively. Thermal comfort conditions in the chosen acceptability band are met when T_o is within the range of $T_n \pm \varepsilon_{90/85/80}$.

1.2. Elevated Air Speed for Enhancing Thermal Comfort in Mixed-Mode Buildings and Resulting Energy Savings

In warm and hot climates, air movement near the skin enhances the evaporation of sweat, reduces heat stress, and helps in maintaining thermal comfort. Studies conducted through the use of thermal mannequins [27], human subjects [27–29], and transient computational fluid dynamics [30–32] consistently show that compared to a certain temperature that provides thermal comfort, similar levels of thermal comfort can be felt at higher temperatures with a corresponding increase in air velocity (i.e., due to elevated air speed).

Various empirical indices and normographs are used to assess the effects of elevated air speed on thermal comfort [33,34]. This study uses a widely accepted method, the Standard Effective Temperature (SET) method provided in the international standard, ASHRAE standard 55 Thermal Environmental Conditions for Human Occupancy. As per ASHRAE standard 55, if air velocity, v, is increased by Δv, the maximum operative temperature, T_{o_max} ($T_{o\_max} = T_n + \varepsilon_{90/85/80}$), in a comfort band, can be increased correspondingly, by ΔT_o (cooling effect), to a new adjusted maximum operative temperature, $\dot{T}_{o\_max}$ $\left(\dot{T}_{o\_max} = T_{o\_max} + \Delta T_o \right)$ [25]. However, as per ASHRAE standard 55, this is only applicable to enhance thermal comfort in buildings with natural ventilation. It further recommends limiting indoor air speed to 1.2 m/s when local control over airspeed is enabled. Without control, the limits for air speed are 0.8 m/s and 0.15 m/s for operative temperatures above 25.5 °C and below 22.5 °C, respectively [25]. The latter limit is to avoid cold draughts [35]. However, in warm climates, field studies indicate a clear preference for higher air speeds than the limits prescribed by ASHRAE standard 55 [28,36,37], including in India [5,38–41]. Studies indicate that air velocity limits may be appropriate for functional reasons, but they have a limited effect on thermal comfort conditions and behavioural adaptation [28].

In mixed-mode buildings, the cooling effect (ΔT_o) due to elevated air speed reduces space cooling energy by maximizing $\dot{T}_{o\_max}$, which enables extending the natural ventilation period, and increasing the cooling set point temperature (during air-conditioning period). This is often substantiated by building energy performance simulation studies [42] and limited field studies exist [43]. However, the application and benefits of the cooling effect due to elevated air speed through the use of ceiling fans in Indian mixed-mode buildings is unclear, especially through field studies.

1.3. Gaps in Current Research

In research on AC usage behaviour, detailed recordings of AC set point temperatures are not usually available [44–47]. Limited studies in India report AC and ceiling fan usage behaviour (e.g., preferences for AC set point temperature and fan speed) and its impact on energy consumption [4,48]. However, these are based on 'right here and right now' thermal comfort surveys and the behavioural parameters are not continuously monitored.

The effect of elevated air speed on thermal comfort is usually studied in controlled laboratory settings (typically in thermal comfort chambers) and via thermal comfort surveys. However, in the real world, the use of ceiling fans may increase indoor air temperature because convective surface heat transfer from the interiors (internal mass) and interior building surfaces increases with air velocity. The convective heat flux (exchange) (Q) between a surface i and the air is given by the equation:

$$Q = h_{c\ i} * (T_a - T_{sur\ i}) \tag{3}$$

where $h_{c\ i}$ is the surface convective heat transfer coefficient between air and the surface i, T_a is the air temperature, and $T_{sur\ i}$ is the surface temperature.

Peeters et al. analysed the effect of an unsteady flow on convection coefficient induced by various factors such as walking in the space, due to fans or the closing or opening of doors; obstructions within the zone such as furniture and window blinds; and internal gains. They observed that unsteady flow due to fan-induced air movement (air velocity in the range of 0.2 m/s to 1.2 m/s) leads to a considerable mixing of air in the space and resulted in a uniform space temperature, which only takes a short time (approx. 5 min) to stabilize [49]. Choosing appropriate surface heat transfer coefficients is important for accurately calculating space cooing and heating loads while conducting dynamic building energy performance simulations [50,51]. In thermally insulated buildings and during air-conditioned periods, a sensitivity study shows that increasing the surface heat transfer coefficient from 8.3 Btu/h-ft2 (47.12 W/m²K) to 12.0 Btu/h-ft2 (68.13 W/m²K) (44% increase) changes cooling loads by less than 2%, which is negligible [52]. However, most buildings in India do not have thermal insulation, which may lead to higher indoor surface temperature for external surfaces compared with building with thermal insulation. Moreover, building simulation studies that show energy savings due to elevated air speed often simply change the AC set point temperature with a corresponding increase in the air speed (e.g., by using the SET method). It is unclear whether the static or dynamic values for surface heat transfer coefficients assumed in such studies sufficiently represent the actual values. In addition, heat is dissipated from the motor of the ceiling fan (although, the motors are increasingly becoming efficient). These factors may result in an increase in the operative temperature and may reduce the benefits of the cooling effect due to elevated air speed. This phenomenon is not widely studied and is not clearly captured in thermal comfort chambers and surveys.

1.4. Objective of the Study

This paper analysed the impact of AC usage behaviour on energy consumption and the effect of elevated air speed, through the use of a ceiling fan, on operative temperature. This helps to increase the understanding on how to achieve an optimum AC set point temperature and air velocity, which would allow us to maintain thermal comfort while achieving energy conservation in mixed-mode buildings in India.

2. Methods and Materials

AC usage behaviour as a measure of thermal comfort and energy consumption and the effect of elevated air speed, through the use of ceiling fans, on indoor operative temperature are investigated through field studies. For monitoring and collecting key parameters, such as AC set point temperature (including on/off state), operative temperature and energy consumption, the study uses custom-built and low-cost micro-controller devices.

Three separate field studies were conducted. In the field study 1, AC usage behaviour was studied. In the other two field studies, 2a and 2b, the effect of elevated air speed through the use of ceiling fans on indoor operative temperature was studied.

The location and procedure of the field studies, instruments used in the study and their accuracy, and data collection and cleaning procedures are explained in the following sub-sections.

2.1. Location and Procedure of the Field Studies

All the three field studies were conducted in typical Indian residential bedrooms. The pictures have not been presented for privacy reasons. In general, the bedrooms contain items of furniture, such as furnished double beds, dressing tables, and wardrobes (either free standing or built into the wall). Further specifications of the rooms, such as dimensions and occupancy and their geographical location, can be found in the following sub-sections.

2.1.1. Field Study 1: AC Usage Behaviour

Field study 1 was conducted in the bedroom of a typical high-rise two-bedroom residential unit (2BHK) (middle floor) in the city of Ahmedabad, India, which has a hot-dry climate as per ECBC. The room was equipped with a remote-controlled wall-mounted split AC with a capacity of 1.5 TR (5.3 kW approximately) and a ceiling fan with a diameter of 1200 mm. The dimensions of the room are 3 m × 3.5 m × 3 m (height) and a window (single glazed and UPVC frame) of approximately 9 m^2 is located on one of the two external walls. Typically, the room is occupied during the nights (08:00 p.m.–06:00 a.m.) by two adults (30–40 years old) and one child (5-year-old) and intermittently occupied during the day on weekends or holidays. The volunteers of the study use the bedroom in mixed-mode operation. That is, they turn on the AC only when they feel that the thermal comfort conditions are not met, e.g., through natural ventilation. Windows are usually kept closed and the curtains are drawn over when the AC is turned on. The field study was conducted between 28 June 2021 and 8 August 2021. Key parameters that influence AC usage behaviour, i.e., air and globe temperature and relative humidity in the bedroom, were continuously recorded. Each time AC was used, the infrared (IR) signal from the remote control was recorded. A smart plug was used to measure the daily energy consumption of the AC (see Section 2.2 for more details on instruments).

2.1.2. Field Study 2a: Effect of Elevated Air Speed through Ceiling Fan Operation on Indoor Operative Temperature

This is a pilot study to verify and explain, in principle, the phenomenon of 'cooling effect reduction'. Field study 2a was conducted in a ground-floor bedroom of a three-storey residential building in the city of Hyderabad, India, which has a composite climate as per ECBC. The room was equipped with a remote-controlled wall-mounted split AC of 1.5 Ton (5.3 kW approximately) and a ceiling fan. The dimensions of the room are 3 m × 3.5 m × 3 m (height) and two windows (single glazed and wooden frame) of approximately 1.8 m^2 are located on each of the two external walls. During the experiment, textile curtains were drawn over the window. The experiment was conducted for one day (on 30 April 2021), during the afternoon. The room was never occupied during the experiment. The ceiling fan was operated for approximately 4.5 h at each of the available four speed settings for half an hour, in descending and ascending orders of speed, with zero speed setting in between them. The AC set point temperature was set to 24 °C. Before beginning the experiment, the room was maintained at the AC set point temperature of 24 °C and fan speed setting of five for half an hour to one hour to achieve thermal stabilization. During the experiment, the air and globe temperatures and relative humidity were recorded.

