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Classification of Thermal Comfort in Heterogeneous Space from a PMV Model Perspective

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Global warming is accelerating the need for air conditioner units in households, leading to an endless increase in the environmental burden. To mitigate this negative effect, the combined usage of sensors and air conditioner units is researched to assess the effectiveness in ensuring thermal comfort across a space. However, with comfortability being a complex index and the current sensors operating under the assumption of empty space, their application to real-life situations is left impractical. To bridge this gap in research, this paper examines the thermal environment of a heterogeneous space using the Predicted Mean Vote model. A mathematical sensitivity analysis was performed to identify the key parameters where air velocity showed the most significant influence, with the potential to fluctuate the PMV score by - 5 to - 40. Focusing on flow velocity, Particle Image Velocimetry was conducted using water as the medium, resulting in the space being divided into four zones. Through the ranking of each zone according to its influence on the PMV score, zones that are prone to fluctuations in thermal comfort are identified. Through the addition of sensors in these zones, the adjustment of the AC's output can be facilitated to promote thermal comfort.

1. Introduction

In Japan, Air Conditioner (AC) is the third top household electronic that consumes 27.5 % of the total electric energy (Ministry of Economy Trade and Industry, 2022). AC's energy consumption is further expected to rise due to the combined effect of global climate change and the rise in living standards (Mordor Intelligence, 2021). To compensate for the thermal discomfort caused by climate change, new buyers enter the market, and the existing users feel compelled to add another unit to their households. With the foreseen increase in AC usage for thermal comfort, the rise in electricity demand, emission rate, and the strain on power grids is anticipated (Climate Central, 2020).

To prevent the over-burdening of the environment, many AC industries focused on obtaining thermal comfort with the addition of sensors near the duct to prevent the AC from over-running (Matsuda, 2013). However, the current implementation of a sensor has two major limitations. The first is the possibility of the blown-out air being directly consumed by the duct, causing a short circuit. In the event of a short circuit, premature thermal shutdown occurs when the AC stops operating before the room reaches the set temperature (Ito et al., 2019). The second limitation arises from the height difference between the sensors and the users. With limited human activities being expected near the ceiling, the temperature detected at the duct differs from what the users sense (Nelson and Ali Duze, 2022).

With both limitations preventing the sensors from representing the room's thermal environment, the AC is incapable of controlling its output in a way that will reflect the demand of the users. The energy consumed during the time in which the AC ineffectively conditions the air is useless. To combat these challenges of energy conservation and thermal comfort, researchers explored the possibility of allocating the sensors to the users themselves. Studies include monitoring the room performance through the direct assessment of human thermal physiology as a real-time feedback index (Yang et al., 2020). However, human physiological parameters are

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not suitable for an AC system to control because of its inherent subjectivity. Consequently, research on sensors that monitor environmental parameters, such as temperature and relative humidity, has been pursued (Valinejadshoubi et al., 2021).

Despite these endeavors, the sensor's ability to represent the thermal comfort level across the room is still limited due to the complex nature of comfort. First, as comfort is a measure of “the condition of mind that expresses satisfaction” (Fanger, 1986), the presence of subjectivity of the user persists. This abstract concept of comfort has been numerically translated to a mathematical model of Predicted Mean Vote (PMV), which merges the principles of heat balance and the experimental survey data that rates the comfortability of numerous room conditions. The PMV model quantifies comfort through the combination of 4 environmental parameters of room temperature (t_r), the mean radiant temperature (t_a), relative humidity (p_a), air velocity (v_{ar}), and 2 personal variables of metabolism (M) and clothing (f_{cl}). The integration of the model into the AC unit allows the AC to align its output with what is considered acceptable by the ISO standards (Fanger, 1986). The second issue of measuring comfort is in the current methodologies. Sensor-AC units are primarily being investigated in an empty space, which lacks in reproducibility when applied in real-life situations (Ueno et al., 2021).

Considering the current limitations, this paper uses the PMV model to empirically explore the possibility of the tandem use of sensors and AC in a non-empty room to promote thermal comfort. Through a mathematical sensitivity analysis, the key environmental parameters are identified, where human-activity-based parameters are omitted to strictly keep the focus on AC-controllable factors. Taking the focal parameters, the spread of thermal comfort across an asymmetric model room is examined over time. By tracing the change in the parameters across the space, zones that show proneness to PMV score degradation are determined. By locating the zones that require improvements in terms of thermal comfort, the allocation of a sensor that can lead to an optimum operation of an AC is deduced.

