Thermal Comfort: A Review on Methods of AC Control in a Small Indoor Space

I. I. Ibrahim[1,a], S.A. Abdul Shukor[1], K. Kohlhof[2]

[1]Faculty of Electrical Engineering Technology, University Malaysia Perlis, 02600 Perlis, Malaysia.
[2]Faculty of Information, Media and Electrical Engineering, Cologne University of Applied Sciences, 50679 Cologne, Germany.
[a]ismailishaq@unimap.edu.my

Abstract. This paper discusses the comparison of two methods to achieve thermal comfort utilising air conditioning (AC) system in a small indoor space – adaptive control and fuzzy control. Thermal comfort indoors is performed to provide comfortability individually or for a group of people. Due to the small indoor space which usually a bit cramped, crowded and less airy, the ambience can be very uncomfortable either for doing sedentary or active work, thus the AC system can be very useful to provide thermal comfort. Both methods can be utilised depending on how thermal comfort is viewed and how the level of thermal comfort is decided. Every method has its own advantage and limitations, and will be covered in this paper as well.

1. Introduction
The definition of thermal comfort in The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) is the state of mind that is satisfied with the thermal of environment [1][2]. Thermal comfort is very important especially indoors as occupants really want to live and spend their time comfortably within the space. There are a lot of parameters when defining thermal comfort. The most common parameters are air temperature [3], air velocity [4], radiant temperature and humidity [2]. Apart from these, others are also considering others such as weather forecast [5][6], energy consumption [7][8], air ventilation [9][10], space size [11], building materials [12][5] and many more. There are also parameters that are individual-based and more to establishing a personal or a meticulous thermal comfort. These parameters includes metabolic rates [13][14], zone temperature in a space [15], clothing insulation [16][10], and activity level [4].

All of these parameters can affect the thermal comfort of individual or a space indefinitely and every individual perception of thermal comfort differ from each other although they are technically in the same space [17]. With this information in mind, a more general approach in identifying the level of comfort needs to be established. Thus, Predicted Mean Vote (PMV), an index suggested by Fanger, and accompanying Predicted Percentage of Dissatisfied (PPD) were developed that aims to predict the mean value of votes of a group of occupants on a seven-point thermal sensation scale as in Table 1 [16].

Table 1. Thermal Sensation Scale [16].

Sensation	PMV	
	Sign	Value
Hot	Positive	3
Warm		2
Slightly Warm		1
Neutral		0
Slightly Cool	Negative	1
Cool		2
Cold		3

Linear relationships of mean skin temperature and evaporative heat loss required for comfort at different activity levels were the basis of Fanger's model [18]. Six variables were used in Fanger's model which is relative air velocity, humidity, air temperature, mean radiant temperature, activity level and insulation value of the clothing. Even though Fanger introduced the PMV, it is still common knowledge that there is no definite way to objectify the sensation of thermal environment. But it is well accepted that the Fanger's thermal sensation scale is the most widely used today and it is primarily used in ISO Standard 7730 (1994) [18].

Air-conditioning (AC) system is one of the tools that can be used to control the thermal comfort environment indoors [19]. The usage of AC nowadays increased significantly, especially in hot and humid countries [13]. Generally, the AC only takes into account the temperature of the environment instead of human thermal comfort. Furthermore, energy efficiency is only often considered in the design of the system [20].

In addition to that, it is common sense that there is different thermal preference for each and every person in an air-conditioning room [21]. Controlling the thermal comfort will save a lot of energy where the controller can consider the thermal comfort of the individual person or the group within the room and use the control model to maintain the thermal comfort without wasting more energy in maintaining the environment of the room. Thus, appropriate methods can be utilised to be integrated with the AC in providing a thermal comfort ambience, and the two-mostly used, which are adaptive control and fuzzy control, will be discussed here.