2.1.3. Field Study 2b: Effect of Elevated Air Speed through Ceiling Fan Operation on Indoor Operative Temperature

This study is in continuation of field study 2a to analyse the principle of cooling effect reduction at various AC set point temperatures. Field study 2b was conducted in a top-floor bedroom of a three-storey residential building in the city of Hyderabad, India, which has a composite climate as per ECBC. The room was equipped with a remote-controlled wall-mounted split AC of 1.5 Ton (5.3 kW approximately) and a ceiling fan. The dimensions of the room are 4 m × 3.5 m and a window of approximately 4 m^2 is located on one of the two external walls. The experiment was conducted for four days, mostly during the afternoon. During the experiment, textile curtains were drawn over the window. The room was intermittently occupied during the experiment by an adult (34 years old) and one child (eight years old). On all four days, the ceiling fan was operated for approximately 5.5 h at each of the available five speed settings for half an hour, in descending and ascending orders of speed, with zero speed setting in between them. The AC set point temperature was set to 24, 26 and 28 °C on days one, two and three, respectively. On day four, the room was naturally ventilated. Before beginning the experiment for the day, the room was maintained at the AC set point temperature of the day and fan speed setting five for half an hour to one hour to achieve thermal stabilization. During the experiment, the air and globe temperatures and relative humidity were recorded.

2.2. Instruments and Accuracy

For data collection, two modules were developed and used. One is a comfort module that records the air temperature, globe temperature and relative humidity, and the second is an IR module that records the AC IR signals (Figure 1). The comfort module was carefully placed to avoid any proximate heat sources or heat sinks. Both modules use suitable sensors that are connected to Arduino-based Wi-Fi microcontroller boards with 4MB flash based on ESP-8266EX microchip and are powered by a micro-USB cable. For measuring globe temperature, a DS18B20 temperature sensor was inserted into a 40 mm diameter ping-pong ball and was sealed so it was air-tight. At lower airspeeds and radiant loads (such as in this study), such a small globe thermometer can provide reliable results [53–55]. The data were recorded at specified intervals on an on-board micro-SD card and additionally sent to a remote MySQL database [56]. A smart plug was placed between the AC power plug and mains socket to record the AC energy consumption. Table 1 shows the details of various sensors and components used in the modules.

Figure 1. Comfort module (on the left side in the above picture); IR module (on the right side in the above picture). A ballpoint pen was placed in the front for scale.

Table 1. Sensors and components.

Module	Sensor/Component and Library	Parameter to Be Measured or Recorded
Comfort module	SHT30 [57]	Air temperature
		Relative humidity
	DS18B20 [58]	Globe temperature
	RTC module [59]	Real time clock module to record time
	SD card module [60]	Data logging
IR module	VISHAYTSOP4838:38KHz [61]	IR signal receiver
	RTC module [59]	Real time clock module to record time
	SD card module [60]	Data logging
Smart plug	Helea 16Amp smart plug [62]	Daily energy consumption

Prior to the field studies, a prototype of the comfort module was assembled and tested for its accuracy. However, the prototype used an SHT31 sensor, which is technically similar to the SHT30 sensor that was used in the comfort module in the study. For assessing its accuracy, the readings from the prototype were compared with a reference instrument, an accurate ALMEMO board in a rapid assessment approach. The measurements from the prototype and ALMEMO were taken by placing them side-by-side for approximately three hours in a centrally heated open hall (Figure 2). For brief durations, a variety of ambient temperature and humidity and air velocity (AV) conditions were maintained by opening and shutting the external shutters of the hall, and by using a pedestal fan (see Table 2). Self-heating in the sensors, and localized heating due to the heat emitted by the micro-controller located at the base of the prototype may affect the accuracy of the measurements from the sensors, which are approximately 10 cm above the base. To study the influence of self-heating, the prototype base was covered with aluminium foil during the first half and the foil was removed during the second half of the procedure. In addition, infrared images of the equipment were taken at different intervals.

Figure 2. Testing configuration with the prototype base covered by aluminium foil.

Although all comfort modules that are used in the field studies were not tested in this manner, the results from prototype testing showed they can be reliably used. Especially, the changes in the air and globe temperatures and relative humidity were measured at sufficient resolution to reliably study the difference (delta) in values and patterns. Furthermore, uncertainty analysis was carried out to analyse the results by considering errors in measurements, where analyses with absolute values are necessary (e.g., in thermal comfort PMV-PPD and ATC). The results of the testing are presented in Appendix A. Programming language R [63] was used to analyse the results of testing and plotting was carried out by using R package ggplot2 [64].

Table 2. Ambient conditions during the comparison procedure.

Time	Ambient Condition	Description
11:34:00	Calibration begins	The experiment began after achieving steady-state conditions.
12:05:00	External shutter opened	The shutters of the testing hall were opened to let in cold air.
12:21:00	External shutter closed	The shutters of the testing were closed. They remained closed for all subsequent periods.
12:40:00	Fan on (mean AV~1.1 m/s)	Air velocity was increased using a pedestal fan.
12:50:00	Fan on (mean AV~0.7 m/s)	Change in air velocity.
12:58:00	Fan off (foil off)	Pedestal fan was turned off to maintain still air conditions and the aluminium foil was removed from the base of the prototype. The foil was removed for all subsequent periods.
13:57:00	Fan on (mean AV~1.3 m/s, alu foil off)	Change in air velocity.
14:11:00	Fan on (mean AV~1.7 m/s, alu foil off)	Change in air velocity.

2.3. Data Collection and Cleaning

In the comfort module, air temperature and relative humidity were recorded at two-second intervals, and the globe temperature was recorded at an interval of 10 s on the on-board micro-SD card. In addition, all these parameters were sent to the remote MySQL database by using the HTTP protocol via Wi-Fi in 10-minute intervals. The IR module recorded the AC IR signals on the on-board micro-SD card and transmitted it to the MySQL database whenever a signal was received. Outdoor weather data were taken from OpenWeatherMap [65].

For field study 1, data from the MySQL database were used and for field study 2, data from the on-board micro-SD card were used. An insignificant number of corrupt entries of the date–time format were found and removed from the data on comfort modules. Data from the IR remote required extensive parsing, visual inspection, and cleaning. Discrepancies in the data primarily include duplicate, stray and missing signals. Data of interest from the IR module include the timestamp of the signal, AC set point temperature including on and off signals, and AC fan speed. Signals for each day were plotted with temperature and humidity data and visually inspected for their accuracy and were slightly adjusted, if necessary, to correctly reflect the temperature and humidity profile. For field study 1, data from 17 days with complete and accurate data from both comfort and IR modules were considered for the study. Data from smart plug were collected via a smartphone app. Although the app shows instantaneous values of power voltage, current and power consumption, these values could not be recorded. Only daily energy consumption was recorded. Primarily, programming language Python [66] was used for data analysis and plotting, including the packages Pandas [67], SciPy [68] and statsmodels [69] for data analysis, and packages Matplotlib [70] and Seaborn [71] for plotting.

3. Results

3.1. Field Study 1: AC Usage Behaviour

In the following sub-sections, AC on/off behaviour is studied by analysing three features. The first feature considers air temperature and relative humidity, as these can be easily measured, and can be used for controlling the AC. The second and third features are based on two thermal comfort standards, which consider more parameters than air temperature and relative humidity. Thermal comfort satisfaction was analysed by using a static temperature model, i.e., Fanger's PMV-PPD model, and an adaptive model, i.e., Indian Model for Adaptive Comfort (IMAC).

3.1.1. Air Temperature and Relative Humidity

Figure 3 (left) shows the instantaneous values of air temperature and relative humidity when turning the AC on and off. Because the distributions of air temperature and relative humidity are not normal, and assuming that both these parameters are paired, a Wilcoxon Signed-Rank test was performed to assess whether these values are distinct when turning

the AC on and off. The p-values for air temperature and humidity for turning the AC on and off are 4×10^{-9} and 0.00149, respectively, indicating that the values are from different distributions and are distinct. Figure 3 (right) shows the (periodic) time-weighted average of air temperature and relative humidity for each period, i.e., the period between whenever the AC set point temperature changed. The usual preference for AC set point temperature is between 25 and 29. The mean and median values of air temperature and relative humidity that result in turning the air conditioner on and off are shown in Table 3. The difference between the mean/median air temperatures and relative humidity values that result in turning the air conditioner on and off are 1.95/2.14 K and 5.62/4.92%, respectively.
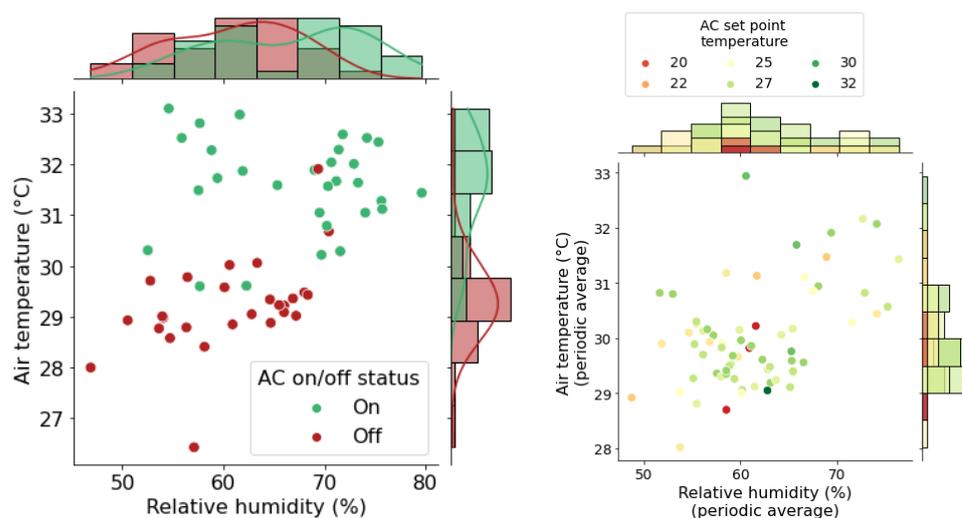
Figure 3. Relation between air temperature and relative humidity and AC on and off status (**left**); relation between periodic average of air temperature and relative humidity and AC set point temperature (**right**).

