



# Air quality and relative humidity in commercial aircrafts: An experimental investigation on short-haul domestic flights



Carlo Giaconia, Aldo Orioli\*, Alessandra Di Gangi

D.E.I.M. Dipartimento di Energia, Ingegneria dell'Informazione e Modelli Matematici, Università degli Studi di Palermo, Viale delle Scienze Edificio 9, 90128 Palermo, Italy

## ARTICLE INFO

### Article history:

Received 18 March 2013

Received in revised form

6 May 2013

Accepted 8 May 2013

### Keywords:

Aircraft cabins

Cabin comfort

Aircraft ECS

Hygrometrical control

Air quality

Carbon dioxide

## ABSTRACT

Nowadays the achievement of a comfortable environment in aircraft cabins is a factor of paramount importance in air travel business competition; on the other hand, the need of reducing the propulsion fuel cost has driven the airline companies to adopt air handling systems that may reduce the levels of thermal comfort and air quality inside the cabins of commercial airliners. With the aim of contributing to a better knowledge of this matter, this paper reports the results of an experimental study upon the indoor air quality aboard commercial aircrafts for 14 domestic flights less than 1 h and half long. The parameters monitored were temperature, relative humidity and carbon dioxide concentration; the measurements were performed during the whole flight from the take-off to the landing.

The relative humidity inside the cabin was also calculated using the rates of outside air and the carbon dioxide as a ventilation tracer; the theoretical results were compared with the measured data. The relationship between relative humidity and carbon dioxide concentration during flights was highlighted in order to define the environmental conditions that may provide acceptable levels of both the air quality and hygrometric comfort to the crew and passengers. The results of calculations confirmed the possibility of improving the hygrometric conditions in aircraft cabins without the need of using humidification systems.

© 2013 Elsevier Ltd. All rights reserved.

## 1. Introduction

The assessment of the air quality in commercial airliners is still an open problem that requires further investigation owing to the continuously increasing number of people that use airplanes to travel. Aircraft cabins are crowded places where the passengers have to seat for long and the lack of room and the high occupant density make people feel cramped and uncomfortable and put them at the risk of health problems. The inhalation of recirculated air can increase the probability of infection due to the spread of microbiological contaminants all around the cabin. Irritants and allergens, which are dispersed through air movements, can affect respiratory health and exacerbate chronic conditions. The concentrations of gaseous contaminants, due to the metabolic processes or to the combustion of the engine fuel, may surpass the tolerable levels. The changes in the air pressure inside the airplane during take-offs and landings can involve middle ear and paranasal sinus problems, often accompanied by dental pains.

Since the 1970s, airliners are flying at an altitude of about 12,000 m in order to reduce the propulsion fuel cost; at these heights the environmental conditions do not allow human organism to survive and the environmental control system (ECS) of the aircraft has to provide at the same time the air supply, thermal control and cabin pressurization for the crew and passengers. In order to achieve the required cabin ventilation, the outside air is bled from a compressor stage of the gas turbine engines, upstream of the combustor. Because the temperature and pressure of this air are not suited to be delivered to the cabin, the bled air is adequately cooled and expanded before to be mixed with the recirculated air. The energy cost of providing adequate outside air for ventilation generally tends to increase with the altitude.

The assessment of the air quality has been faced following experimental approaches based both on simulated and real flights. Dechow et al. [1] used the cabins of Airbus A310 and A340 aircrafts to measure the particulate matter, the microbiological contamination and the concentration of volatile organic compounds during medium-distance and long-distance flights. A total number of 8 sensors were installed aboard the aircraft for about one year. Compared to the usual indoor atmospheres, the obtained results did not indicate more relevance to health risks or comfort restriction.

\* Corresponding author. Tel.: +39 09123861914/905; fax: +39 091484425.

E-mail address: [orioli@dream.unipa.it](mailto:orioli@dream.unipa.it) (A. Orioli).

Indoor air quality inside the cabins of Boeing 747-400, Airbus A330 and Airbus 340 aircrafts was investigated by Lee et al. [2] for 16 flights, during which the level of CO<sub>2</sub> and the air temperature and relative humidity were measured every 5 min. The measured carbon dioxide concentrations were below the limit set by FAA standard but exceeded the ASHRAE standard 62-1989 of 1000 ppm, ranging from 2000 to 2500 ppm. The air was quite dry, with a relative humidity varying in the range of 4.9%–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 on the aircraft ranged from 19.3 °C to 27.1 °C. Cabin crew, which completed 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. The symptoms that were more frequently experienced during flights, whose durations ranged from 1 h and 25 min to 14 h and 15 min, were dry itchy or irritated eyes, dry or stuffy nose, skin dryness or irritation and too hot or too cold air temperature.

