Chinese Journal of Aeronautics, (2014),**27**(2): 210–216

CSAA

Chinese Society of Aeronautics and Astronautics
& Beihang University

Chinese Journal of Aeronautics

cja@buaa.edu.cn
www.sciencedirect.com

Thermal comfort assessment in civil aircraft cabins

Pang Liping *, **Qin Yue, Liu Dong, Liu Meng**

School of Aviation Science and Engineering, Beihang University, Beijing 100191, China

Received 17 April 2013; revised 21 August 2013; accepted 2 December 2013

KEYWORDS

Adaptive model of thermal neutrality temperature;
Civil aircraft cabin;
Mean outdoor effective temperature;
Optimal operative temperature;
PMV;
Thermal comfort assessment

Abstract Aircraft passengers are more and demanding in terms of thermal comfort. But it is not yet easy for aircraft crew to control the environment control system (ECS) that satisfies the thermal comfort for most passengers due to a number of causes. This paper adopts a corrected predicted mean vote (PMV) model and an adaptive model to assess the thermal comfort conditions for 31 investigated flights and draws the conclusion that there does exist an uncomfortable thermal phenomenon in civil aircraft cabins, especially in some short-haul continental flights. It is necessary to develop an easy way to predict the thermal sensation of passengers and to direct the crew to control ECS. Due to the assessment consistency of the corrected PMV model and the adaptive model, the adaptive model of thermal neutrality temperature can be used as a method to predict the cabin optimal operative temperature. Because only the mean outdoor effective temperature ET* of a departure city is an input variable for the adaptive model, this method can be easily understood and implemented by the crew and can satisfy 80–90% of the thermal acceptability levels of passengers.

1. Introduction

Civil air transportation passengers are becoming more and more demanding in terms of comfort. Aircraft cabin issues are playing an increasingly prominent role in influencing the satisfaction of passengers. Passenger thermal comfort is one significant aspect in cabin-related issues and has become a key market competition factor for the civil airline industry. Major aircraft manufacturers, such as Boeing and Airbus, have been improving the comfort level of their cabins in order to meet this demand. The European aviation industry has also carried out two famous projects, friendly aircraft cabin environment (FACE) and ideal cabin environment (ICE), to investigate and improve cabin comfort. These studies on thermal comfort in aircraft can be classified into three types.

The first method conducts tests in laboratory chambers. This method is a very basal one and the well-known predicted mean vote (PMV) model was established by using this method. For civil aircraft, some researchers used this method to study the thermal comfort in cabins. Tejsen et al.[1] measured thermal manikins in a full-scale 21-seat section of an aircraft cabin and correlated the manikin measurements with the subjective assessments of thermal sensation of various body parts from a previous investigation. Their results indicated that local thermal sensation could be predicted from the manikin measurements. Further study showed that objective measurements of finger temperature could be used to predict group mean thermal sensation.[2] Ref. [3,4] used a Dornier 728 facility to survey

---

* Corresponding author. Tel.: +86 10 82313186.
E-mail address: pangliping@buaa.edu.cn (L. Pang).

Peer review under responsibility of Editorial Committee of CJA.

ELSEVIER **Production and hosting by Elsevier**

http://dx.doi.org/10.1016/j.cja.2014.02.022

the thermal comfort in an aircraft cabin mock-up. Park et al.[5] carried out an approximate flight environmental experiment in the well-known flight test facility (FTF), which was a real low pressure aircraft cabin. They investigated the interrelationship between local and overall thermal comfort of passengers and developed a statistical model to indicate local and overall thermal comfort based on a subject study with long flight duration simulation.

The second method for studying cabin thermal comfort is to adopt a thermoregulation model which can show a heat exchange process in detail. In this method, the multi-segment physiological model is often combined with computational fluid dynamics (CFD) to predict the local skin temperature on a human body.[6,7] Kok et al.[8] developed a simulation environment with CFD and an existing normal thermoregulation model to predict thermal comfort. In order to reflect the impact of low pressure and relative humidity (RH) carefully, Muijden et al.[9] developed a corrected multi-node human model to predict temperature distributions over the passenger and heat exchange with the environment for an average passenger. They assessed the thermal sensation by using the PMV model. Their study may be the most comprehensive for aircraft cabin environments.