Table 3. Instantaneous conditions that result in turning the air conditioner on and off.

Conditions	AC Turned On	AC Turned Off
Mean air temperature	>31.49 °C	<29.54 °C
Median air temperature	>31.66 °C	<29.35 °C
Mean relative humidity	>67.19%	<61.57%
Median relative humidity	>69.96%	<62.27%

Figure 4 shows the drop in air temperature and relative humidity for each cycle, i.e., cycle between whenever the AC is turned on and off (on/off cycle), and the duration of the cycle. The mean/median values for drop in air temperature and relative humidity for on/off cycle are −2.09/−1.95 K and −5.63/4.77%, respectively. The mean/median values for the duration of the on/off cycle are 2.95/1.9 h. The drop in air temperature increases with the running time of the air conditioner up to approximately four hours of continuous running time. However, the continuous running time (duration) of the on/off cycle does not necessarily result in a corresponding and proportionate decrease in the room air temperature and relative humidity. Beyond six hours of continuous running time of the air conditioner, the drop in air temperature does not significantly increase with running time, although a certain drop is maintained as per the AC set point temperature. This is expected as the rate of change of air temperature is high initially when the AC is turned on or set point temperature is changed, and later, the air temperature is maintained accordingly.
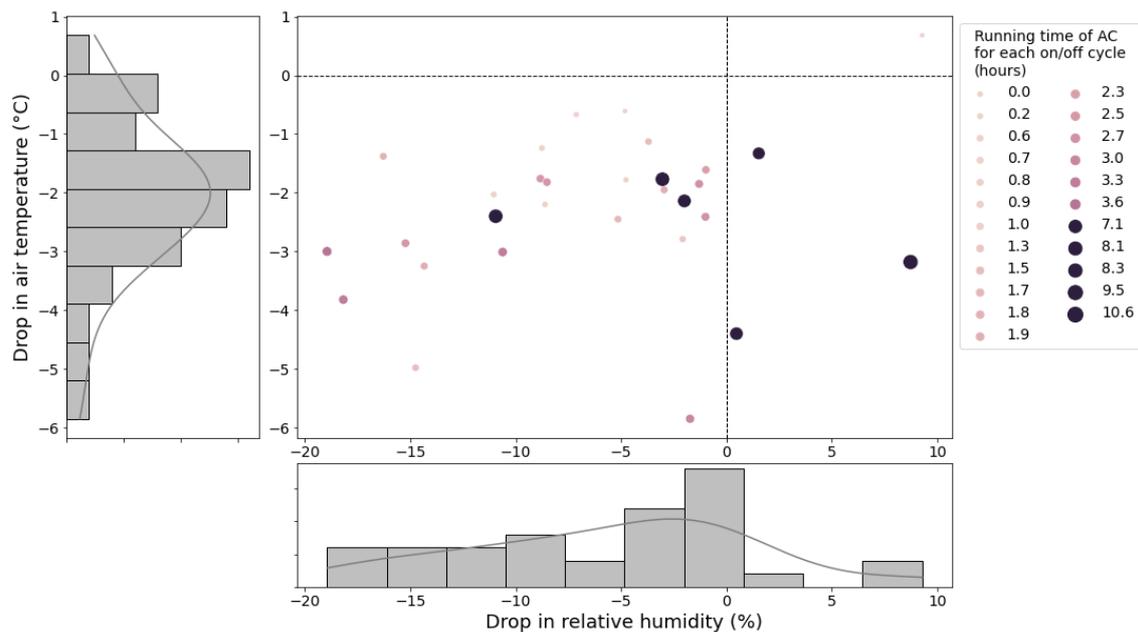
Figure 4. The drop in temperature and relative humidity for each cycle when the air conditioner is turned on and off.

3.1.2. Thermal Comfort: PMV-PPD

For calculating PMV-PPD, environmental variables—air temperature and relative humidity—were measured and mean radiant temperature was calculated using the measurements of globe temperature; air velocity was assumed to be approximately 0.2 m/s based on the occupant reported regulator speed of the ceiling fan, which is one; occupant variables—clo and met values—were taken as 0.96 and 0.7, respectively, which are suitable for sleeping activity. PMV-PPD indices were calculated using the Python package pythermalcomfort, as per the ASHRAE standard 55 [72].

Figure 5 shows the relationship between the PMV and PPD indices corresponding to turning the AC on and off. The graph on the top right shows the PMV-PPD values based on field measurements. Because the comfort module was not calibrated, an uncertainty analysis was conducted to build confidence in the results obtained from recorded measurements. For this purpose, an error band was assigned for all the variables based on the results of prototype testing and the literature (see Table 4) and the resultant PMV-PDD values corresponding to turning the AC on and off were plotted as boxplots adjacent to the results from measurements. For the uncertainty analysis, 14,336 samples were generated and analysed using the Python package SALib [73]. Furthermore, a *z*-test test was performed to assess whether the values of PMV and PPD are distinct for turning the AC on and off. The *p*-values of the *z*-test for both PMV and PPD are almost equal to zero, indicating that the values are from different distributions and are distinct.

Table 4. Assumed ranges of values for calculating uncertainty in PMV-PPD.

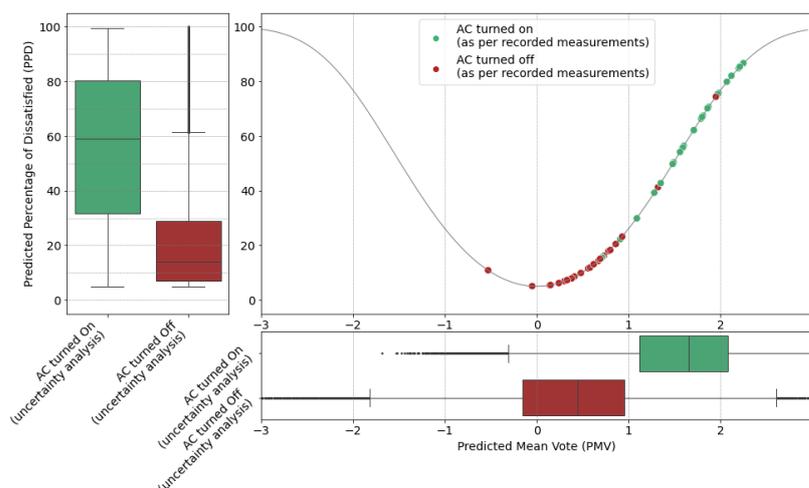| Parameter	Recorded Measurement/Assumed Value	Range of Error Band
Air temperature	Measured value on comfort module	−0.5–+0.5 °C
Mean radiant temperature	Measured value on comfort module	−1.5–+1.5 °C
Air velocity	0.2 m/s	−0.1–+0.1 m/s
Relative humidity	Measured value on comfort module	−5–+5%
Clothing resistance	0.96	−0.2–+0.2 clo
Activity level	0.7	−0.1–+0.1 met

Figure 5. Relation between thermal comfort indices PMV-PPD and AC on and off status.

The PMV-PPD results from both measured and uncertainty analyses show that most instances (i.e., interquartile range between 25 and 75 percentiles) of turning on the AC can be found between sensation votes one and two and most instances of turning off the AC can be found between sensation votes zero and one (Figure 5). Similarly, the AC is mostly turned on when the PPD is above 30%. This indicates that up to 70% of the occupants are satisfied with the thermal comfort conditions between PMV of zero and one and that they do not require AC usage at these conditions.

Figure 6 shows the probability of the AC being turned on and off at various values of PPD from uncertainty analysis binned in 5% values. The probability of the AC being turned off is very high when the PPD is between 5 and 10% and it reduces considerably in the next two bins of PPD between 10–15% and 15–20%, although the probability of the AC being turned on is still higher than the AC being turned off in those bins. Between a PPD of 30 and 40%, the probability of the AC being turned on was almost equal to that of the AC being turned off, and beyond a PPD of 40%, the probability of the AC being turned on increased compared with that of the AC being turned off.
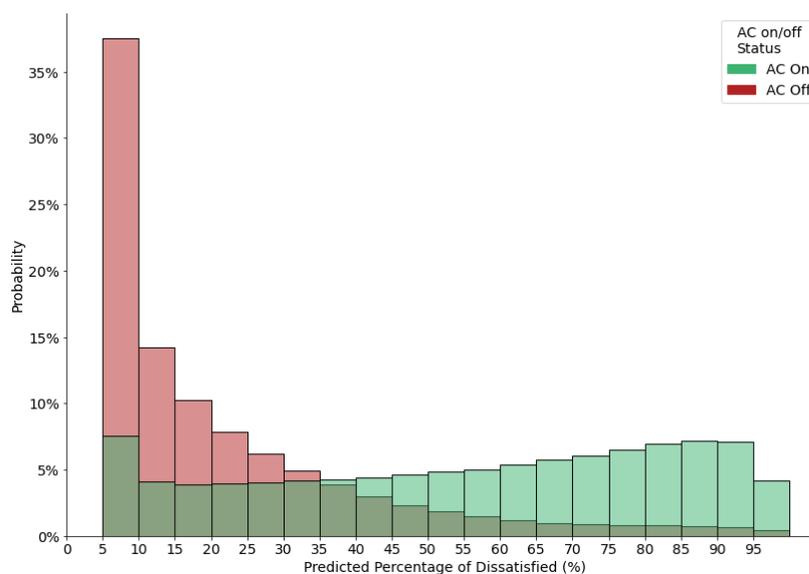
Figure 6. AC on/off probability at various PPD values from uncertainty analysis.