Haghighat et al. [3] measured the temperature, relative humidity and carbon dioxide concentration aboard 43 flights on commercial airlines with duration of more than 1 h. The data, which were collected on DC9, Boeing 767 and Airbus A320 and A340 aircrafts, were compared with the ASHRAE standards for thermal comfort and indoor air quality. The comparison showed that the air temperature was often below the recommended range and the humidity was always too low. The average values of temperature and humidity ranged between 20.2 °C and 23.8 °C and 1.8% and 18.5%, respectively. The levels of relative humidity were very low for all flights and did not meet the lower limit of thermal comfort in ASHRAE standard 55-92. The relative humidity in the DC9, which used 100% fresh air, was higher than in the other newer aircraft models. Carbon dioxide concentration was used as the indicator of the ventilation performance and indoor air quality. A CO<sub>2</sub> level of 1000 ppm was exceeded in 13 out of 22 flights for Airbus flights, 11 out of 15 DC9 flights and 1 out of 5 for Boeing 767 flights. Because passengers produce the carbon dioxide, it would be expected that, the fewer of them on board, it would result in better air quality. Probably, as the recirculation rate is usually controlled by the pilot and crew, who are mainly concerned with energy saving rather than passenger comfort, the air quality levels was not significantly affected by the number of passengers.

In order to evaluate the ventilation effectiveness and characterize the air distribution, Wang et al. [4] used a full-scale section of a Boeing 767 aircraft cabin containing 35 manikins, which were equipped with body heaters and outlets of CO<sub>2</sub> to simulate breathing. Carbon dioxide was used as the tracer gas to determine the local mean age of the air and the ventilation effectiveness factor. Forced and mixed convection in a replica of a section of the Airbus A380 upper deck was experimentally investigated by Kühn et al. [5]. Large scale particle image velocimetry and temperature field measurements were conducted in a cross sectional plane of the cabin mock-up.

The results of monitoring the ozone in the cabin on a representative number of flights and aircraft, the pesticide exposure of passengers and crew, the cabin air pressure and altitude, the incidents of air contamination and the residue from aircraft ventilation ducts and filters were described in the report to the FAA issued by the Airliner Cabin Environmental Research (ACER) Program [6]. Ozone levels were measured during 68 flights domestic. Measurements of pesticides were made on 15 domestic flights and 46 international flights. In order to monitor air contamination incidents, a simple, small portable sampling device was developed and used on nearly 200 flights. The concentrations of carbon dioxide ranged between 900 and 1700 ppm, with only occasional measurements registering higher values. 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% relative humidity 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 answers related to respiratory and visual symptoms, which can be connected to the air dryness, showed the presence of eye irritation (10.8%), blurred vision (7.5%), sinus congestion (29.0%), nose irritation (5.0%), sore throat (7.0%), cough (10.8%) and hoarseness (5.1%), suffered for more than 5–6 days a week.

The ACER Center [7] also conducted an environmental monitoring in the passenger cabin of 83 commercial flights on six aircraft models (2 Airbus and 4 Boeing), flying U.S. domestic and international routes. Environmental conditions and air quality, including carbon monoxide, carbon dioxide, particles, ozone, VOCs, semi-VOCs, carbonyls, and tricresyl phosphate were monitored. Except for low pressure, occasionally high ozone, extremely dry air and perhaps slightly higher noise levels, the air quality and environmental conditions in the passenger cabin of commercial airplanes were found to be comparable or better than conditions reported for offices, schools and residences, with a few exceptions. Ventilation rates on high-passenger load flights were found to be below the required 3.5 L/s/person, as indicated by higher carbon dioxide levels.

Gładyszewska-Fiedoruk [8] measured the carbon dioxide concentration and the values of air temperature, relative humidity and pressure during a 200 min long flight of an airliner with 150 passengers on board. The carbon dioxide concentration exceeded the recommended standards of the World Health Organisation and the pressure in cabin was half the permissible value recommended by the FAA standard. The high air temperature found and the long exposition to low values of relative humidity were considered sufficient to induce early skin degeneration and concentration problems in pilots and attendants who fly regularly.

Airborne disease transmission in airliner cabins has always been a topic of wide interest. Chen et al. [9] found that the bulk airflow pattern in the cabin played the most important role on the transport of the expiratory droplets. Further experimental and computational fluid dynamics (CFD) investigations revealed that in-flight movement of passengers and crew had a significant impact on infectious disease transmission. Transport of contaminants and particles in enclosed environments, such as aircraft cabins, has been the object of many studies [10–14]. In order to provide a healthy and comfortable environment for passengers and crew, Zhang et al. [15] studied a novel under-floor displacement air distribution system, matched with a personalized air distribution system, able to reduce the spread of infectious airborne diseases.

Possou et al. [16] and Muzumdar et al. [17] used validated CFD and a small-scale water model to assess the impact of scaling and body movement on contaminant transport in airliner cabins. Gupta et al. [18,19] developed a method to predict the amount of expiratory droplets inhaled by the passengers in an airliner cabin for any flight duration; the method was used to determine the amount of droplets inhaled by the susceptible passengers over a 4-h flight, under three common scenarios. They also computed the transport of the droplets exhaled by the index patient seated in the middle of a seven-row, twin-aisle, fully-occupied cabin using CFD simulations. Gupta et al. [20] presented a comprehensive approach to assessing the spatial and temporal distribution of airborne infection risk in an aircraft cabin. Deterministic and probabilistic approaches were used to quantify the risks based on the amount of inhaled influenza virus. The study carried by Chen et al. [9] also showed that influenza survival on stainless steel surfaces are impacted by relative humidity.