The third method is to conduct field thermal comfort surveys. This method considers the influence of passengers' features, which cannot be reflected in experiments conducted in a chamber. Many researchers[10–12] provided comprehensive sets of measurements of cabin air environmental conditions. Recently, Chen's research team[13] carried out large-scale investigations and studies on the effects of air pressure on human health, and their studies involved a series of American domestic and international flights.

The above studies all aim at facilitating the improvement of cabin thermal environments. However, the control for cabin thermal comfort has become a particular challenge because of its special features. Its control performance is closely related to the ECS, which includes the air-conditioning system (ACS) and the pressure regulation system (PRS). The cabin pressure is controlled independently by the PRS and it is not regulated arbitrarily due to the personal safety requirements.[14] It is also difficult to control cabin RH level due to other safety issues. The RH inside a cabin is generally much lower than the minimum required by ASHRAE's comfort standard value.[15,16] The temperature is the only variable which can be controlled to its optimal level, but this optimal control is only permitted in the cruise process, not in the ascent and descent processes because the temperature control will affect the engine performance during these times. In short, cabin environmental control is restricted by many factors. However, the aircraft crew expects the use of a simple way to set the optimal control value of cabin temperature. Actually, this is also difficult because at times the crew may not know the thermal requirements of passengers of different places, which will lead to unreasonable settings of the optimal control value of cabin temperature. Therefore, it is necessary to develop an easy way to set the cabin temperature.

In this paper, we first investigate the cabin environment of 31 flights. Based on the measured data, the unreasonable thermal phenomenon in some surveyed flights is revealed by using a corrected PMV model of thermal comfort assessment. Because there are multiple factors concerned in the corrected PMV model, it is not easy for the cabin crew to control the thermal comfort according to the results of PMV. A relatively simple model, an adaptive model which is only concerned with the mean outdoor effective temperature ET* of a departure city, is used later to assess the thermal condition for these 31 flights. Analysis shows that the assessment results of the two models are consistent. Therefore, we suggest the use of the adaptive model as a method of setting the optimal cabin operative temperature.

2. Onboard measurement method and measurement data

In order to obtain basic data, the authors collected cabin environmental data from 31 flights from the winter of 2010 to the summer of 2012. The measurements were performed continuously during the entire flight from the boarding time to the arrival time. The measured data consisted of temperature, RH and absolute pressure. The measured positions were mostly at the seats near the engines and at the rear of the cabin. The measurement instruments were the P-RH-T101 data recording instruments manufactured by Madgetech, an American company and the T-RH-P recording instruments made by Qingsheng, a Chinese company. The instruments were placed on the tray of each seat or hanging on the seat pockets.

These flights were classified into intercontinental and continental routes. For the intercontinental flights, the lowest cabin pressure was 77.6 kPa and none of the recorded flights had pressure readings below 74.0 kPa, which corresponded to the pressure in a cabin at 2.4 km altitude as specified in FAR 25.831.[17] The cabin temperatures ranged from 20 °C to 27 °C during the cruise time. Cabin RH showed a trend of starting at around 25–55% RH at the beginning of the flight and dropping to around 10–15% as the flight progressed. These measured data are shown in Fig. 1, in which "FI" represents that the measured flight is intercontinental flights.

For the continental fights, the lowest cabin pressure was 76.5 kPa. The cabin temperature ranged from 21 °C to 31.7 °C during cruise time. Cabin RH showed a trend of starting at around 15–60% RH at the beginning of the flight and dropping to around 10–30%. Only the measured temperature data of the continental fights are shown in Fig. 2, in which "F" represents that the measured flight is continental flights.

We will assess the thermal comfort conditions in these surveyed flights by using the above data.