3.1.3. Thermal Comfort: ATC Model Using Indian Model for Adaptive Comfort (IMAC)

For analysing thermal comfort as per ATC, this study used IMAC for mixed-mode office buildings, due to the lack of an alternative and authoritative adaptive model for ther-

mal comfort in Indian residential buildings [27]. IMAC is expressed as a function of neutral operative temperature (thermal neutrality) and 30-day outdoor mean air temperature (see y in Equation (2)). IMAC proposes temperature acceptability bands for 80%, 85% and 90% when the occupants are satisfied.

Figure 7 shows the relation between thermal comfort as per IMAC for mixed-mode buildings and turning the AC on and off. The graph shows the recorded measurements as points. Because the comfort module used in the study was not calibrated, an uncertainty analysis was conducted to build confidence in the results obtained from recorded measurements. For this purpose, an error band was assigned for all the variables (see Table 5) and the resultant values of indoor operative temperature corresponding to turning the AC on and off were plotted as boxplots adjacent to the results from measurements. For the uncertainty analysis, a total of 8192 samples were generated using the Python package SALib.
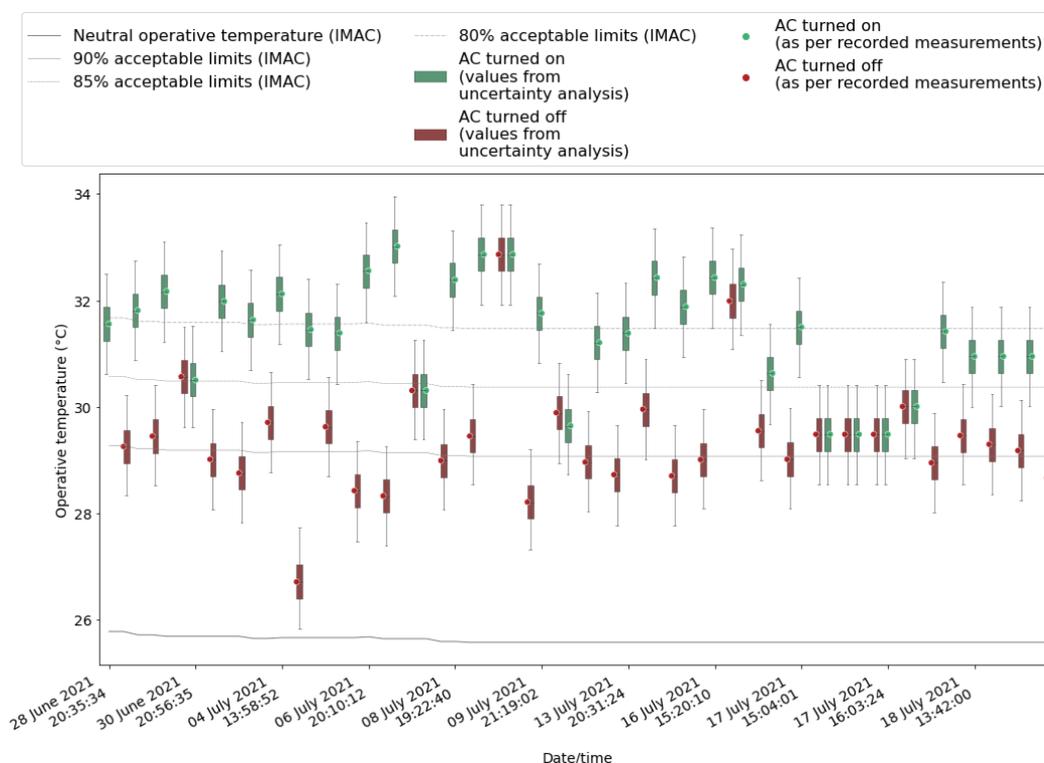
Figure 7. Relation between thermal comfort as per IMAC for mixed-mode building and AC on and off status.

Table 5. Assumed ranges of values for calculating uncertainty in IMAC.

Parameter	Recorded Measurement/Assumed Value	Range of Error Band
Air temperature	Measured value on comfort module	−0.5–+0.5
Mean radiant temperature	Measured value on comfort module	−1.5–+1.5
Air velocity	0.2 m/s	−0.1–+0.1

The results from measurements and uncertainty analysis show that most instances of turning on the AC are near to and beyond the upper bound of 85% acceptable limit band, while the AC was mostly turned off between the neutral operative temperature and upper bound of 90% acceptable limit band (Figure 7). Furthermore, a *z*-test test was performed to assess whether the values of indoor operative temperature are distinct for turning the AC on and off. The *p*-value of the *z*-test is almost equal to zero, indicating that the values are from different distributions and are distinct.

Figure 8 shows the probability of the AC being turned on and off within various bands of thermal comfort as per IMAC model. The probability of the AC being turned off is very high within the bounds of 90% limit band. Beyond the upper bound of 85% limit band, the instances of AC turned on increase significantly.
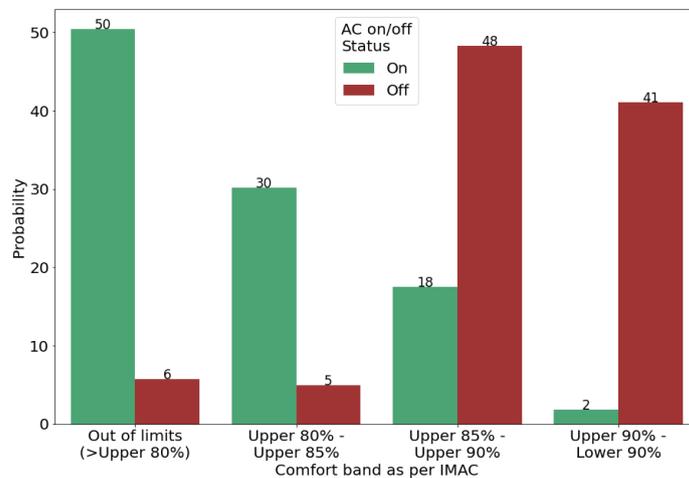

Figure 8. AC on/off probability within various IMAC comfort bands.

3.1.4. Energy Consumption of the Air Conditioner

The measurements obtained from the field study that influence energy consumption of the air conditioner include: indoor relative humidity; AC set point temperature; outdoor relative humidity; difference between indoor and outdoor temperatures; difference between indoor and outdoor relative humidity; outdoor temperature; drop in indoor relative humidity during each period of change in AC set point temperature; difference between indoor air temperature and AC set point temperature; drop in indoor air temperature during each period of change in AC set point temperature; drop in indoor globe temperature during each period of change in AC set point temperature; indoor globe temperature; indoor air temperature; and the total running time of the air conditioner.

As the energy consumption values are only available as daily values, the time-weighted averages were considered for all the parameters, except for the total running time of the air conditioner.

Energy consumption with respect to the most influential parameters shows that the data are not always normally distributed and is possibly non-linear and non-monotonic. However, it has a monotonic relationship with the total running time of the air conditioner. Therefore, a linear and second-order polynomial regression was conducted between energy consumption and total running time and other parameters. This was conducted for a dataset of total 17 days, and another dataset of 11 days without the outliers. Energy consumption (in kWh) showed a significant linear relationship with the total running time (in hours) and AC set point temperature (typically, in °C or simply set point number). The standardized regression coefficients (SRC) for these influential parameters are shown in Table 6. There is almost no difference in SRC between data with and without outliers. The *p*-values for both data are <0.05. However, the R-squared, and adjusted R-squared values are 0.845 and 0.806, and 0.649 and 0.651 for data with and without outliers, respectively, which implies the difference in the predictive capability of the model with and without outliers, respectively.

Figure 9 shows the relationship between the two influential parameters on a scatterplot for all values of daily energy consumption (including the outliers). The energy consumption increases with total running time and decreases with AC set point temperature. A residual analysis was conducted to further determine the significance of the results from linear regression, which are provided in Appendix B.