2. PMV sensitivity analysis

To narrow down the focus of thermal comfort to strictly AC operation, sensitivity analysis is carried out on the environmental parameters within the PMV model (Fanger, 1986). Taking the partial derivative of the model's equation shown in Eq.(1), each parameter's level of influence on thermal comfort is ranked. The environmental parameters are room temperature (t_r), the mean radiant temperature (t_a), relative humidity (p_a), and air velocity (v_{ar}) which is incorporated in the convective heat transfer coefficient shown in Eq.(2). The mean radiant temperature is often regarded as the same as the room temperature to amend the uncontrollable nature of the parameter (Humphreys et al., 2007). The partial derivative of the three environmental parameters was taken under the setting of office work during summertime, where metabolism is set to be 60 W/m^2, clothing insulation at 0.57clo which is equivalent to a short-sleeved shirt paired with trousers, and clothing surface temperature at 27.3 °C. Additionally, the accepted range of the parameters from ISO7730 standard was assessed, which are 10 to 30 °C for room temperature, 0 to 1 meters-per-second for air velocity and 0 to 2,700 Pa for relative humidity.

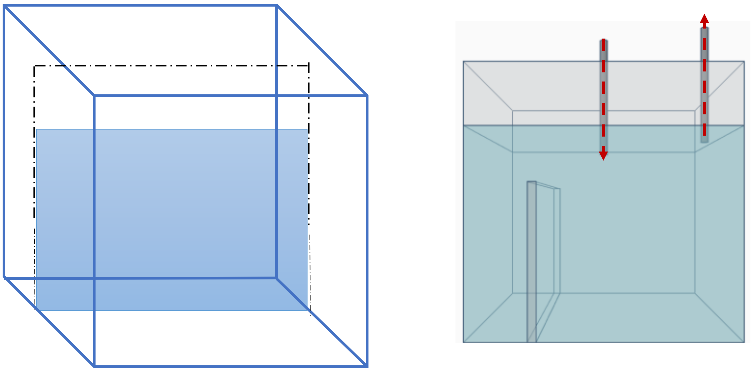
$$\begin{aligned}\mathrm{PMV} = {} & (0.303e^{-0.0336M} + 0.028)\\ & \times [(M - W) - 3.5 \times 10^{-3}\{5733 - 6.99(M - W) - p_a\} - 0.42(M - 58.5)\\ & - 1.7 \times 10^{-5}M(5867 - p_a) - 0.0014M(34 - t_a)\\ & - 3.96 \times 10^{-8} f_{cl}\{4(t_{cl} + 273) - 4(t_r + 273)\} - f_{cl} \times h_c(t_{cl} - t_a)]\end{aligned} \tag{1}$$

$$h_c = 12.1\sqrt{v_{ar}} \quad for\ 2.38|t_{cl} - t_a|^{0.25} < 12.1\sqrt{v_{ar}} \tag{2}$$

As a result, the level of influence is in the increasing order of relative humidity being the lowest with a constant sensitivity of 0.00023, room temperature with a sensitivity ranging from 0.5172 to 0.5177, and air velocity with sensitivity largely fluctuating from - 40 to - 5. According to the ISO7730 sta,ndard, PMV between - 0.50 to 0.50 is deemed acceptable with the percentage dissatisfied (PPD) being below 10 %. The key environmental parameters within the PMV model are room temperature and air velocity, where the parameters exhibit the potential of altering the room's thermal comfort from acceptable to unacceptable.

3. Experimental methodology

Considering the high availability of temperature sensors that can work in tandem with an AC, namely soft sensors that computationally monitor the temperature distribution of a space (Xu et al., 2022), the integration of the already established temperature sensor is prioritized in this paper. As a result, the spread of air velocity is analyzed in this paper where a Particle Image Velocimetry (PIV) experiment was conducted to visualize the flow pattern in the 2-dimensional region, as seen in Figure 1(a). Office space was emulated by an aquarium of width 184 mm, length 184 mm and height 194 mm, as seen in Figure 1(b).