3. Assessment methods of cabin thermal comfort

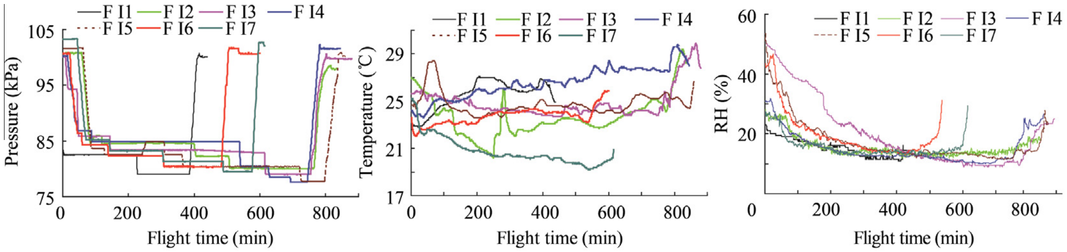
In this section, two different models will be adopted to assess the thermal comfort in an aircraft cabin. The first is a corrected PMV based on the human heat balance equation. The second is the adaptive model based on the outdoor climate parameters of the departure city. The adaptation of passenger thermal neutrality temperature is considered in the second model.

3.1. Corrected PMV (CPMV) model

The PMV equation can be written as[18,19]:

$$\mathrm{PMV} = (0.303\mathrm{e}^{-0.36M} + 0.028) \times (M - W - E_{\mathrm{sk}} - E_{\mathrm{c}} - E_{\mathrm{lr}} - E_{\mathrm{dr}} - E_{\mathrm{r}} \qquad (1)$$

where E_{sk} is the heat loss through skin diffusion and sweating, E_{c} the heat loss by convection, E_{lr} the latent respiration heat



(a) Cabin pressure (b) Cabin temperature (c) Cabin RH

Fig. 1 Measured environmental parameters of 7 intercontinental flights.

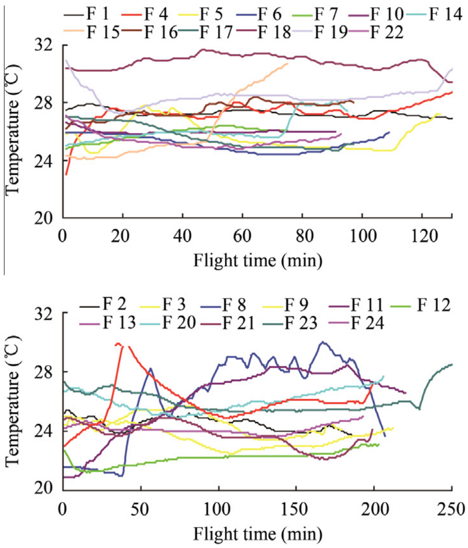


Fig. 2 Measured temperature data of 24 continental flights.

loss, E_{dr} the dry respiration heat loss, E_r the heat loss by radiation, M the metabolic rate, W the effective mechanical power.

The PMV model can assess thermal comfort for an environment at sea level pressure and proper RH, and its prediction of PMV is given by a 7-point thermal sensation scale. But for a civil aircraft cabin, its cabin pressure and RH are far lower than the normal figures at sea level. These lower levels will have an impact on several terms in the bio-heat balance equation. We will correct some terms in Eq. (1) so that it can be adapted to evaluate the heat comfort in the cabin environment.

We assume that all the properties of the individual tissue as well as the insulation properties of garments worn are independent of the air pressure. The detailed calculation for Eq. (1) is listed clearly in the standard of ASHRAE Standard 55 (2010) and ISO 7933. Here, we just discuss how to correct some terms in Eq. (1) due to the lower levels of the cabin pressure and RH,[9,20] and develop a CPMV model.

(1) Skin wettedness

The skin wettedness, w, is used to calculate the evaporative heat loss from the skin, E_{sk}, and it can be written as[9,21]:

$$w = \frac{\max\{0.42(M-58.15),0\}\times R_e}{5733-6.99(M-W)-p_a} + w_b \tag{2}$$

where w_b is the basal wittedness, p_a the environmental pressure, R_e the clothing water vapor resistance.[18,22,23]

RH is usually in the order of 5%-15% in intercontinental flights. Such a low RH is believed to affect the basal wettedness of the skin, which may cause a normal value of 0.06 to drop to as low as 0.02 in a very dry environment. The following linear model is proposed to create a dependency of w_b on RH:

$$w_b = \min(0.06, 0.02 + \mathrm{RH}\times 0.06/60) \tag{3}$$

(1) Lewis ratio

The Lewis ratio, L, is used to calculate R_e in E_{sk}. It is defined as the ratio of heat to mass diffusivity and it is 0.0165 °C/Pa at sea level. This number can be corrected with the consideration of the low pressure in a civil aircraft cabin during flight:

$$\frac{L}{L_0} = \frac{p_0}{p} \tag{4}$$

where the subscript "0" indicates sea level values; p is the cabin pressure.