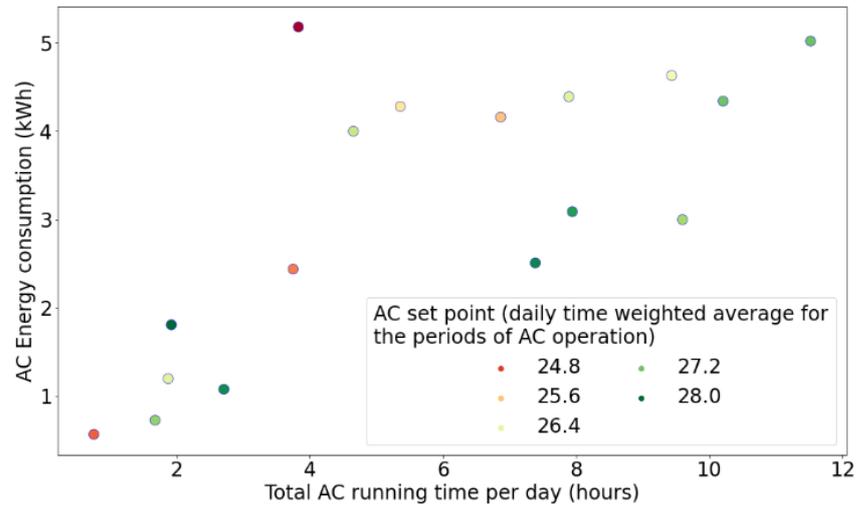**Table 6.** SRC and *p*-values of linear relationship between AC energy consumption and total running time of the air conditioner and periodic average of AC set point temperature.

Influential Parameter	SRC with Outliers	SRC without Outliers
Total running time of air conditioner	0.8655	0.8321
AC set point temperature	−0.4027	−0.4265

Figure 9. Relationship between AC energy consumption and total running time of the air conditioner and periodic average of AC set point temperature.

3.2. Field Study 2a: Effect of Elevated Air Speed through the Use of Ceiling Fans on Indoor Operative Temperature

Figure 10 shows the indoor operative temperature at AC set point temperature 24 °C at various fan speeds and the mean operative temperature for each fan speed. Compared with the operative temperature at fan speed one, the operative temperature increased by up to a maximum of 2.33 °C at fan speed four.
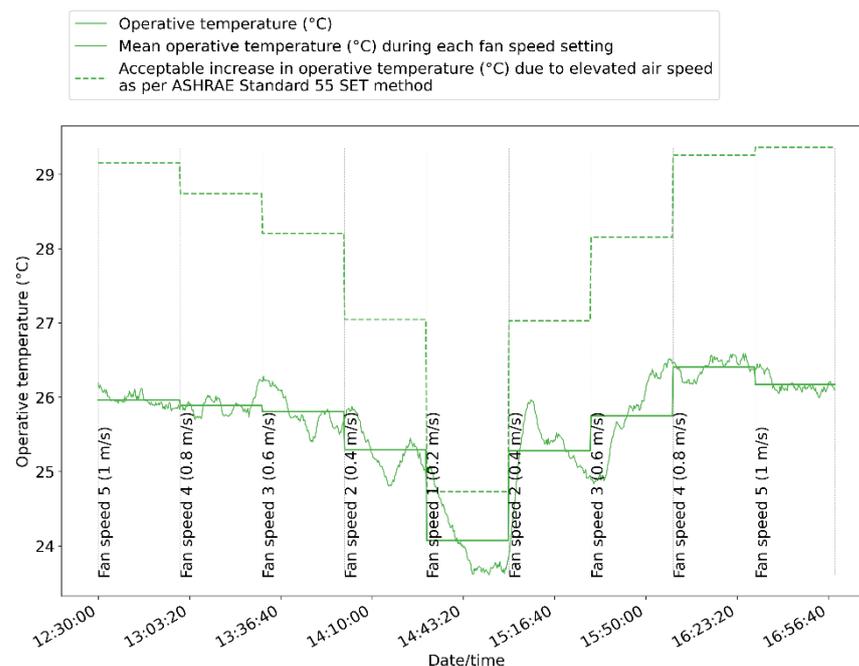
Figure 10. Indoor operative temperature and fan speeds during the experiment.

The cooling effect (ΔT_o) and rise in operative temperature because of elevated air speed at various fan speeds compared to the operative temperature at fans speed two are shown in Figure 11 (left). The cooling effect from elevated air speed was derived theoretically using the SET method. The fan speeds were not measured and are assumed conservatively (on the higher side) at the height of a working plane (900–1200 mm) based on the values in the literature [27,74–76]. When the fan speed was increased from one to two, the cooling effect predicted that the operative temperature can be increased by 1.09 °C to 1.75 °C to retain a similar thermal sensation that can be felt at the operative temperature at fan speed one. However, an increase in the fan speed from one to two increased the operative temperature and thereby reduced the predicted benefit of the cooling effect by 1.2 °C. Although the cooling effect reduction was higher when the fan speed increases from one to five than it decreases from five to one, cumulatively, the effect is still substantial as at least 60% of the benefits of the cooling effect are reduced due to rise in operative temperature (see Figure 11 (right)).
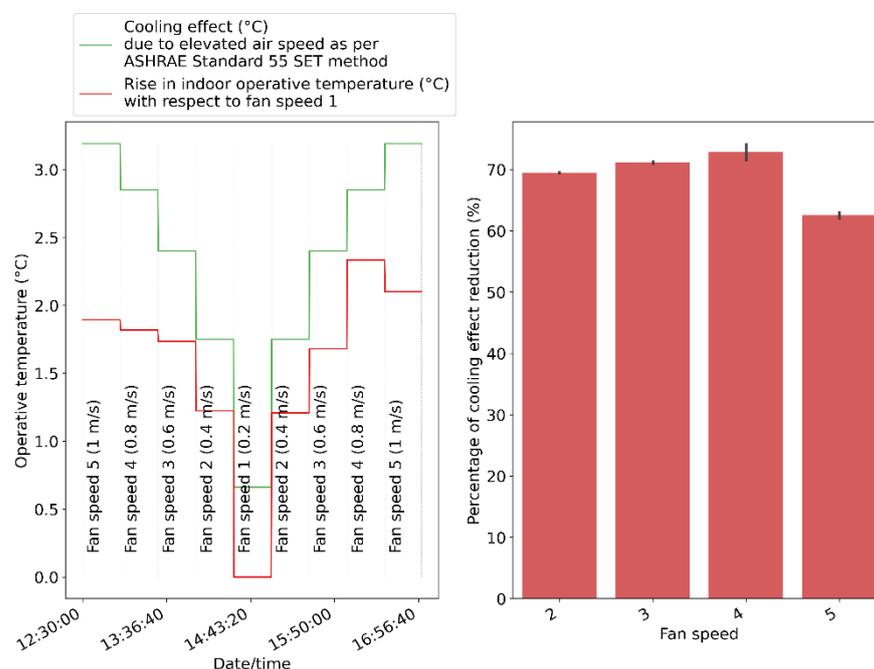
Figure 11. Cooling effect and rise in indoor operative temperature due to elevated air speed (**left**); percentage of negated cooling effect due to rise in indoor operative temperature (**right**).

3.3. Field Study 2b: Effect of Elevated Air Speed through the Use of Ceiling Fan Operation on Indoor Operative Temperature

Figure 12 shows the indoor operative temperature and its mean at AC set point temperatures of 24 °C, 26 °C, and 28 °C and during natural ventilation and at various fan speeds (FS). In addition, the acceptable increase in operative temperature as predicted by the cooling effect at various air speeds as compared to the operative temperature at fan speed zero is shown. At all AC set point temperatures, the operative temperature increases with fan speed, although, the increase in operative temperature is higher at lower AC set point temperature. During natural ventilation, an increase in fan speed had a insignificant effect on operative temperature. Our analysis showed that intermittent occupancy did not have any significant impact on indoor operative temperature.
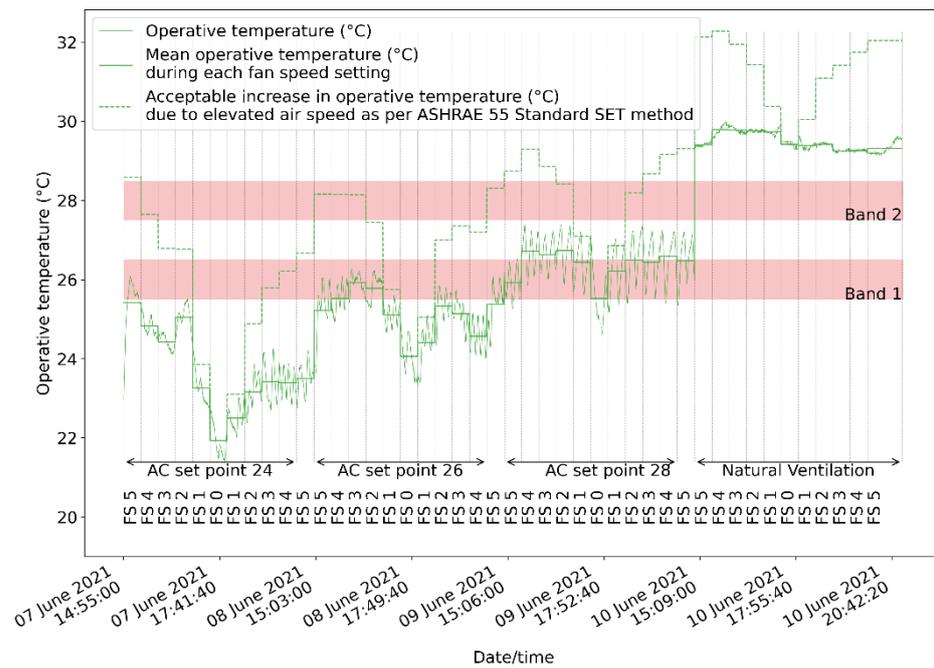
Figure 12. Indoor operative temperature, set point temperatures and fan speeds during the second experiment. Please see discussion for explanation of bands one and two. FS = Fan Speed.

