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A correlation linking the predicted mean vote and the mean thermal vote based on an investigation on the human thermal comfort in short-haul domestic flights

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ABSTRACT

The results of an experimental investigation on the human thermal comfort inside the cabin of some Airbus A319 aircrafts during 14 short-haul domestic flights, linking various Italian cities, are presented and used to define a correlation among the predicted mean vote (PMV), a procedure which is commonly used to assess the thermal comfort in inhabited environments, and the equivalent temperature and mean thermal vote (MTV), which are the parameters suggested by the European Standard EN ISO 14505-2 for the evaluation of the thermal environment in vehicles.

The measurements of the radiant temperature, air temperature and relative humidity during flights were performed. The air temperature varied between 22.2 °C and 26.0 °C; the relative humidity ranged from 8.7% to 59.2%. The calculated values of the PMV varied from −0.16 to 0.90 and were confirmed by the answers of the passengers. The equivalent temperature was evaluated using the equations of Fanger or on the basis of the values of the skin temperature measured on some volunteers.

The correlation linking the thermal sensation scales and zones used by the PMV and the MTV resulted quite accurate because the minimum value of the absolute difference between such environmental indexes equalled 0.0073 and the maximum difference did not exceed the value of 0.0589. Even though the equivalent temperature and the MTV were specifically proposed to evaluate the thermal sensation in vehicles, their use may be effectively extended to the assessment of the thermal comfort in airplanes or other occupied places.

1. Introduction

A comfortable environment in aircraft cabins is a priority concern in mass transportation. The parameters most frequently complained by passenger are the humidity, temperature, odor, and noise (Lee et al., 2000). Also the seat comfort, flight smoothness, and air quality are important for passenger comfort (Rankin et al., 2000); passengers who remain seated throughout the flight may risk edema or deep vein thrombosis (Brundrett, 2001).

The airline cabin attendants are exposed to several potential occupational hazards, including cosmic rays (Blettner et al., 2002). The crew operates within an environment that involves circadian dysrhythmia, reduced atmospheric pressure, mild hypoxia, low humidity, and exposure to sound, vibration and magnetic-field (Butler et al., 2000). Symptoms more often reported by the crew include: irritation of the eyes, nose and throat, headaches, light-headedness and dizziness, fatigue, weakness and a decrease in performance, a general increase in feeling unwell, concentration difficulties and confusion, diarrhea, nausea, vomiting and gastro-intestinal problems, numbness (head, limbs, lips, fingers), short-term memory impairment and joint pain/muscle weakness (Michaelis, 2003). Some reports highlighting increased incidence of cancer among airline pilots and cabin crew have renewed concerns about possible exposure to harmful levels of cosmic radiation. Such a low energy ionizing radiation has been shown to cause DNA damages and induce genomic instability in human chromosomes (Lim, 2002). There have been some suggestions that crews have a higher-than-normal probability of developing cancer, since they are exposed to potential genotoxic factors. These also include airborne pollutants such as the engine combustion products, ozone, and

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electromagnetic fields (Cavallo et al., 2002). Actually, it was observed that airline pilots had an increased incidence of malignant melanoma of the skin and military pilots of other skin cancer (Hammar et al., 2002).

When aircraft operators have sought to reduce fuel cost by flying at higher altitudes, the energy cost of supplying an adequate amount of outside air for ventilation has increased; the increased pressurization of the outside air required for ventilation can add up to 2% to the fuel cost (Hocking 2000. The small air volume available per person in a fully occupied aircraft cabin accentuates the human bioeffluent factor in the maintenance of air quality (Hocking, 2002). The poor level of air quality may also cause intolerance to contact lenses and may be a health hazard to both passengers and crew members (Backman and Haghighat, 2000). The increased level of ozone can lead to respiratory problems for the upper airways and increased carbon dioxide may cause hyperventilation (Bergau, 1999).

The aircraft's environmental control systems (ECS) have to provide air supply, thermal control and cabin pressurization for the crew and passengers because the environmental conditions at the cruising altitudes, which since the 1970s are about 12,000 m, would not allow human organism to survive. To achieve the appropriate cabin ventilation and air conditioning, the outside air is bled from an intermediate stage of the engine compressor, adequately cooled and expanded before to be mixed with the recirculated air. Unfortunately, the need of reducing the fuel cost in airlines business competition has driven to adopt air handling systems that may lead to inadequate levels of thermal comfort inside the cabins of commercial airliners. Moreover, in order to reduce the risk of corrosion of metallic components and prevent the growth of microorganisms, the relative humidity in the cabin is usually set to very low levels that may affect the thermal comfort and increase the stress that is often felt by the crew and passengers. Most notable are "dryness" symptoms attributable to the low humidity and "fatigue" symptoms associated with factors such as disruption of circadian rhythm (Nagda and Koontz, 2003). Sometimes, perceived stress due to excess of work was associated with fatigue, feeling heavy-headed, headache and facial dermal symptoms (Lindgren et al., 2002). The cabin pressure can also impact on many aspects of the well-being of aircraft passengers. Some recent studies have shown that while the overall probability of achieving moderate hypoxia is low for healthy people, the risk is higher in passengers 60 years old and over, with cardiovascular or pulmonary diseases (Muhm et al., 2007; McNeely et al., 2011; Grun et al., 2012).