It is known that low levels of relative humidity in airplanes are usually considered advisable in order to reduce the risk of corrosion of structural elements, electrical malfunction and degradation of insulating, due to condensate, and prevent the growth of micro-organisms. For this reason, and to prevent ice from forming and clogging the system, air bled from the gas turbine engine is also sent through a water separator even if, at cruise altitudes, the outside air contains very little moisture. Because the main sources of humidity in the cabin are respiration and evaporation from the skin of occupants, the relative humidity in the cabin usually reaches values of 10–20% that can affect the comfort of the occupants.

Many authors have investigated the effects of the low levels of relative humidity, which meanly are dry nose, eyes, throat and skin, by questioning the crew members and passengers [21–24]. Nagda and Hodgson [25] pointed out that some subjects were not always able to perceive low humidity or changes in the humidity level and that the perception of humidity did not vary with the duration of exposure. Moreover, it was observed that the complaints of dryness decreased by lowering the air temperature with a constant relative humidity; adversely, the perceived staleness of air increased and the perceived acceptability of air decreased with a rise in either the air temperature or humidity. The effect of humidifying the air cabin was investigated by Lindgren et al. [26] on eight intercontinental flights with a Boeing 767 aircraft.

Using realistic pollution sources, Strøm-Tejsen et al. [27] 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, which simulated 7-h 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) and yielded 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 between the four conditions, except that the reduced outside air flow intensified other complaint commonly associated with air travel (headache, dizziness and claustrophobia).

Using a 30 m long pressure vessel holding the first 16 m of a complete wide-body A310-200 aircraft and adequately controlling the air pressure, air and fuselage temperature, relative humidity, ventilation rate, noise and vibration, Grün et al. [28] analyzed the impact of low humidity levels on the human well-being during 7 h long-haul simulated flights. Questionnaires were filled in by 40 subjects who experienced relative humidity, varying between 10% and 40% at a temperature range of 21 °C–25 °C, and atmospheric pressure between 753 hPa and ambient conditions. Even if it was observed a trend of decreasing dissatisfaction with increasing the relative humidity, the study confirmed the evidence of the difficulty of relating the perceived dryness to the relative humidity. Moreover, at very low levels of relative humidity around 10%, the

subjects showed a significant decrease in the perception of dryness between 90 and 240 min after start of exposure.

To increase the hygrometric comfort the cabin air should be theoretically humidified to suited values. Unfortunately, humidification implies many problems that include the biological growth, which is often associated with humidifiers, the maintenance requirements of the humidification system and the weight penalty due to the water necessary to make the humidifier work. Moreover, it is sensible to minimize the risks related to structural elements corrosion and electrical malfunction. For this reason cabin humidification systems are normally not included on aircrafts.

In order to avoid too low values of the humidity when an airliner is flying at cruise altitudes, the flow rate of outside air may be reduced. Actually, there is an inherent conflict between air quality and humidity. A reduction of the flow of outside air increases the relative humidity, but also the concentration of contaminants will increase. On the other hand, in order to control the level of contaminants, it is necessary to use appropriate flows of outside air.

With the aim of contributing to a better knowledge of the topic, in this paper it is presented the experimental study of the air quality that was carried out on domestic flights linking some Italian cities. The air temperature, relative humidity and the CO<sub>2</sub> concentration data inside the cabin of an Airbus A319 aircraft were collected in order to test the air quality and the effectiveness of the ventilation system. The relative humidity inside the cabin from take-off to touchdown was calculated using the rates of outside air evaluated using carbon dioxide as a ventilation tracer and compared with the measured data. The relationship between relative humidity and carbon dioxide concentration during flights was highlighted in order to define the environmental conditions that may provide acceptable levels of both air quality and hygrometric comfort to the crew and passengers.

## 2. Experimental assessment of the air quality and relative humidity

The experimental assessment of the air quality was performed by measuring the concentration of CO<sub>2</sub> in the cabin. It is known that carbon dioxide, which is produced by human breathing, is not considered to be a toxic air contaminant, but it can be an asphyxiant in confined spaces. The rate at which carbon dioxide is produced depends on the diet and the physical activity. With a normal diet mix of fat, carbohydrate and protein, the CO<sub>2</sub> generation is 310 mL/min for an activity level of 1.2 met units [29].

Some studies [30–32] have shown that, if a ventilation rate of 7.5 L/s per person is provided, odours of human bio-effluents from sedentary persons can kept to levels that satisfy about 80% of unadapted visitors to a space. The steady-state CO<sub>2</sub> concentration,

**Table 1**  
Data of flights.

Flight no.	Air route	Passengers	Distance [km]	Altitude [m]	Date	Take-off	Landing	Duration
1	Palermo–Verona	140	818	11,278	08 Sep. 2011	08:34	09:57	1:23
2	Verona–Palermo	70	818	11,278	08 Sep. 2011	10:45	11:52	1:07
3	Palermo–Verona	143	818	11,278	12 Sep. 2011	07:23	08:40	1:17
4	Verona–Palermo	113	818	11,278	12 Sep. 2011	09:27	10:37	1:09
5	Palermo–Milan	146	887	11,278	12 Sep. 2011	12:15	13:32	1:17
6	Milan–Palermo	134	887	11,278	12 Sep. 2011	14:37	15:57	1:20
7	Palermo–Rome	87	426	9754	08 Oct. 2011	14:59	15:47	0:48
8	Rome–Palermo	95	426	9754	08 Oct. 2011	17:11	17:50	0:39
9	Palermo–Turin	81	905	10,680	08 Oct. 2011	18:49	20:15	1:26
10	Turin–Palermo	84	905	10,680	08 Oct. 2011	21:05	22:12	1:07
11	Palermo–Rome	107	426	9754	10 Oct. 2011	15:12	16:01	0:49
12	Rome–Palermo	74	426	9754	10 Oct. 2011	17:16	17:53	0:37
13	Palermo–Rome	102	426	9754	10 Oct. 2011	19:55	20:45	0:50
14	Rome–Palermo	80	426	9754	10 Oct. 2011	22:26	23:03	0:37