(1) Convective heat transfer coefficient

The convective heat transfer coefficient, h_c, is used to calculate the heat losses of E_c and E_{sk}. A dependency of the convective heat transfer on pressure can be written as:

$$\frac{h_c}{h_{c_0}} = \left(\frac{p}{p_0}\right)^n \tag{5}$$

where the exponent n is variable and the proposed value is 0.6[9,24]

With these three corrected terms, we can use the method in the standard of ASHRAE Standard 55 (2010) and ISO 7933[19,20] to calculate Eq. (1).

3.2. Adaptive model

Another method for assessing the thermal sensation is the adaptive model of thermal neutrality temperature, T_n. It uses the outdoor climate parameters of the departure city as input parameters to assess the thermal sensation. Assume that the cabin environment is an artificially maintained environment and the sensation of the thermal neutrality temperature does not change with the pressure, then the following equation is recommended to evaluate a comfort temperature range[25]:

$$T_n = 21.5 + 0.11\mathrm{ET}^* \tag{6}$$

Here, the limits for 90% acceptability are taken as $T_n \pm 2.5$ °C.

4. Thermal comfort assessment

The thermal comfort in the surveyed aircraft cabins was assessed by using the CPMV and the adaptive model.

4.1. Comparisons of assessment results

4.1.1. Intercontinental flights

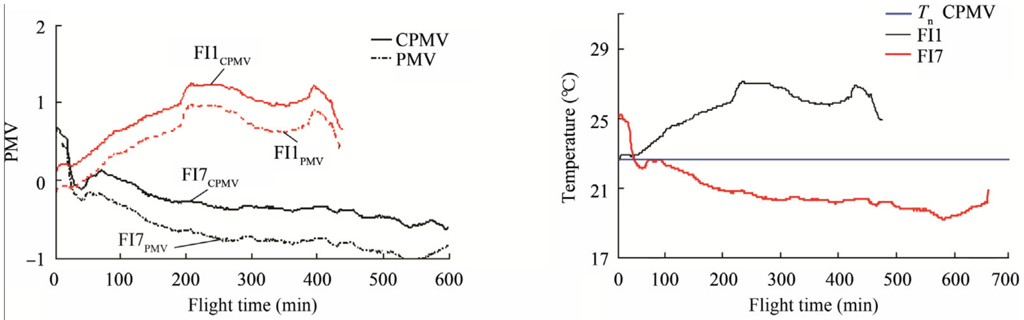
For these flights, the climates of their departure cities were very similar. These flights are classified according to the flying season. The assessment results of CPMV are shown in Fig. 3(a1), (b1) and (c1). The adaptive thermal neutrality temperatures T_n are shown in Fig. 3(a2), (b2) and (c2), in which the blue solid line is T_n, the gray thin lines are respectively the limits of (T_n − 2.5) and (T_n + 2.5) for 90% acceptability, and the other lines are the measured cabin temperature.

From Fig. 3, we can observe that:

(1) In Fig. 3(a1), the subscripts of "CPMV" and "PMV" indicate the thermal sensation results calculated by CPMV and PMV models, respectively. From Fig. 3(a1), we know that the thermal sensation of the corrected PMV model is higher than the one of the PMV model. This higher figure of thermal sensation leads to a positive deviation of thermal sensation from the normal pressure and RH to the low cabin pressure and RH. The corrected PMV model is able to evaluate the cabin environment better than the PMV model.

(2) From Fig. 3(a1), (b1) and (c1), the assessment results of the corrected PMV model show that the thermal comfort in the surveyed intercontinental flights was satisfied very well except for FI1, which was obviously a bit too warm.