2. Thermal Comfort Methods

2.1. Adaptive Control
Adaptive control is an approach to deal with systems with uncertain and/or time-varying parameters [22]. It is a system that adapts to the parameters that occurs and changes the system according to the new parameters that the system received. This changes then will affect the outcome of the system. By using adaptive control on thermal comfort, for instance, in a flight cabin, the thermal environment can be simulated and the adaptive control system can be implemented. By taking into account the air pressure, weather forecast and humidity in the cabin, the system can calculate the thermal comfort of the cabin with regards to Table 1 [23]. This basically saying that if there is discomfort due to changes in certain parameter, people will react and try to restore their comfort [1].

By incorporating adaptive control into thermal comfort, all the feedback from the parameters can be fed back into the system. With this, the system can keep up with either the comfort temperature, humidity, or any other parameters that being evaluate, provided, the system's feedback loop is fast enough to make the changes needed. An example of adaptive control can be seen in Xu Wei [1].

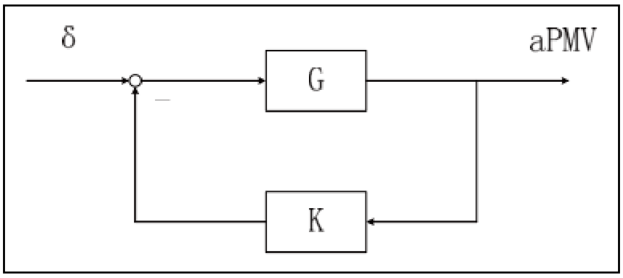

Figure 1. Xu Wei's Thermal Comfort Adaptive Model [1]

Thermal comfort adaptive model in Figure 1 shows the basic closed-loop control where aPMV is a group of people's thermal impression, including psychology and behavioural alterations [1]. δ is the physical stimuli, G is transfer function (human's thermoregulatory system and thermal sensation), K represents psychological and behavioural impact coefficient, where Equation (1) can be derived:

$$\text{aPMV} = G \times \delta - \text{aPMV} \times K \times G \quad (1)$$

In other words, aPMV could also be defined as in Equation (2):

$$\text{aPMV} = \frac{G \times \delta}{1 + K \times G} \quad (2)$$

The steady-state of the model can be shown as Figure 2.

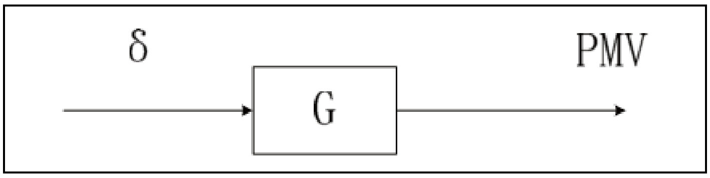

Figure 2. Steady-state model

The equation from Figure 2 can be shown as in Equation (3):

$$\text{PMV} = G \times \delta \quad (3)$$

By substituting Equation (3) into Equation (2), we get

$$\text{aPMV} = \frac{PMV}{1 + \lambda \times PMV} \quad (4)$$

From Equation (4), $\lambda = K / \delta$, where λ is the adaptive coefficient [1], and with the assumption of:

$$\delta = T_m - T_n \quad (5)$$

where T_m is the air temperature, and T_n is the thermal neutral temperature. It is defined that when T_m is higher than T_n, the environment is warm and when T_m is lower than T_n then it is cool condition.

When the condition is warm, Equation (4) illustrates that $T_m > T_n$, $\lambda = K / (T_m - T_n) > 0$, PMV is bigger than aPMV. In winter, $T_m < T_n$, $\lambda = K / (T_m - T_n) < 0$. If $\lambda = 0$, aPMV = PMV which means there is no adaptive actions and this is the same as PMV model in Figure 2.

Based on the proposed model, the system can adapt to the temperature, therefore saving energy [1].

2.2. Fuzzy Control

Fuzzy control is a controller that uses fuzzy-logic, i.e., a system that uses a series of rules to generate a result for each rule, then combine the results of the rules. This concept of the system usually would use the IF-THEN rules. Fuzzy logic normally incorporates parameters such as clothing insulations, activity level and air temperature in thermal comfort [4].