Several studies, which adopted experimental approaches based both on simulated and real flights, have taken into account the thermal comfort and air quality in aircraft cabins. The indoor air quality inside the cabins of Boeing 747-400, Airbus A330 and Airbus 340 aircrafts was investigated by Lee et al. (1999) for 16 flights during which the level of CO_2 and the air temperature and relative humidity were measured every five minutes. Sometimes, the air was felt quite dry because the relative humidity varied between 4.9%, which is a very small value, and 76.8% with a temporal variation dominated by a gradual decrease during the beginning and an increase at the end of the trip. The temperature in the aircraft cabin ranged from 19.3 °C to 27.1 °C. The crew, which filled 185 questionnaires, rated the overall air quality in the surveyed flights to be acceptable (36%) and adequate (32%), while the air quality was considered poor by 21% of the crew. Haghighat et al. (1999) measured the temperature, relative humidity and carbon dioxide concentration aboard 43 flights on commercial airlines with duration of more than one hour. The data, which were collected on Douglas DC9, Boeing 767 and Airbus A320 and A340 aircrafts, were compared with the ASHRAE standards for thermal comfort and indoor air. The average values of temperature and humidity ranged within 20.2÷23.8 °C and 1.8%÷18.5%, respectively. The data showed that the air temperature was often below the recommended range (20.2÷24.7 °C in winter, 24.0÷27.4 °C in summer, with U.R. = 50%) and the humidity was always too low. To evaluate the thermal comfort of the passengers on an Airbus A320, the PMV and the PPD were calculated during 21 flights. Assuming a light activity level and two air velocities of 0.1 and 0.15 m/s, the values of the PMV varied from −2.71 to −1.19 and from −1.26 to −0.21 in correspondence of the summer and winter conditions, respectively. The levels of relative humidity were very small on all flights and did not meet the lower limit of thermal comfort in ASHRAE standard 55-92.

The EC CabinAir Project monitored 14 flights that ranged from approximately 1 to 3 h (Ross et al., 2003). The parameters related to the air quality, cabin pressure, air and globe temperature, relative humidity and air speed were measured not only during passenger boarding and disembarkation, but also during all phases of flight – from take-off, through cruise and then to descent. Moreover, the concentrations of carbon monoxide, carbon dioxide, nitrogen dioxide, volatile and semi-volatile organic compounds, bacteria and fungi, surface dust, dust mite and cat allergens, and ultrafine particles were collected. The ASHRAE Research Project RP-1262 aimed to investigate the link between perceived health symptoms and discomfort on one hand, and aircraft cabin environmental conditions and human factors on the other (Spicer et al., 2004). The measured data on aircrafts generally agree that cabins are non homogeneous thermal environments where about 25% of the occupants feel dissatisfied. Strøm-Tejsen et al. (2005a,b) performed measurements in a simulated section of an aircraft cabin with 21 seats installed in a climatic chamber capable of providing fresh outside air at very low humidity. Experiments simulating 7-hour transatlantic flights were carried out at four supply rates of outside air (1.4, 3.3, 4.7 and 9.4 L/s per person), yielding average relative humidity levels of 28%, 16% and 11%, respectively. A total of 68 subjects filled in questionnaires, but no significant differences of symptoms were found among the above four conditions. In order to investigate thermal effects, the temperature inside the cabin was set at three different levels (20.6 °C, 23.3 °C and 26.1 °C), while maintaining the outside air supply rate and total air supply to the cabin at constant values.

Wang et al. (2008) used a full-scale section of a Boeing 767 cabin containing 35 manikins, which were equipped with body heaters and outlets of carbon dioxide to simulate breathing. The results of monitoring the environment quality in the cabin of a representative number of flights and aircraft were described by Chen in the report to the FAA issued by the Airliner Cabin Environmental Research (ACER) Program. Ozone levels were measured during 68 domestic flights (Chen et al., 2010). Measurements of pesticides were made on 15 domestic flights and 46 international flights. On most of the flights, the cabin temperature ranged from 22 °C to 29 °C and the humidity data demonstrated a trend of starting at around 35–50% at the beginning of the flight and dropping to around 10–25% as the flight progressed. Moreover, about 3700 flight attendants, selected in order to get a representative distribution of flight attendant characteristics, were queried about their symptoms, diagnoses, care seeking, treatment and work-related injuries.

The interrelation between local and overall thermal comfort of passengers in a 30 m long pressure vessel holding the first 16 m of a complete wide body A310–200 aircraft was investigated by Park et al. (2011). During 11 simulated 3.5h flights and two 7h flights, 40 test persons filled out questionnaires concerning their perceived overall and local thermal comfort at temperatures ranging from 20 °C to 25 °C. In order to verify if the high ratio of thermal dissatisfaction in the aircraft cabin reported in literature were caused by local discomfort, the physical and subjective data related to 11 body segments were used to evaluate the PMV, the thermal