calculated with a generation of 310 mL/min per person, will be about 700 ppmv higher than the carbon dioxide concentration in the ventilation air. Because CO<sub>2</sub> concentrations in acceptable outdoor air typically range from 350 to 500 ppmv, a level of 1000–1200 ppmv has been suggested as being representative of delivery rates of 7.5 L/s per person of outside air, when carbon dioxide is measured at equilibrium concentrations.

The experimental assessment reported in this paper was conducted in the passenger cabin of an Airbus A319 during the 14 short-haul domestic flights listed in Table 1 [33].

To monitor air quality and environmental parameters in an airliner cabin it is necessary to place sensors, which are often bulky and expensive. The study of the optimal sensor placement was faced by Zhang et al. [34] and Mazumdar et al. [35] who showed that the best location for a sensor is in the middle of the ceiling even if, to effectively detect contaminants, multipoint sampling systems for each row should be used because they can reduce the number of sensors required in the cabin. Moreover, also the practicality of using wireless sensors in airliner cabins was verified [36].

In the present study, air temperature and relative humidity measurements were performed by means of DS1923 iButton® devices, which are temperature and humidity wireless micro data loggers produced by Dallas Semiconductors. The data were sampled every minute from boarding to disembarking. With the aim of verifying the uniformity of the environmental conditions in the cabin, the air temperature and the relative humidity were measured at same time in 15 points that were regularly distributed throughout the airplane in order to divide the cabin in five sections with about the same volume, as it is shown in Fig. 1.

The temperature/humidity sensors were placed in the middle of the ceiling and in the upper part of the walls of the cabin, as it is shown in Figs. 2 and 3.

The CO<sub>2</sub> concentrations were measured every 5 min by means of an LSI-Lastem BSO 103 probe connected to a BABUC/M portable equipment located in the middle of the cabin. The measured values of carbon dioxide concentrations were used to calculate the rate of outside air provided to the cabin during flights. Calculations were performed supposing the steady-state conditions, by means of the following equation [29,37]:

$$V_0 = \frac{N_{CO_2}}{C_{S,CO_2} - C_{0,CO_2}} 10^6 \quad (1)$$

where  $V_0$  = outside airflow rate per person [L/s];  $N_{CO_2}$  = CO<sub>2</sub> generation rate per person [L/s];  $C_{S,CO_2}$  = CO<sub>2</sub> concentration in the cabin [ppmv];  $C_{0,CO_2}$  = CO<sub>2</sub> concentration in the outside air [ppmv].

As it has been investigated by many authors [38–41], the concentration of CO<sub>2</sub> in the atmosphere averagely ranges from 365 to 390 ppmv; a value of 380 ppmv was used to evaluate  $V_0$  with Eq. (1). For the carbon dioxide generation rate, a value of 310 mL/min per person was used. The measured CO<sub>2</sub> concentrations, the



Fig. 2. Position of a temperature/humidity sensor in the ceiling of the cabin.

corresponding outside airflow rates calculated with Eq. (1) and the measured values of the relative humidity are listed in Table 2.

The concentrations of CO<sub>2</sub> varied between 734 and 2252 ppm, which correspond to outside airflows of 14.60 and 2.76 L/s per person, respectively. The relative humidity ranged from the very low value of 8.7%, to 59.2%. The greatest values of the relative humidity were reached in correspondence of take-offs. At cruise altitudes, which the airliners keep for the most part of the time, the values of relative humidity were close to the minimum values. The average relative humidity ranged from 17.9% to 27.0%.

Many Authorities have set guidelines and standards for the ECSs of aircrafts. The Federal Aviation Administration, which operates in the U.S.A., and the European Joint Aviation Authorities have established design regulation FAR/JAR Part 25 that states that each crew member must have a minimum of 4.7 L/s of fresh air to perform their duties without undue stress or discomfort. FAR Amendment No. 25-87 sets that under normal operating conditions the ventilation system must be designed to provide each occupant with airflow containing at least 0.25 kg of fresh air per minute, which is about 5 L/s at 2400 m.