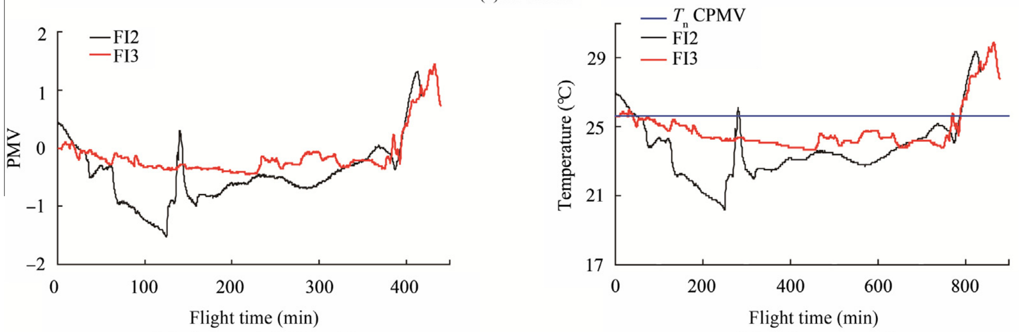
(3) From Fig. 3(a2), (b2) and (c2), the assessment results of the adaptive model show that the cabin temperature in the surveyed intercontinental flights was controlled well during the cruise time and satisfied the 90% acceptability of comfort temperature except for FI1. Therefore, the assessment results of the corrected PMV model and adaptive model tend to be consistent.



(a1) Corrected PMV model

(a2) Adaptive model

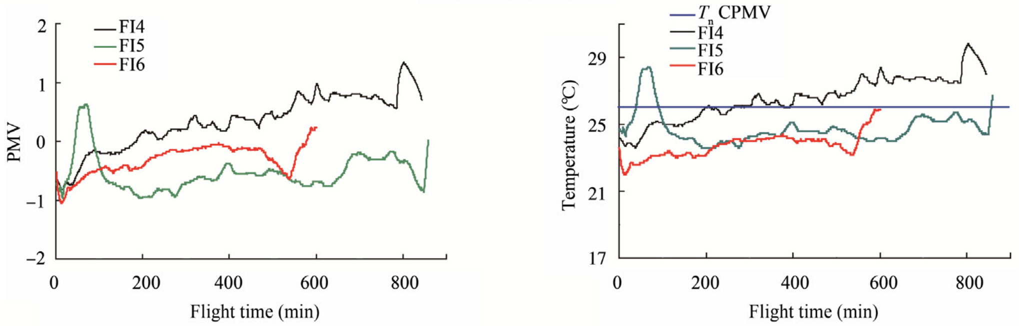
(a) In winter



(b1) Corrected PMV model

(b2) Adaptive model

(b) In spring and fall



(c1) Corrected PMV model

(c2) Adaptive model

(c) In summer

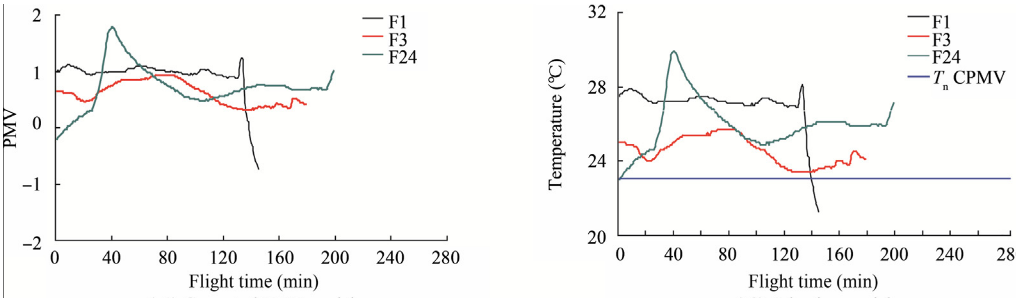
Fig. 3 Assessment results for intercontinental flights.

4.1.2. Continental flights

These surveyed continental flights were classified into 4 groups according to the ET* of the departure city in order to show the results clearly: 14–15 °C; 18–20 °C; 23–27 °C; 28–30 °C. Fig. 4 shows the assessment results by using the corrected PMV model and the adaptive model for continental flights.