Figure 13 shows the percentage of cooling effect reduction due to the rise in operative temperature during the second experiment. In general, the cooling effect reduction decreases with fan speed and AC set point temperature. For all AC set point temperatures, the cooling reduction effect is significant when the fan speed increases from zero to one and from one to two, i.e., from seemingly still conditions to slight air movement compared with the increase in subsequent fan speed steps.
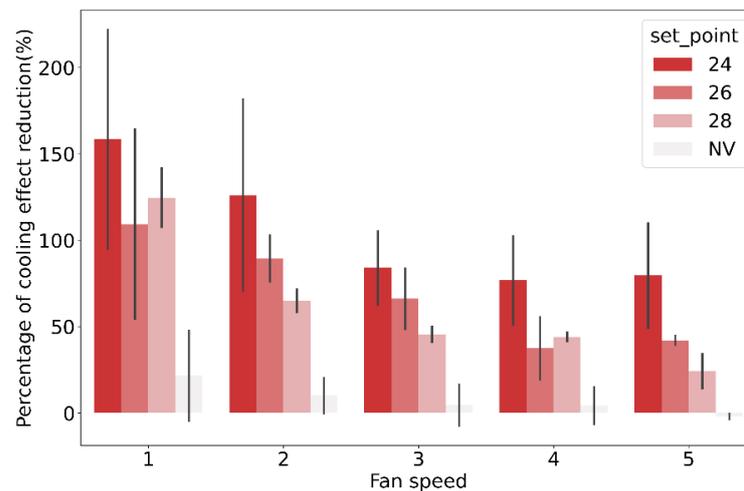
Figure 13. Percentage of negated cooling effect due to rise in indoor operative temperature (right).

4. Discussion

4.1. AC Usage Behaviour and Thermal Comfort Satisfaction

It appears that turning the AC on and off is significantly driven by air temperature and relative humidity. However, while both air temperature and relative humidity are significant parameters for turning on the AC, only air temperature appears to be a significant parameter for turning off the AC (see Figures 3 and 4). Furthermore, the AC usage behaviour in the field study suggests a clear need for the use of AC to achieve thermal comfort satisfaction and can be considered as energy-conscious behaviour. While the PMV-PPD

model predicts that the probability of the AC being turned on and off within the bounds of 90% people being satisfied is approximately 12% and 55%, respectively (see Figure 6, cumulative value of probability of PPD bins five and 10), the IMAC model predicts these values to be 20% and 89%, respectively (see Figure 8, cumulative value of probability of upper 85%–upper 90% and upper 90%–lower 90%). Although, the AC usage behaviour correlates with the PMV-PPD thermal comfort model, the PPD value is as high as 30% when the AC is turned off (usually, <20% is considered desirable). Considering that the AC is turned on when there was thermal discomfort and turned off when the thermal comfort satisfaction was met, the thermal comfort predictability of the IMAC model is higher than the PMV-PPD model.

4.2. AC Usage Behaviour and Energy Consumption

As the total running time of AC increases the energy consumption, the results were further analysed to find the parameters that influence the total running time of AC, such as indoor and outdoor temperatures. However, there were no clear patterns or significant correlations found. Reasonably, a key aspect that determines the total running time is turning off the AC, which has a strong correlation with indoor air temperature. The drop in air temperature, for each cycle of turning the AC on and off, increases with the running time (at least up to first four hours; see Figure 4) and consequently, the running time increases the AC energy consumption.

Figure 14 shows the empirical cumulative distributive function of drop in air temperature between each on and off cycle. The probability of drop in air temperature of at least $-3\,^\circ$C is 79%, and the percentage of hours the air conditioner runs to achieve a temperature drop of at least $-3\,^\circ$C is 67.5%. This indicates that there is a 79% probability that comfort conditions can be maintained by achieving a temperature drop of 3K. If this drop can be achieved, as much as possible, through passive measures (e.g., improved shading, thermal insulation, etc.), the running time of the air conditioner can be reduced by 67.5%, and consequently at least 58.4% of AC energy can be saved at a constant set point temperature based on the SRC value of 0.8655 for the relation between running time and energy consumption (see Table 6). Similarly, even a 1K drop in temperature could reduce the running time by 32.2% and energy consumption by at least 27.8%. As the occupants have a clear preference for air speed during the operation of the air conditioner, additional energy savings due to elevated air speeds are not possible. Similarly, there is a 70% probability that comfort conditions can be maintained by achieving a relative humidity drop of 15% with a running time of 70.9%. However, as a drop in air temperature is more significant than relative humidity for turning off the air conditioner, reducing relative humidity may not significantly impact the AC running duration.
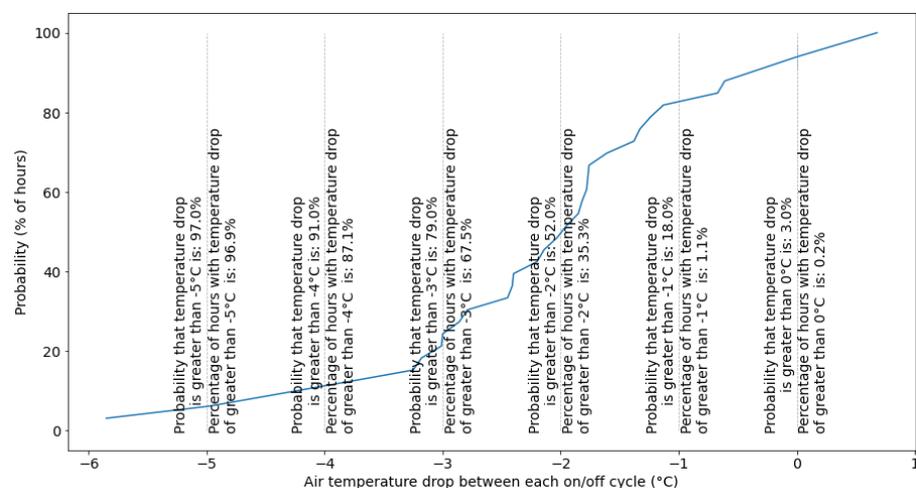

Figure 14. ECDF of air temperature drop between each on/off cycle.

4.3. Optimum AC Set Point Temperature and Air Velocity for Energy Conservation While Maintaining Thermal Comfort

In Figure 10, from field study 2a, a similar thermal comfort sensation can be felt at an operative temperature of 24.6 °C and at fan speed one, and at an operative temperature of 27 °C and at fan speed two (due to cooling effect). Although ceiling fan energy consumption increases with its speed, the net energy consumption of both the AC and ceiling fan is, presumably, lesser in the latter conditions, because, typically, cooling energy saving due to increase in the AC set point by approximately 2 °C, to achieve an operative temperature of 27 °C, is higher than the additional energy consumption of the ceiling fan by increasing its speed by one step (to fan speed two). Although it appears that elevated air speed results in energy savings, despite the cooling effect reduction, further questions arise:

- Is the operative temperature of 27 °C maintained at an AC set point temperature of 27 °C and fan speed 2?
- What would be the profile of the cooling effect and cooling effect reduction at various AC set point temperatures and air speeds?
- What would be, and how do we choose, an optimum combination of AC set point temperature and fan speed to optimize energy savings due to elevated air speeds?

These questions can be answered with the results of field study 2b, which was conducted to observe the effects of elevated air speeds on indoor operative temperature at three different AC set point temperatures, 24 °C, 26 °C, and 28 °C, and in addition, during natural ventilation (see Figure 12). The band at operative temperature 26 ± 0.5 °C (band 1) can be taken as an example, say, as the desired temperature band that can be achieved because of elevated air speed relative to the operative temperature at AC set point temperature of 24 °C and fan speed zero. Theoretically, at an AC set point temperature of 24 °C and fan speed zero, the operative temperature in the range in band 1 can be achieved by increasing the fan speed to three or four. Logically, as a consequence, the AC set point temperature can be increased to 26 °C and fan speed to three or four to maintain the conditions in band 1. In agreement with this, the results show that band 1 can be achieved at AC set point temperature to 26 °C and at fan speeds to 2, 3 and 4. However, band 1 can also be achieved more energy efficiently at an AC set point temperature of 28 °C and at fan speeds 0, 1, 2, and possibly 3. Moreover, when the operative temperature is within the desired temperature band, it is efficient to maintain the fan speed at zero or at lowest possible fan speed, if a certain air speed is desired. Similarly, to maintain a desired temperature band of 28 ± 0.5 °C, say band 2, from a base AC set point temperature of 26 °C, theoretically, the AC set point temperature and fan speed can be at 28 °C and five. However, practically, there is a clear opportunity to increase the AC set point temperature beyond 28 °C, which will be more energy efficient.

In general, in air-conditioned environment, beyond 26 °C, thermal comfort satisfaction is a complex phenomenon influenced by a combination of air temperature, relative humidity and air velocity [27,28,31], although the acceptance of a high temperature may be higher at high air speeds [77]. Alternatively, as seen from field study 1, occupants may have a preferred air speed setting while using the air conditioner, which is mostly one in this case. In addition, beyond an operative temperature of 30 °C, thermal comfort studies in naturally ventilated buildings indicate that preference for air speed usually plateaus at about 0.6 m/s [40] or a preference for air velocity of up to 1 m/s was noticed [78]. Furthermore, this allowable increase in AC set point temperature is, however, case specific, and depends on multiple factors that affect heat load in the space. In addition, when there is a high cooling effect reduction, increasing the fan speed with or without increasing the AC set point temperature can be counterproductive.