Hocking [42] analyzed the problem of the aircraft cabin air quality considering trends, effects and corporate costs and made some suggestions aimed to improve passenger comfort. As it is reported by this author, coinciding with the escalation of oil prices in 1974, the rate of outside air provided per person, which was 7 L/s since 1970, began to be gradually reduced up to 2.8 L/s, which is the value nowadays provided by some commercial aircraft. Hocking calculated that with 1000 L of space per person, which is a typical value for a fully loaded aircraft, and without any air change it would take only 2.3 min for the concentration of CO<sub>2</sub> to exceed the 1000 ppmv comfort upper limit recommended by ASHRAE [29]. In the opinion of this author it would have been necessary to provide to passengers an outside air ventilation rate close to the 7–9.4 L/s per person, which are the levels provided in good current building

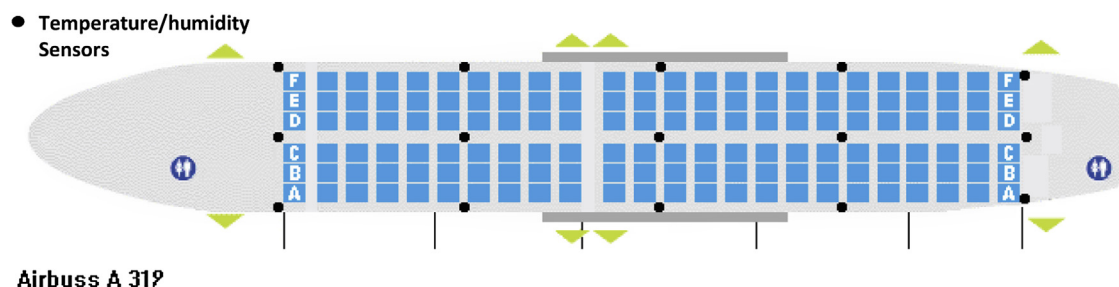


Fig. 1. Position of the temperature/humidity sensors in the cabin.





Fig. 3. Position of a temperature/humidity sensor in the wall of the cabin.

ventilation practise. Such ventilation rates should reduce the risk of transmission of airborne diseases and limit the possible discomfort effects connected to the presence of much higher than normal carbon dioxide concentrations in conjunction with the lower oxygen partial pressure, which is common at cruising altitudes. Unfortunately, as it is shown in Table 2, because no humidification is usually performed by ECSs, when very high flow rates of outside air are provided, very low levels of relative humidity in the cabin are achieved.

### 3. Assessment of the expected relative humidity in the cabin

In order to investigate the possibility of improving the hygro-metric conditions in the cabin by means of a suitable reduction of the outside airflow rate, the following procedure was used. Water vapour concentration in the cabin was calculated by means of Eq. (1), which is valid in steady-state conditions:

$$C_{C,H_2O} = \frac{N_{H_2O}}{V_0} 10^6 + C_{0,H_2O} \quad (2)$$

where  $C_{C,H_2O}$  = water vapour concentration in the cabin [ppmv];  $N_{H_2O}$  = water vapour generation rate per person [L/s];  $V_0$  = outside airflow rate per person [L/s];  $C_{0,H_2O}$  = water vapour concentration in the outside air [ppmv].

The water vapour generated by a person depends on the thermal comfort, or discomfort, conditions; thermal comfort corresponds to the situation in which the net difference between the total metabolic rate within the body and the rate of accomplished mechanical work is equal to heat dissipated from the body to the

immediate surroundings. If this thermal equilibrium is achieved, it is possible to keep the optimal internal temperature of the body. To reach this goal, the human thermoregulation system activates many complex mechanisms, such as vasoconstriction of skin blood vessels and shivering in cold environments, and vasodilatation and sweating in hot environments. The human body dissipates latent heat by evaporation from skin, natural diffusion of water through the skin and vapour loss from the respiratory tract to the inhaled air during respiration.

The rate of evaporative heat loss of the body is traditionally described with the following relations [43–46]:

$$E = E_{rs} + E_{dif} + E_{res} \quad (3)$$

with:

$$E_{rs} = 0.42(M - W - 58.15) \quad (4)$$

$$E_{dif} = 3.05[5.73 - 0.007(M - W) - p_v] \quad (5)$$

$$E_{res} = 0.0173M(5.87 - p_v) \quad (6)$$

where  $E_{rs}$  = rate of heat loss due to sweating [ $W/m^2$ ];  $E_{dif}$  = rate of heat loss due to water diffusion through the skin [ $W/m^2$ ];  $E_{res}$  = rate of heat loss due to respiration [ $W/m^2$ ];  $M$  = rate of metabolic heat production [ $W/m^2$ ];  $W$  = rate of mechanical work accomplished [ $W/m^2$ ];  $p_v$  = vapour pressure in the cabin [kPa].

The water vapour generation rate per person can be calculated considering the body surface area of a person and the thermal energy that is necessary to transform the liquid water, or sweat, into vapour:

$$M_{H_2O} = \frac{ES_b}{\Delta h} \quad (7)$$

In Eq. (7),  $M_{H_2O}$  is the amount of water vapour, in kg/s, that is emitted by sweating, natural diffusion of water through the skin and respiration;  $S_b$  is the body surface area and  $\Delta h$  is the thermal energy associated with the vapour generation, which can be calculated as the difference of the water vapour enthalpy at the ambient temperature and the liquid water enthalpy at the skin temperature:

$$\Delta h = h_v(t_a) - h_l(t_{sk}) \quad (8)$$

where  $h_v$  = specific enthalpy of the water vapour [J/kg];  $t_a$  = air temperature [°C];  $h_l$  = specific enthalpy of the liquid water [J/kg];  $t_{sk}$  = skin temperature [°C].

Table 2  
Carbon dioxide concentration, relative humidity and outside airflow rates.

