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Thermal comfort assessment in civil aircraft cabins

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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

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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