(a) (b)

Figure 1: (a) Focal region of PIV Experiment; (b) the model room with a 90 mm partition

Additionally, 35 °C water was chosen to represent the room temperature, where water helps to extend the system's retention time when compared to the medium of air. The AC system is reproduced by inserting two nozzles from the top of the model room, where one is located at the center and supplies 10 °C water, while the other one is located adjacent to the tank wall and vacuums out excess water. Additionally, the room is manipulated into a heterogeneous space by inserting a 90 mm high partition at 1/3 position from the tank wall, as seen in Figure 1(b). The positioning of the partition allows the incoming cold water to directly mix on the right-hand side, while thermal mixing on the left is limited to when the cold water flows over the partition wall and enters the left-hand side. The asymmetry of the room induces uneven thermal environments, where the intentional spread of PMV value is traced.

4. Results of flow analysis

4.1 Overall space

The flow velocity is numerically analyzed through the combination of Particle Image Velocimetry (PIV) and FlowExpert (Katokoken, Version 1.3.3) software analysis. To start, the entire space is analyzed to see if there are any holistic patterns. As seen in Figure 2, regions that exhibit a steady flow of either above 20 mm/s or below 2 mm/s are seen. Specifically, regions below the supplied water, including the aquarium floor on the right and the bottom-right of the partition, constantly flow above the set maximum velocity of 20 mm/s, indicated in the color red. Contrarily, the top area on both sides of the supply nozzle, the bottom corners, and the top-right of the partition show a constant flow velocity of just above stationary level, shown in blue or absent vectors.