From Fig. 4 we know that:

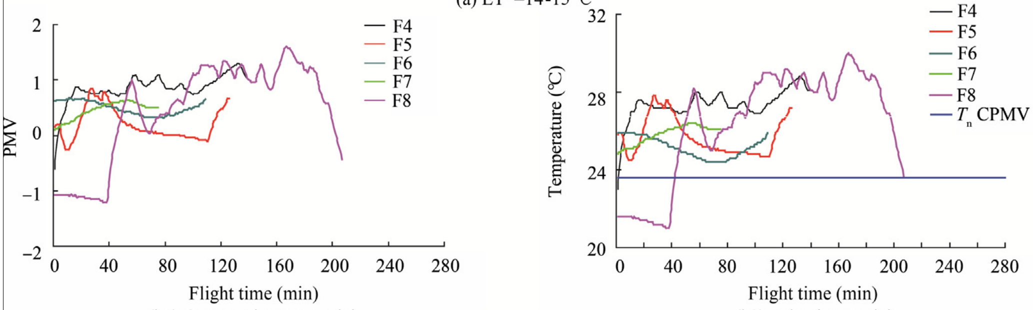
(1) The thermal comfort of the corrected PMV model in the surveyed continental flights is not controlled as well as in the intercontinental flights. The controlled temperature on American flights was too low. On F21, passengers were not comfortable with the low temperature and the lack of blanket service. The temperature in some flights in China was controlled too high. On F1, F4, F8, F16, F18 and F19, passengers felt "warm" or "slightly warm" on the average. Additionally, the variation range of temperature on F11 from 21 °C to 28 °C was too large. Sometimes the reason for this phenomenon may come from the difference in thermal requirements between the crew and passengers. For example, the overheating phenomena might stem from the crew's



(a1) Corrected PMV model

(a2) Adaptive model

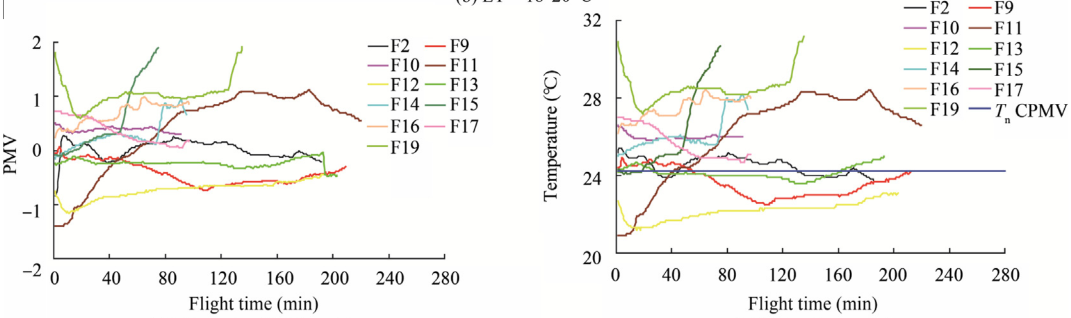
(a) ET*=14-15 ℃



(b1) Corrected PMV model

(b2) Adaptive model

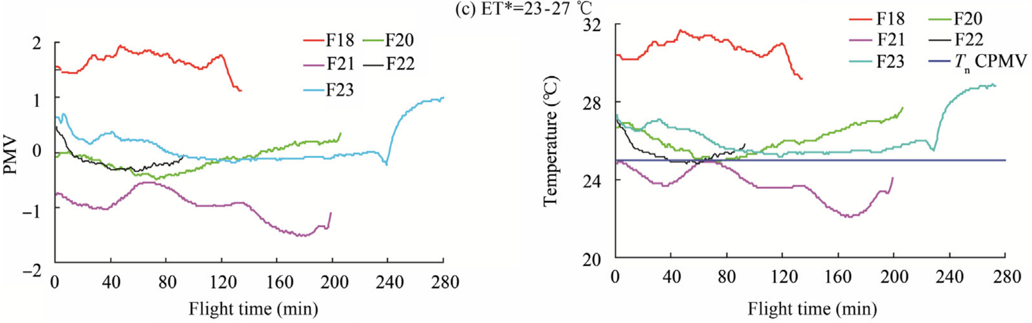
(b) ET*=18-20 ℃



(c1) Corrected PMV model

(c2) Adaptive model

(c) ET*=23-27 ℃



(d1) Corrected PMV model

(d2) Adaptive model

(d) ET*=28-30 ℃

Fig. 4 Assessment results for continental flights.

expectation that passengers would self-regulate their body temperatures by removing their outer layers of clothing and by not providing the service of blanket, while passengers expect the cabin temperature to be lower.