Flight no.	CO <sub>2</sub> concentration [ppmv]			Outside airflow rate [L/s person]			Relative humidity [%]		
	Min.	Max.	Average	Min.	Max.	Average	Min.	Max.	Average
1	867	1344	1070	5.36	10.61	7.74	10.5	55.0	20.2
2	734	1497	925	4.63	14.60	10.56	8.7	51.5	20.2
3	957	2252	1201	2.76	8.95	6.96	11.2	59.2	22.1
4	850	2004	1238	3.18	10.99	6.86	10.7	54.0	20.7
5	817	1837	1116	3.55	11.82	7.87	11.6	54.5	21.1
6	824	1163	960	6.60	11.64	9.12	10.3	43.8	17.9
7	879	1581	1060	4.30	10.35	8.28	13.0	44.0	22.3
8	1143	1496	1286	4.63	6.77	5.81	17.5	33.0	22.1
9	961	1725	1135	3.84	8.89	7.22	14.9	37.9	19.0
10	990	1525	1247	4.51	8.47	6.20	14.4	31.1	19.2
11	1058	1911	1258	3.37	7.62	6.24	16.1	39.0	23.2
12	1119	1913	1401	3.37	6.99	5.32	19.1	38.5	24.7
13	1115	2180	1449	2.87	7.03	5.18	18.6	42.3	27.0
14	1148	2213	1345	2.82	6.73	5.87	17.5	40.0	25.9

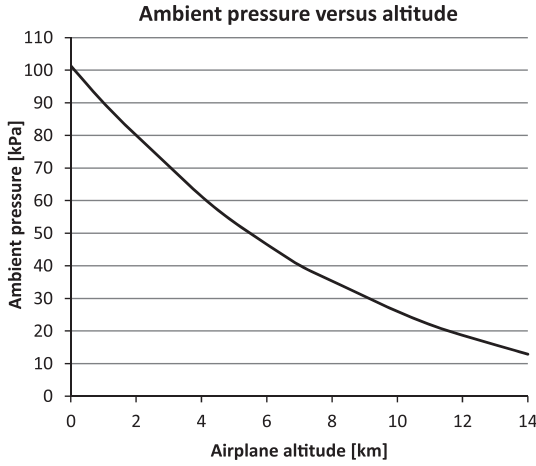


Fig. 4. Variation of ambient pressure with altitude.

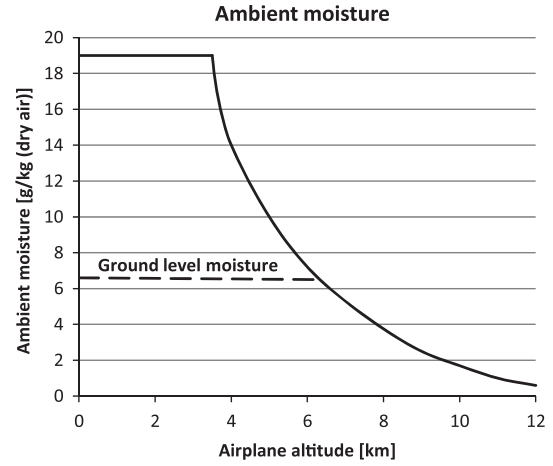


Fig. 6. Variation of ambient moisture with altitude.

To calculate the water vapour enthalpy the following equation can be used [47];

$$h_v(t_a) = (2501 + 1.86t_a)10^3 \quad (9)$$

Assuming a value of the specific heat of the liquid water equal to 4179 J/kg°C, enthalpy  $h_l$  can be evaluated as:

$$h_l(t_{sk}) = 4179(t_{sk} - 0.01) \quad (10)$$

The skin temperature can be calculated by means of the equation proposed by Rohles and Nevins [45]:

$$t_{sk} = 37.5 - 0.0275(M - W) \quad (11)$$

Even if the surface temperature of the respiratory duct may be different from the skin temperature, the present study did not consider such a difference in assessing the water emitted by respiration. The body surface area was calculated by means of the relation proposed by DuBois and DuBois [48]:

$$S_b = 0.202m^{0.425}l^{0.725} \quad (12)$$

where  $S_b$  = body surface area [m<sup>2</sup>];  $m$  = mass [kg];  $l$  = height [m].

In the hypothesis of ideal gas, which is commonly assumed dealing with moist air, water vapour generation rate  $N_{H_2O}$  in L/s per person is given by:

$$N_{H_2O} = M_{H_2O} \nu_{H_2O} 10^3 = M_{H_2O} \frac{R_u T_a}{n_{H_2O} p_a} 10^3 \quad (13)$$

where  $\nu_{H_2O}$  = water vapour specific volume [m<sup>3</sup>/kg];  $R_u$  = universal gas constant, 8.31447 kJ/kmol K;  $T_a$  = absolute ambient temperature [K];  $n_{H_2O}$  = water molar mass, 18.02;  $p_a$  = ambient pressure [Pa].

Water vapour concentration  $C_{0,H_2O}$  in the outside air is given by:

$$C_{0,H_2O} = \frac{V_{w,0}}{V_{a,0} + V_{w,0}} 10^6 \quad (14)$$

where  $V_{w,0}$  = volume of water vapour in the outside air [m<sup>3</sup>];  $V_{a,0}$  = volume of dry air in the outside air [m<sup>3</sup>].