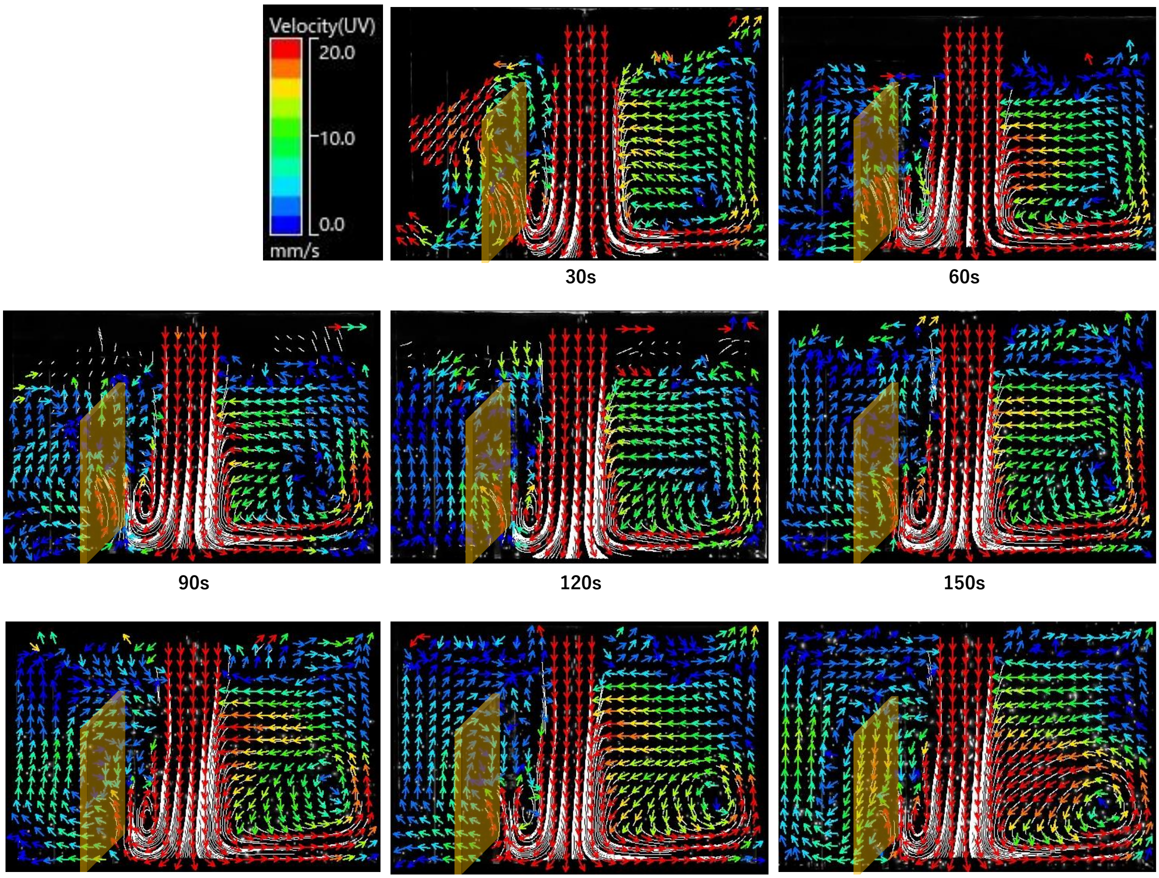
4.2 Right of the partition

After identifying the regions with constant flow velocity, the focal area is narrowed down by splitting the space at the partition. On the right side of the partition, an intermediate region emerges between the fast flow at the bottom and the slow region at the top. Simply analyzing the color change of the vectors in this region, according to Figure 2, a decrease in flow velocity is observed from the start to the 90 s timestamp, where the number of blue vectors increases. However, from the 90 s threshold time, the direction of change reverses, where the vector color gradually changes from green to red, indicating the doubling of flow velocity from 10 to 20 mm/s.

4.3 Left of the partition

When the left-hand side of the partition is observed, a similar shift in the change of velocity is seen on the right, where the threshold time is postponed to 120 s. The difference exists in the magnitude of change, where the left side experiences a greater decrease in flow velocity while the right side experiences a greater increase in velocity. In terms of vector colors, the left side changes from red to blue during the decreasing period while it is green to blue on the right. On the contrary, during the accelerating period, the right side has more red vectors being detected in the final 300 s timestamp when compared to the left side, which primarily consists of green vectors.

Overall, from the flow velocity perspective, the aquarium as a whole demonstrates 2 traits. The first trait simply exhibits consistency in the flow velocity, while the other exhibits a time-dependent trait where it reverses its course of velocity change at a specific time. Notably, the threshold time is faster for the right-hand side.



30s 60s

90s 120s 150s

180s 210s 300s

Figure 2: Time-lapse of the flow with vector colors representing the velocity. The partition wall is shown in orange, where some vectors are reflected due to the wall being an acrylic board

5. Discussion

Returning to the main focus of thermal comfort in the modeled space, human activities are assumed to take place in the order of middle, bottom and top layers. This variance in occupancy leads to a range of zones that experience a change in the PMV score caused by the shift in flow velocity, and zones that do not experience such changes. With the concept of occupancy being added to the discussion, the model space is segmented into 4 zones that demonstrate different levels of influence on the PMV score.

5.1 Insignificant zone ①

First, the zone with no relevancy in the PMV scoring exists symmetrically on both sides of the partition, which includes areas near the ceiling and at the bottom corners, as seen in Figure 3. As this zone is assumed to be unoccupied by the users, the absence of high-speed flow acts to strengthen the efficiency of the system as the effort to cool down the space is mostly consumed in areas with human activities.

5.2 Changing zone ② and ③

In contrast to the above, Zone 2 and 3 are located in areas where human activities are expected. Both zones follow the flow pattern characterized by a decrease followed by an increase in flow velocity, which corresponds with the time-dependent areas in the flow analysis. Notably, near the aquarium wall on the right, a new vortex with a larger radius than the one near the partition can be observed. This emergence of a vortex is not reflected on the left side due to the slow overflow of water from the partition wall, which fails to initiate significant turbulence.

The difference between Zone 2 and 3 exists in the flow acceleration, where Zone 3 on the right undergoes a faster change compared to Zone 2. This difference influences how significant each zone is, because the PMV score calculation includes a threshold flow velocity, as seen in Eq.(2). With Zone 3 reaching a faster flow velocity than Zone 2, its influence on the PMV score is reflected earlier, resulting in a higher rank in significance. It is important to note that the ranking of the two zones is solely based on how fast it reaches the threshold velocity, and not its ability to reach the threshold velocity itself. There is the possibility of both zones becoming PMV significant, especially when the system has not yet reached a steady-state in terms of temperature.

5.3 Constant zone ④

The final zone consists of areas near the partition vortex and underneath the supply nozzle, where they show a constant fast flow velocity. Since this zone exhibits the potential to constantly be above the threshold flow velocity, it is ranked as the most significant area that affects the PMV score. Interestingly, relatively slow Zone 2 and the fastest Zone 4 merge like a jigsaw puzzle near the partition, with high-speed flow observed at the bottom half and low-speed flow observed at the top half. This coexistence is facilitated by the presence of a high-speed vortex beside the partition, which acts as a shear layer between the high-speed supply and the slow-moving fluids. As the same phenomenon is also seen in CFD simulated experiments assumed in air, the applicability of this research is proven even with the use of different mediums (Posner et al., 2003).