In mixed-mode buildings, the expectation of energy savings and thermal comfort satisfaction due to elevated air speed through the use of ceiling fans could be case specific and could present an unfulfilled potential if a SET model is used to determine the allowable increase in operative temperature for a corresponding increase in air velocity. Therefore, in mixed-mode buildings, during air-conditioned periods, it is recommended to set the AC

set point to maintain the desired temperature band and set the ceiling fan to the minimum speed setting, at least until the operative temperature of 28 °C is reached. This is especially true for buildings that are prone to having high internal surface temperatures, e.g., in buildings without thermal insulation.

4.4. Limitations of the Study and Perspectives for Future Work

A key limitation of the study is the limited number of field studies. In field studies 2a and 2b, the actual energy consumption of the AC and fan at various AC set point temperatures and fan speed settings was not measured. In addition, the actual indoor air velocity was not measured in all field studies. However, this study is supported by reasonable assumptions, sufficient statistical analyses and discussion to illustrate the often overlooked and less studied aspects of AC usage behaviour and elevated air speed for thermal comfort. Moreover, the cheap cost of setting up the experiment and expanding its scope to include other observations, such as collecting energy consumption data in better time resolution, e.g., through the use of cost-effective energy metering modules [79] and measuring supply and condenser air temperature of the air conditioner, can provide further significant insights into real-world AC energy consumption. The results of this study could be applicable to office buildings of similar size and construction.

Although the thermal comfort models show strong correlation with turning the AC on and off, they usually require precise measurements of air and globe temperatures and air velocity. However, challenges in taking accurate measurements can be overcome, for example, through machine learning techniques that are able to learn patterns for control, instead of relying on accurate measurements. Such data could be used to train machine learning models that can automatically control the air conditioner to maximize comfort and reduce energy consumption. They can further help in the predictive maintenance of ACs by using automatic fault detection and diagnostics management. For example, as bedroom AC is typically operated during night-time, and for longer durations, users may not be inclined to turn off the AC until they feel cold. Although most modern ACs are equipped with a timer function to automatically turn on/off the AC, the on/off function could be linked to influential parameters such as indoor air temperature and relative humidity to enhance thermal comfort and reduce energy wastage. Moreover, users can be provided with real-time feedback on energy consumption that motivates them to use AC judiciously and at high set point temperature. For example, in the present study, the automatic control of the AC can be accomplished by the addition of an IR LED to the IR module and providing it with a control logic [80]. Furthermore, such devices can be easily integrated into homes, thus making them smart homes, and help smart grids to improve demand-side management, such as the Dispatchable Air-Conditioning Pilot Project (DAC) project in Auroville, India [81,82].

5. Conclusions

This study shows the significance of two critical parameters that influence the energy consumption of air conditioners, i.e., the AC set point temperature and running time, which is substantiated by a field study. In the current study, an indoor air temperature drop of 1–3 K, if achieved by passive means, resulted in significant energy savings with regard to space cooling. This range of temperature decreases is easy to achieve through passive means, such as improved shading, adding thermal insulation, improving the solar reflective index of walls and roof, and through optimum ventilation (e.g., night-time ventilation). Furthermore, we attempted to identify the phenomenon of cooling effect reduction due to the use of ceiling fans in mixed-mode buildings. The results indicate that it is energy efficient to use ACs at a high set point temperature and use ceiling fans at the lowest possible speed setting, especially at indoor operative temperatures of less than 28 °C, approximately. Although this study identifies the existence and potential for 'cooling effect reduction', further studies are required to reliably confirm this phenomenon. Especially, cooling effect reduction should be looked at holistically by considering its impact

on space cooling energy consumption and thermal comfort satisfaction in various building typologies and construction types, e.g., in residential and office buildings; building with and without thermal insulation; and buildings with varying number of external surfaces.

Nomenclature

Item	Description	Unit
Clo	Clothing thermal insulation	clo
$h_{c\,i}$	Internal Surface heat transfer coefficient	W/m^{2}K
Met	Metabolic rate (metabolic equivalent of task)	met
Q	Convective heat flux	W
rh	Relative humidity	%
T_a	Air temperature	°C
T_{mrt}	Mean radiant temperature	°C
T_o	Operative temperature	°C
T_{o_max}	Maximum operative temperature	°C
$\dot{T}_{o\_max}$	Adjusted maximum operative temperature	°C
T_n	Neutral temperature	°C
$T_{sur\,i}$	Surface temperature	°C
ΔT_o	Increase in operative temperature	°C
v	Air velocity	m/s
W	Adjusted (heat transfer) coefficient	-
$\varepsilon_{90/85/80}$	Thermal comfort bands of acceptability for adaptive thermal comfort models	°C

Appendix A. Results of the Rapid Assessment Testing of the Comfort Module Prototype

For assessment, the readings from the comfort module prototype were compared with an accurate reference instrument, ALMEMO. The measurements from the prototype and ALMEMO were taken by placing them side by side for approximately three hours in a centrally heated open hall (Figure 2). For brief durations, a variety of ambient temperature and humidity, and air velocity (AV) conditions were maintained by opening and shutting the external shutters of the hall, and by using a pedestal fan. Table 2 describes the ambient conditions maintained during the comparison procedure. The following sub-sections

discuss the results of the testing process for ait temperature, relative humidity, globe temperature and infrared thermography.

Appendix A.1. Air Temperature

The graph and boxplot below show the measurements of air temperature and difference in air temperature between both devices, respectively (Figures A1 and A2). During the steady-state conditions, when the rate of change of temperature is less than 0.2 K/min, the mean difference between air temperature measurements from both devices is 0.09 K. The difference increases during dynamic conditions (0.2–0.6 K/min) caused by the opening and closing of the external shutters, with mean and maximum differences of 0.2 K and 0.37 K, respectively. The difference is also lower when the aluminium foil covers the base, and when the air velocity is higher. During the entire period of the testing procedure, the mean difference was 0.07 K, and the error (difference) between the measurements was systematic, suggesting that the measurements of the prototype are reliable.
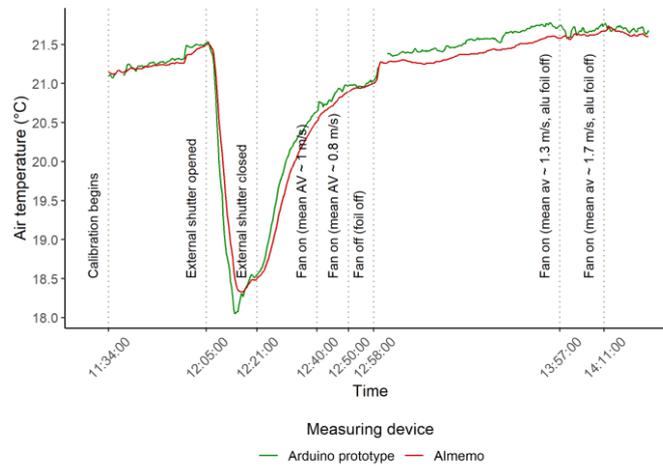

Figure A1. Air temperature recorded by the Arduino prototype and Almemo instrument during various ambient conditions.
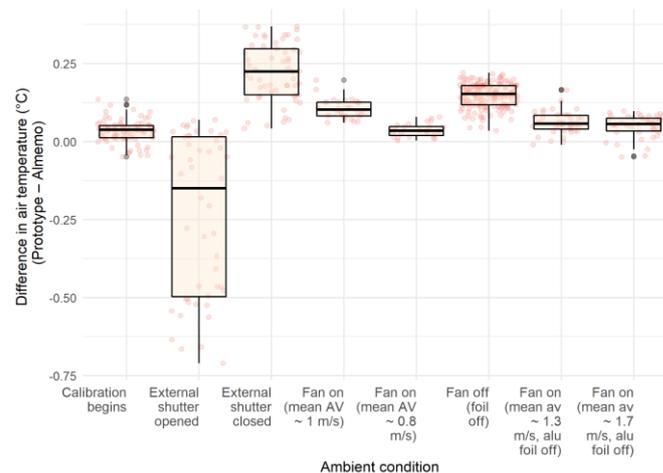

Figure A2. Difference in air temperature recorded by the Arduino prototype and Almemo instrument during various ambient conditions.