Example work utilising fuzzy control is in [24]. The most important task is implementing the model into the air-conditioning fuzzy controller:

$$\sum \in f\,(T_s \times H_s \times V_s \times T_{in} \times H_{in}) \tag{6}$$

where T_s = air-conditioning temperature setpoint, H_s = air-conditioning humidity setpoint, V_s = air-conditioning velocity setpoint, T_{in} = indoor temperature, H_{in} = indoor humidity. $\{T_s , H_s , V_s\}$ is the input set and $\{T_{in} , H_{in}\}$ is the output set.

A degree-based fuzzy sets need to be specified first for $\{T_s , H_s , V_s\}$ and $\{T_{in} , H_{in}\}$, where:

$$E_{T_s} = \{t_{s1} , t_{s2} , t_{s3}\} \; ; E_{H_s} = \{h_{s1} , h_{s2} , h_{s3}\} \; ;$$

$$E_{V_s} = \{v_{s1} , v_{s2} , v_{s3}\} \; ; E_{T_{in}} = \{t_{in1} , t_{in2} , t_{in3}\} \; ;$$

$$E_{H_{in}} = \{h_{in1} , h_{in2} , h_{in3}\} \tag{7}$$

Assuming that $\{T_s , H_s , V_s , T_{in} , H_{in}\}$ has a fuzzy relation among each other and known as $\sum$, or in other words, $\sum$ is a fuzzy on $T_s \times H_s \times V_s \times T_{in} \times H_{in}$, then there is the membership degree as:

$$\mu_{\sum}(t_{si}, h_{sj}, v_{sk}, t_{inp}, h_{inp}) = \gamma_{ijk}^{pq} ,$$
$$p = q = 1 , 2 , 3 \; ; i = j = k = 1 , 2 , 3 \tag{8}$$

By arranging $\{ \gamma_{ijk}^{pq} \}$ into a matrix:

$$M_{\sum} = \begin{pmatrix} r_{11}^{111} & r_{11}^{112} & r_{11}^{113} & \cdots & r_{11}^{331} & r_{11}^{332} & r_{11}^{333} \\ r_{12}^{111} & r_{12}^{112} & r_{12}^{113} & \cdots & r_{12}^{331} & r_{12}^{332} & r_{12}^{333} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ r_{33}^{111} & r_{33}^{112} & r_{33}^{113} & \cdots & r_{33}^{331} & r_{33}^{332} & r_{33}^{333} \end{pmatrix} \tag{9}$$

Equation (9) can be inversed to obtain the fuzzy relation between indoor thermal and the AC [24].

Given a set of $t_{in} \in T_{in}, h_{in} \in H_{in}$ that in dual structure, they are fuzzy sets. Their vector forms are $V_{t_{in}}, V_{h_{in}}$, thus, the corresponding controls t_s, h_s, v_s is produced by the fuzzy controller as:

$$v_{t_s} \triangleright v_{h_s} \triangleright v_{v_s} = M_{\Sigma}^{-1} \triangleright (V_{t_{in}} \triangleright V_{h_{in}}) \quad (10)$$

From the fuzzy mapping, the result can be turned back to control values. Joined Defuzzification (JD) is used [24].

$$(T_s, H_s, V_s) = \sum_{p=1}^{3} \sum_{q=1}^{3} \left(\frac{b_{ijk}}{\sum_{i=1}^{3} \cdots \sum_{k=1}^{3} b_{ijk}} \right) \overline{\mu}_{T_s \times H_s \times V_s}^{-1} (1) \quad (11)$$

3. Analysis

The adaptive control is much more direct than the fuzzy control as adaptive controller mostly takes into account the Fanger's thermal sensation scale for the decision making and this will make the thermal comfort data closer to practical application. Fuzzy control alone is quite good enough to make a good decision on thermal comfort but surely it is not enough to get an accurate picture on a real-time case. To get a more accurate result, two or more controller is needed to make sure that the data is accurate. Furthermore, the more the parameters is available for the input of the controller, the system can become much more accurate in regulating the temperature for thermal comfort of the given space or individual preferences. At the end, a hybrid method that incorporate both the adaptive and fuzzy control would be more feasible for a real-time practical usage in determining the thermal comfort in a space or a specific individual preference of comfort.