(2) The thermal assessment of the adaptive thermal neutrality temperature T_n also shows similar features. So the assessment results of the corrected PMV model and the adaptive model tend to be consistent.

4.2. Method to predict a cabin optimal operative temperature

The assessment conditions for an acceptable thermal environment can base on either the PMV model or the adaptive model of thermal neutrality temperature T_n. The corrected PMV model shows a possible way to regulate the cabin environmental parameters to assure that thermal comfort is satisfied for most passengers. However, there are numerous related parameters in the corrected PMV. Actually, for a civil aircraft, the cabin temperature is the only operative variable which can be controlled during the cruise process. Since the assessment results of the corrected PMV model and the adaptive model tend to be consistent, and thermal neutrality is close to the thermal comfort temperature, we can refer the thermal neutrality temperature in Eq. (7) to set the controlled comfort temperature for a civil aircraft cabin. Therefore, this consistency can ensure that the adaptive model be a reference for helping the aircraft crew to set the optimal temperature for a civil aircraft cabin.

$$T_{op} = 21.5 + 0.11\text{ET}^* \tag{7}$$

where T_{op} is the optimum operative temperature.

There are some advantages to use the thermal neutrality to predict a cabin optimal operative temperature for the cabin crew. One obvious advantage is there are fewer variables in Eq. (7) than in Eq. (1). In this process, we just use the outdoor climate parameters of the departure city as input parameters to construct the adaptive model. ET* in the departure city is only chosen to represent the outdoor climate and ET* is a function of the outdoor temperature and RH.

This consistency between the corrected PMV and the adaptive model can ensure that the way of setting the optimal controlled temperature satisfies the thermal comfort requirements of passengers and it is easily realized.

5. Conclusions

(1) The corrected PMV model was used to survey the thermal comfort conditions on 31 civil flights. The assessment results indicated that thermal comfort was not controlled very well in some flights, especially in some short-haul flights, and that there were some cases of overheating or undercooling.

(2) The adaptive model of thermal neutrality temperature was also used to survey the thermal comfort conditions on the 31 civil flights. The results of the adaptive model also showed assessment features similar to those of the corrected PMV model and there existed instances with inappropriate control for temperature.

(3) Because the assessment results of the adaptive model and the corrected PMV model are consistent, and the adaptive model can help set the controlled cabin temperature more clearly and directly, we suggest the use of the adaptive model as a method to predict optimum cabin operative temperature for a civil aircraft and for the crew to set the temperature.

Acknowledgment

This research was supported by the Civil Aircraft Pre-research Project of China.

References

1. Tejsen PS, Zukowska D, Jama A, Wyo DP. Assessment of the thermal environment in a simulated aircraft cabin using thermal manikin exposure. In: *Proceedings of the 10th international conference on air distribution in rooms*; 2007.p. 227–34.
2. Tejsen PS, Wyon DP, Żukowska D, Jama A. Finger temperature as a predictor of thermal comfort for sedentary passengers in a simulated aircraft cabin. In: *Proceedings of the 9th international healthy buildings conference and exhibition*; 2009. p. 384.
3. Winzen J, Marggraf-Micheel C. Ventilation is not the same as ventilation – thermal comfort in the aircraft cabin. In: *Proceedings of the Roomvent*; 2011.
4. Fiala D, Lomas KJ, Stohrer M. Computer prediction of human thermoregulatory and temperature responses to a wide range of environmental conditions. *Int J Biometeorol* 2001;**45**(3):143–59.
5. Park S, Hellwig RT, Grun G, Holm A. Local and overall thermal comfort in an aircraft cabin and their interrelations. *Build Environ* 2011;**46**(5):1056–64.
6. Tanabe S, Kobayashi K, Nakano J, Ozeki Y, Konishi M. Evaluation of thermal comfort using combined multi-node thermoregulation (65MN) and radiation models and computational fluid dynamics (CFD). *Energy Build* 2002;**34**(6):637–46.
7. Zhang H. Human thermal sensation and comfort in transient and non-uniform thermal environments [dissertation]. Berkeley: University of California; 2003.
8. Kok JC, Muijden JV, Burgers SS, Dol H, Spekreijse SP. Enhancement of aircraft cabin comfort studies by coupling of models for human thermoregulation, internal radiation, and turbulent flows. In: *Proceedings of the European conference on computational fluid dynamics*; 2006. p. 1–19.
9. Pang LP, Gong MM, Qu HQ. Moisture prediction for aircraft cabin based on a lumped virtual moisture source. *Acta Aeronaut Astronaut Sin* 2012;**33**(6):1030–5 [Chinese].
10. Haghighat F, Allard F, Megri AC, Blondeau P, Shimotakahara R. Measurement of thermal comfort and indoor air quality aboard 43 flights on commercial airlines. *Indoor Built Environ* 1999;**8**(1):58–66.
11. Ross D, Crump D, Hunter C, Perera E, Sheridan A. Extending cabin air measurements to include older aircraft types utilized in high volume short haul operation; 2013 [cited 2013 Feb 17. Available from: http://www.aerohabitat.eu/uploads/media/10-08-2004_-_Aria_di_bordo_nei_voli_BA_146_e_Boeing_737__800_KB_pdf.
12. Murphy MJ. Measurement of physical environmental parameters and apparent ventilation rates aboard passenger aircraft. *J ASTM Int* 2008;**5**(5):1–11.
13. Chen Q. FAA on the airliner cabin environment. Airliner Cabin Environmental Research (ACER) Program. Report No.: RITE-ACER-CoE-2010-1; 2010.
14. Pang LP, Zhang Y, Qu HQ, Hu T, Zhao JQ. Impact of gravitation on gaseous pollutant source identification. *Chin J Aeronaut* 2013;**26**(2):261–8.