If dry air is assumed to be an ideal gas, the volume of water vapour and dry air can be calculated as:

$$V_{w,0} = m_w \nu_{H_2O} = \frac{m_w R_u T_a}{n_{H_2O} p_a} \quad (15)$$

$$V_{a,0} = m_a \nu_a = \frac{m_a R_u T_a}{n_a p_a} \quad (16)$$

where  $m_w$  = mass of water vapour in the outside air [kg];  $m_a$  = mass of dry air in the outside air [kg];  $\nu_a$  = dry air specific volume [kg/m<sup>3</sup>];  $n_a$  = air molar mass, 28.96.

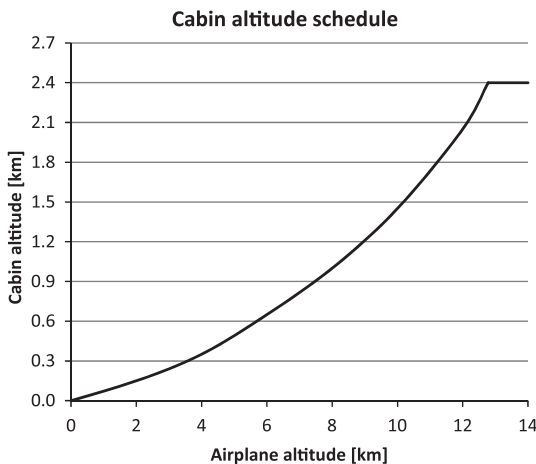


Fig. 5. Cabin altitude schedule.

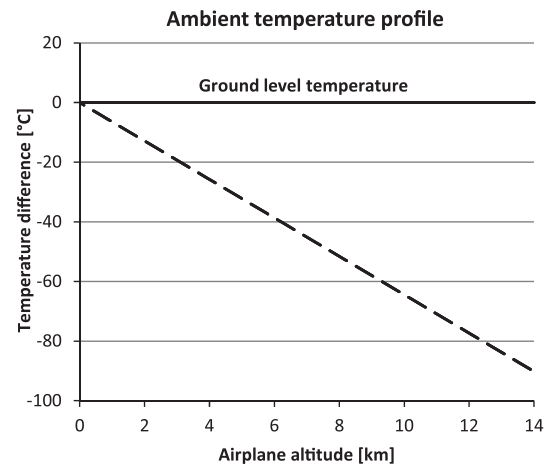


Fig. 7. Ambient temperature profile.

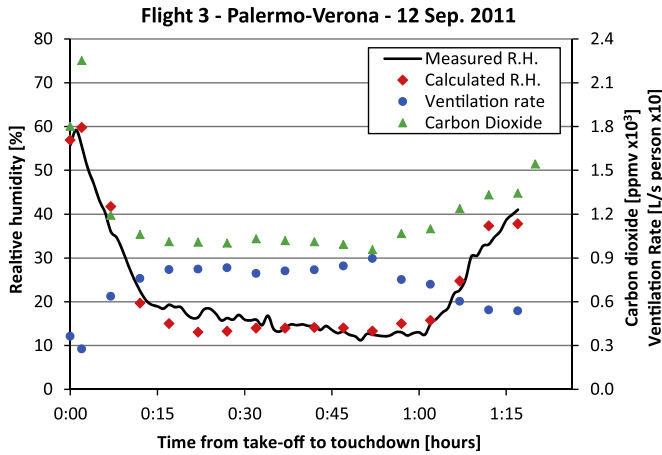


Fig. 8. Calculated and measured relative humidity, ventilation rate and CO<sub>2</sub> concentration during flight 3.

Mass of water vapour  $m_w$  can be evaluated using the outside air humidity ratio:

$$\omega = \frac{m_w}{m_a} \quad (17)$$

where  $\omega$  is the humidity ratio of the outside air [kg water vapour/kg dry air].

Using the above equations it is possible to derive the following relation for evaluating the water vapour concentration in the outside air:

$$C_{O,H_2O} = \frac{\frac{m_w R_u T_a}{n_{H_2O} p_a}}{\frac{m_a R_u T_a}{n_a p_a} + \frac{m_w R_u T_a}{n_{H_2O} p_a}} 10^6 = \frac{\frac{\omega}{18.02}}{\frac{1}{28.96} + \frac{\omega}{18.02}} 10^6 \quad (19)$$

To calculate the relative humidity in the cabin that corresponds to water vapour concentration  $C_{C,H_2O}$ , it is necessary to calculate the ambient water vapour pressure  $p_v$ , which is the pressure of the water vapour if the amount of vapour corresponding to concentration  $C_{C,H_2O}$  would occupy the entire volume of the cabin without any change in the temperature. Water vapour concentration  $C_{C,H_2O}$  is:

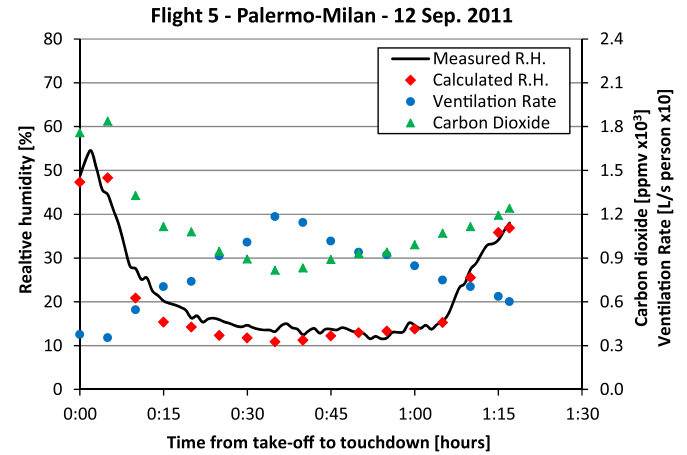


Fig. 10. Calculated and measured relative humidity, ventilation rate and CO<sub>2</sub> concentration during flight 5.