Fuzzy control can give a more comfortable thermal conditions and can save energy by 18% [20]. Fuzzy control also gives better comfort at a lower cost [4]. Adaptive control can control the temperature at a specified values [23] which in turns, can make achieving optimum thermal comfort faster and more accurate. Between these two methods, the best in terms of cost efficiency may be fuzzy control but in term of how fast a person would like to achieve thermal comfort, adaptive control might be the best choice.

4. Conclusion

This paper presents a review on two methods that are utilised in creating thermal comfort utilising AC in a small indoor space – adaptive control and fuzzy control. There are also other methods that can be found in the literature but these two methods are the most widely used. Combining adaptive control and fuzzy control will make the system performs better rather than when a single controller is used. The downside of using multiple controllers is when one of the parameters is falsely obtained, the whole system might give a wrong result with a high probability of damaging the thermal comfort status. To eliminate this problem, an extensive research is needed to obtain the correct data and to rectify any problems that arise in the controller model.

5. References

[1] W. Xu, X. Chen, and J. Zhao, "An adaptive predicted mean vote (aPMV) model in office," *2010 Int. Conf. Mech. Autom. Control Eng. MACE2010*, no. 20070542009, pp. 1887–1891, 2010.

[2] N. Djongyang, R. Tchinda, and D. Njomo, "Thermal comfort: A review paper," *Renew. Sustain. Energy Rev.*, vol. 14, no. 9, pp. 2626–2640, 2010.