15. Wyon DP, Fang L, Lagercrantz L, Fanger PO. Experimental determination of the limiting criteria for human exposure to low winter humidity indoors (RP-1160). *HVAC&R Res* 2006;**12**(2):201–13.
16. Uchiyama E, Aronowicz JD, Butovich IA, McCulley JP. Increased evaporative rates in laboratory testing conditions simulating airplane cabin relative humidity: an important factor for dry eye syndrome. *Eye Contact Lens* 2007;**33**(4):174–6.
17. FAA Federal Aviation Regulations. Transport category airplanes, FAR 25.831-ventilation; 2013 [cited 2013 Feb 17]. Available from: http://www.flightsimaviation.com/data/FARS/Part_25.html.
18. International Standard ISO/FDIS 7933: 2004(E). Ergonomics of the thermal environment-analytical determination and interpretation of heat stress using calculation of the predicted heat strain; 2004 [cited 2013 Feb 17]. Available from: http://www.deparisnet.be/chaleur/Normes/Malchaire_PHS_Predicted_Heat_Strain_standard%207933_22-7-13.pdf.
19. International Standard ISO 7730: 2005(E). Ergonomics of the thermal environment-analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria; 2005 [cited 2013 Feb 17]. Available from: https://moodle.metropolia.fi/pluginfile.php/217631/mod_resource/content/1/EVS_EN_ISO_7730%3B2006_en.pdf.
20. BSR/ASHRAE Standard 55P. Thermal environmental conditions for human occupancy; 2003 [cited 2013 Feb 17]. Available from: http://home.comcast.net/~tureston2011/ASHRAE_Standard55_2004.pdf.
21. Havenith G, Holmer I, Parsons K. Personal factors in thermal comfort assessment: clothing properties and metabolic heat production. *Energy Build* 2002;**34**(6):581–91.
22. Havenith G, Holmér I, den Hartog EA, Parsons KC. Clothing evaporative heat resistance proposal for improved representation in standards and models. *Ann Occupat Hyg* 1999;**43**(5):339–46.
23. Wang F. Clothing evaporative resistance: its measurements and application in prediction of heat strain [dissertation]. Sweden: Lund University; 2011.
24. de Dear RJ, Arens E, Hui Z, Oguro M. Convective and radiative heat transfer coefficients for individual human body segments. *Int J Biometeorol* 1997;**40**(3):141–56.
25. Auliciems A, Szokolay SV. *Thermal comfort*. 2th ed. Queensland: The University of Queensland; 2007. p. 45–53.

Pang Liping received her Ph.D. degree in ergonomics and environmental engineering from Beihang University in 2005, and then joined the faculty there. Her main research interests are environment control and evaluation for human operated vehicles.