5.4 Adaption to the AC Unit

Considering the above segmentations, Zone 4 shows to be the most responsive in terms of PMV score, but an addition of a sensor in this zone will only detect the immediate output, which will lead to a similar outcome as a short circuit. Then, the focus is shifted to Zone 3, which is the second most responsive area with a continuous rapid change in the flow velocity. An addition of a flow sensor in this zone can alert and assist the AC system in adjusting its output to not disturb the PMV score. This will ultimately mitigate the sources of poor thermal comfort. Another method to decrease the fluctuation of flow velocity and minimize vortex formation is to change the angle at which the cold fluid is supplied into the space. In the case of an AC, this will be done by adjusting the fins away from the ground but towards the side. This forces the initial high-velocity flow to be confined at the top where human activity is not assumed (Otsuka, 2008). As the high-velocity flow encounters the closest obstacle, its velocity will decrease with the possibility of vortex formation, as seen in Zone 3 and 4. If the location of this emerging vortex can be adjusted to be above the average human height, a relatively slow and steady flow will travel down to the bottom half of the space.

Specifically, adjusting the incoming angle will shift the zones, where Zone 3 and 4 will be raised to the top while Zones 1 and 2 will dominate the bottom half. This redistribution of the zones allows the bottom half to experience reduced fluctuations in PMV scores, making the controlling of thermal comfort more manageable. Similarly, even in an asymmetrical space, aligning the direction of the fins with the location of the obstacles allows the approximation of the PMV score. This indicates that a homogeneous thermal environment can be achieved even in a heterogeneous space with the support of an AC system. While this proposition of confining the high-energy flow at the top may seem contradictory to the system's efficiency as mentioned earlier, it is the most convenient approach to approximate the PMV score to the optimum score of 0 without major changes to the room layout.

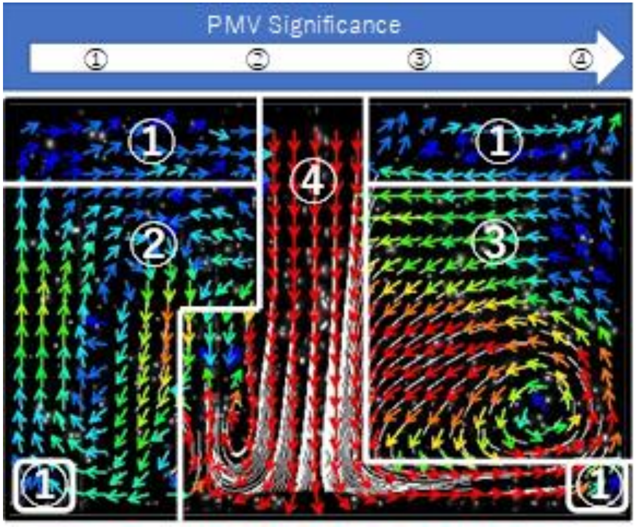


Figure 3: Segmentation of the room according to the PMV score significance

As the PMV model incorporates the value of air velocity, the paper's findings do not directly provide an exact PMV score. However, the mathematical and experimental analysis of this paper indicated that fluid velocity has a significant effect on the spread of PMV scores. Extrapolating this idea, analyzing flow velocity and local temperature in a real-life room with air will allow for the PMV score to be calculated, leading to the provision of thermal comfort across the space.

6. Conclusion

This paper explores the potential of promoting thermal comfort through the combined use of a sensor and an Air Conditioner (AC) unit through the lens of the Predicted Mean Vote (PMV) model. An asymmetrically partitioned space was evaluated based on the main environmental parameters within the PMV model, which were deduced by a mathematical sensitivity analysis. While both temperature and flow velocity were considered to be significant, only the latter parameter was taken into consideration due to the robustness of temperature sensors being implemented with the AC system. As a result of a flow analysis done by Particle Image Velocimetry, the space was segmented into four zones according to the persistent influence of flow on the PMV score. Through the ranking of the four zones, ways to make the PMV distribution independent of flow velocity are understood. This simplifies the control of thermal comfort from the perspective of a sensor-AC system, with temperature becoming the only variable affecting comfort.

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