[3] B. Walek, J. Žáček, M. Janošek, and R. Farana, "Adaptive fuzzy control of thermal comfort in smart houses," *Proc. 2014 15th Int. Carpathian Control Conf. ICCC 2014*, pp. 675–678, 2014.
[4] M. Hamdi and G. Lachiver, "A fuzzy control system based on the human sensation of thermal comfort," *1998 IEEE Int. Conf. Fuzzy Syst. Proc. - IEEE World Congr. Comput. Intell.*, vol. 1, pp. 487–492, 1998.
[5] M. Nowak and A. Urbaniak, "Application of predictive control algorithms for thermal comfort and energy saving in the classroom," *Proc. 2016 17th Int. Carpathian Control Conf. ICCC 2016*, pp. 527–532, 2016.
[6] S. Wang and J. Li, "A Optimal Control Strategy of Building Energy System Considering Thermal Comfort," vol. 2020, pp. 35–39, 2020.
[7] C. Anuntasethakul and D. Banjerdpongchai, "Design of Supervisory Model Predictive Control for Building HVAC System with Consideration of Peak-Load Shaving and Thermal Comfort," *IEEE Access*, vol. 9, pp. 41066–41081, 2021.
[8] G. Gao, J. Li, and Y. Wen, "DeepComfort: Energy-Efficient Thermal Comfort Control in Buildings Via Reinforcement Learning," *IEEE Internet Things J.*, vol. 7, no. 9, pp. 8472–8484, 2020.
[9] Z. Y. Shi and T. Dong, "Coupling effect on thermal comfort in a typical cubicle-based office with personalized floor diffuser control," *2014 36th Annu. Int. Conf. IEEE Eng. Med. Biol. Soc. EMBC 2014*, pp. 840–843, 2014.
[10] K. L. Ku, J. S. Liaw, M. Y. Tsai, and T. S. Liu, "Automatic control system for thermal comfort based on predicted mean vote and energy saving," *IEEE Trans. Autom. Sci. Eng.*, vol. 12, no. 1, pp. 378–383, 2015.
[11] Y. Cheng and C. Langbort, "An Optimal Control Approach to Nudging via Default Setting in the Context of Indoor Thermal Comfort," *Proc. Am. Control Conf.*, vol. 2020-July, pp. 4963–4968, 2020.
[12] A. A. M. Omara, A. A. A. Abuelnuor, A. O. A. Mohammed, O. M. A. Sirelkhatim, and A. A. M. Suleman, "An experimental study on using polyethylene glycol (PEG) 600 as phase change material for thermal comfort and energy saving in buildings," *2018 Int. Conf. Comput. Control. Electr. Electron. Eng. ICCCEEE 2018*, 2018.
[13] A. M. Ali, S. A. Abdul Shukor, N. A. Rahim, Z. M. Razlan, Z. A. Z. Jamal, and K. Kohlhof, "Computational fluid dynamic (CFD) of air conditioning system for human thermal comfort analysis: A simulation study," *Proc. - 8th IEEE Int. Conf. Control Syst. Comput. Eng. ICCSCE 2018*, no. June 2019, pp. 93–98, 2019.
[14] A. S. Ahmad, S. A. Abdul Shukor, K. Kohlhof, Z. A. Zahid Jamal, and A. Mohamad, "Analyzing and evaluating a PMV-based thermal comfort model in controlling air conditioning system," *J. Teknol.*, vol. 77, no. 28, pp. 99–106, 2015.
[15] T. Kannan, C. Lork, W. Tushar, C. Yuen, N. C. Wong, and S. Tai, "Energy Management Strategy for Zone Cooling Load Demand Reduction with Occupancy Thermal Comfort Margin," *2019 IEEE PES GTD Gd. Int. Conf. Expo. Asia, GTD Asia 2019*, pp. 247–252, 2019.
[16] Izhar, W. Xu, X. Wang, R. Wang, and Y. K. Lee, "Low-Cost Micro Predictive Mean Vote (PMV) Sensor and its Application for Smart Personal Ventilation Systems," *Proc. IEEE Int. Conf. Micro Electro Mech. Syst.*, vol. 2019-Janua, no. January, pp. 841–844, 2019.
[17] C. C. Zhang, Y. Q. Xu, and X. G. Chen, "Study on indoor local dynamic thermal comfort models and optimizing control strategy," *2011 2nd Int. Conf. Artif. Intell. Manag. Sci. Electron. Commer. AIMSEC 2011 - Proc.*, pp. 648–652, 2011.
[18] T. C. Models, "2. thermal comfort models," 1971.
[19] A. M. Ali, S. A. A. Shukor, N. A. Rahim, Z. M. Razlan, Z. A. Z. Jamal, and K. Kohlhof, "IoT-Based Smart Air Conditioning Control for Thermal Comfort," *2019 IEEE Int. Conf. Autom. Control Intell. Syst. I2CACIS 2019 - Proc.*, no. June, pp. 289–294, 2019.
[20] Y. Huang, N. Li, X. Yi, and J. Zhan, "Fuzzy model predictive control for a comfort air-conditioning system," *2006 IEEE Int. Conf. Autom. Sci. Eng. CASE*, pp. 530–533, 2006.
[21] X. He, "to Optimal Comfort Control in Air Conditioning."
[22] M. T. Shahab and D. E. Miller, "Adaptive control of a class of discrete-time nonlinear systems

yielding linear-like behavior," *Automatica*, vol. 130, p. 109691, 2021.

[23] L. Dong, P. Liping, C. Yunpeng, and Z. Yue, "Aircraft cabin thermal control strategy based on adaptive temperature and thermal sensation," *2017 IEEE Int. Conf. Cybern. Intell. Syst. CIS 2017 IEEE Conf. Robot. Autom. Mechatronics, RAM 2017 - Proc.*, vol. 2018-Janua, pp. 183–187, 2017.

[24] H. L. Lv, X. H. Hua, P. Y. Duan, J. B. Yu, and C. J. Zhang, "Indoor dynamic thermal control based on fuzzy relation model of air-conditioning system," *Proc. World Congr. Intell. Control Autom.*, vol. 2015-March, no. March, pp. 4088–4093, 2015.