Appendix A.2. Relative Humidity

The graph and boxplot below show the measurement of relative humidity and difference in relative humidity between both devices, respectively (Figures A3 and A4). The difference in relative humidity measurement by both devices increased during the dynamic

period when the external shutters were opened and closed. However, the mean relative humidity values during the dynamic and steady-state conditions are close to each other, at 4.14 and 4.11, respectively, and the error (difference) is systematic. The aluminium foil at the base of the prototype and the change in air velocity did not have an impact on the measurements of relative humidity.
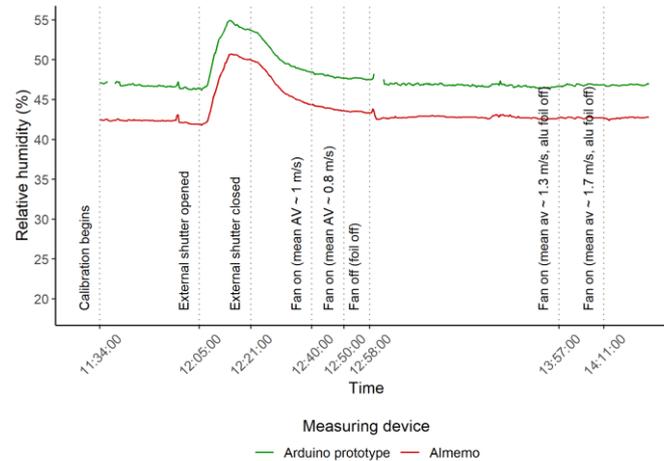

Figure A3. Relative humidity recorded by the Arduino prototype and Almemo instrument during various ambient conditions.
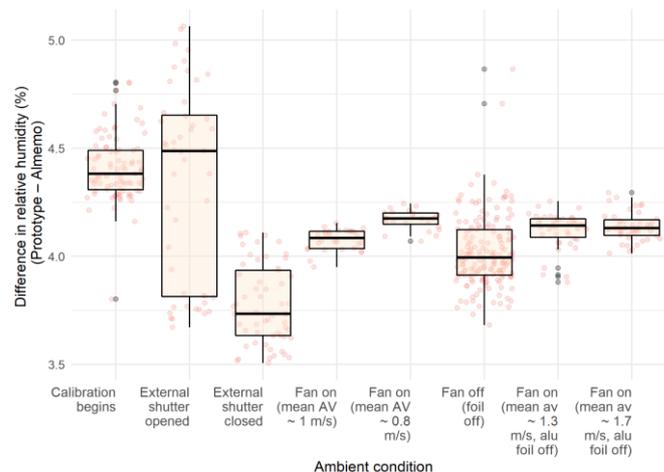

Figure A4. Difference in relative humidity recorded by the Arduino prototype and Almemo instrument during various ambient conditions.

Appendix A.3. Globe Temperature/Mean Radiant Temperature (MRT)

The graph and boxplot below show the measurement of globe temperature and difference in globe temperature between both devices, respectively (Figures A5 and A6). MRT was calculated using the globe temperature in accordance with ISO 7726:1998 using the python package pythermalcomfort. The difference in the measurement of globe temperature is almost twice that of the MRT. Similar to air temperature, the difference in measurements between both devices increases during dynamic periods. As the rate of change of MRT increased from 0.01 K/min to 0.3 K/min, the difference increased from approximately 0.5 K to 1.4 K. Although insignificant, this difference was lower when the aluminium foil was removed from the base and when the air velocity was increased. During the entire measurement period, and during the dynamic periods, the mean MRT differences were very close to each other, at 0.58 K, and 0.55 K., respectively, and the error (difference) between the measurements was systematic, suggesting that the measurements from the prototype are reliable.
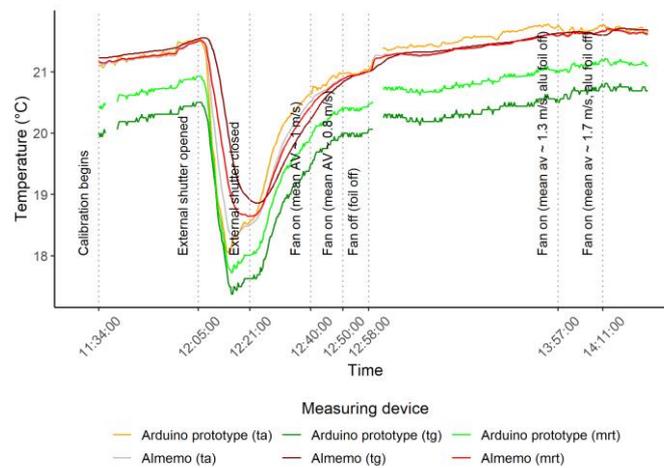
Figure A5. Air (ta), globe (tg) and mean radiant temperature (mrt) recorded by the Arduino prototype and Almemo instrument during various ambient conditions.
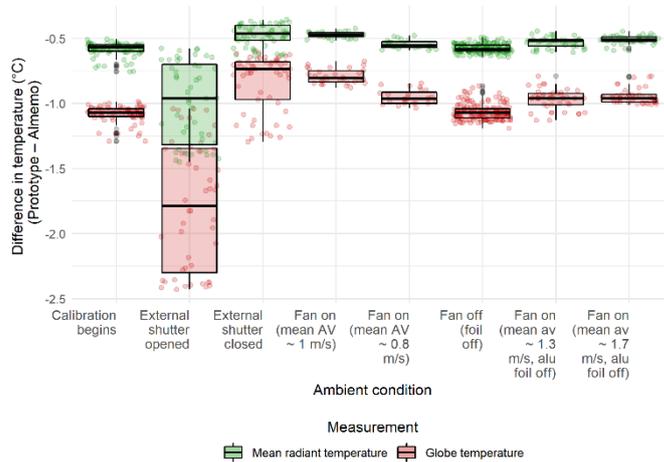

Figure A6. Difference in globe (tg) and mean radiant temperature (mrt) recorded by the Arduino prototype and Almemo instrument during various ambient conditions.

Appendix A.4. Infrared Thermography

Infrared images show the surface temperatures of both devices (Figure A7). Overall, the images show that the influence of localized heating due to the heat emitted from the micro-controller is negligible when the base of the prototype is covered with aluminium foil and when it is removed. For example, during the ambient condition 'external gate opened' and when the base was covered, the difference between the surface temperatures of globes of both instruments was 0.7 K. When the cover was removed and the surrounding air velocity was increased, the board appeared to have considerably cooled down, almost to the level of surface temperatures of the spheres. The difference in the surface temperatures of the spheres is 0.2 K.
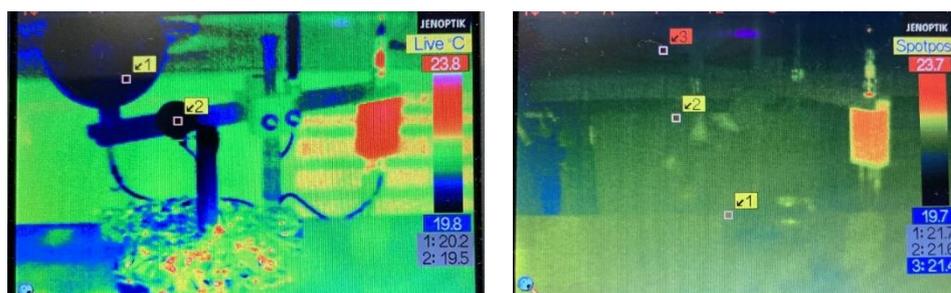
Figure A7. Infrared images of both devices during ambient condition 'external gate opened' (**left**) and 'fan on' (**right**).

Appendix B. Residual Analysis of Linear Relationship between AC Energy Consumption and Total Running Time of the Air Conditioner and Periodic Average of AC Set Point Temperature

A residual analysis was conducted to further determine the significance of the linear relationship between AC energy consumption and the total running time of the air conditioner and periodic average of the AC set point temperature (see section Energy consumption of the air conditioner) (Figure A8). The residuals from the linear regression show a normal distribution (a), and the residuals are randomly distributed around zero against the fitted values (b). This suggests that the linear model satisfactorily explains the relationship.
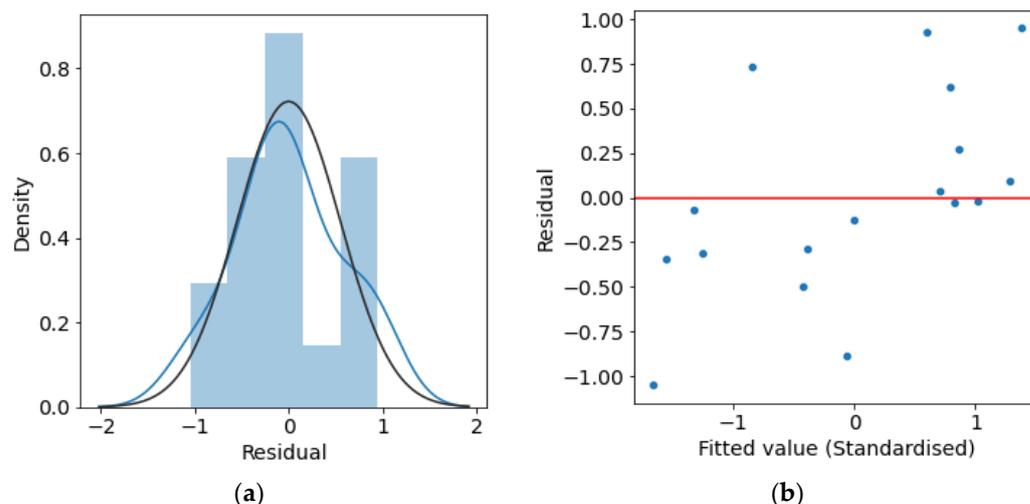

(**a**)

(**b**)

Figure A8. Residual analysis of linear relationship between AC energy consumption and total running time of the air conditioner and periodic average of AC set point temperature: (**a**) residuals showing normal distribution; (**b**) residuals randomly distributed around zero against the fitted values.

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