$$C_{C,H_2O} = \frac{V_{w,C}}{V_{a,C} + V_{w,C}} 10^6 \quad (20)$$

where  $V_{w,C}$  = volume of water vapour in the cabin [m<sup>3</sup>];  $V_{a,C}$  = volume of dry air in the cabin [m<sup>3</sup>].

Because, for the properties of the ideal gas, it is:

$$p_a V_{w,C} = p_v (V_{a,C} + V_{w,C}) \quad (21)$$

The water vapour pressure can be calculated with the following equation:

$$p_v = p_a \frac{V_{w,C}}{V_{a,C} + V_{w,C}} = p_a C_{C,H_2O} 10^6 \quad (22)$$

and, in turn, relative humidity  $\phi$  is:

$$\phi = \frac{p_v}{p_{v,sat@t_a}} 100 = \frac{p_a C_{C,H_2O} 10^6}{p_{v,sat@t_a}} \cdot 100 \quad (23)$$

in which  $p_{v,sat@t_a}$  is the saturation pressure of water vapour at cabin temperature  $t_a$ .

In order to calculate the relative humidity in the cabin it is necessary to know the flow rate of outside air per person  $V_0$ , temperature  $t_a$  and pressure  $p_a$  in the cabin, humidity ratio  $\omega$  of the

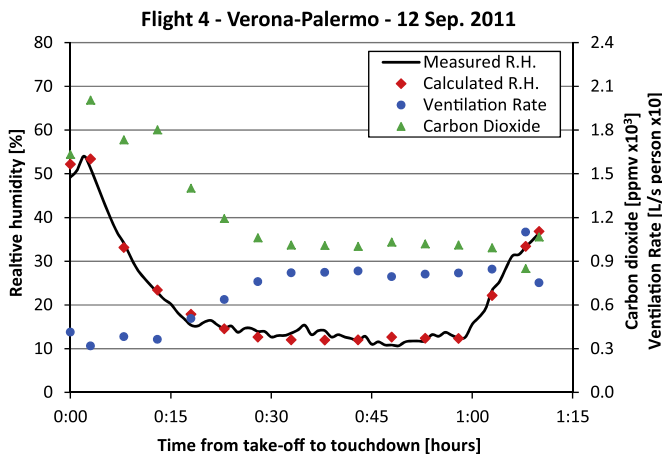


Fig. 9. Calculated and measured relative humidity, ventilation rate and CO<sub>2</sub> concentration during flight 4.

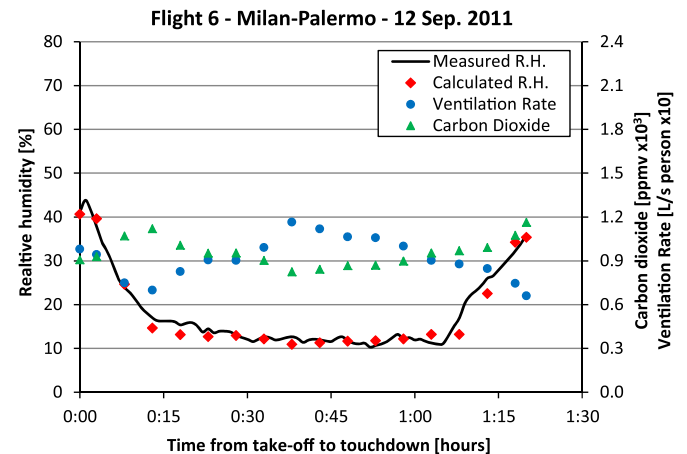


Fig. 11. Calculated and measured relative humidity, ventilation rate and CO<sub>2</sub> concentration during flight 6.

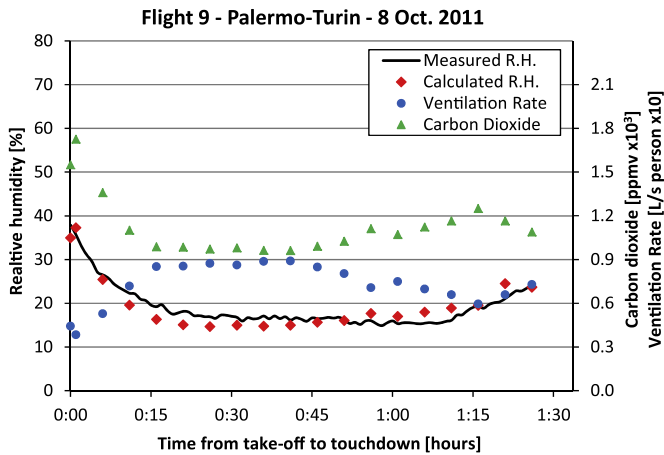


Fig. 12. Calculated and measured relative humidity, ventilation rate and CO<sub>2</sub> concentration during flight 9.

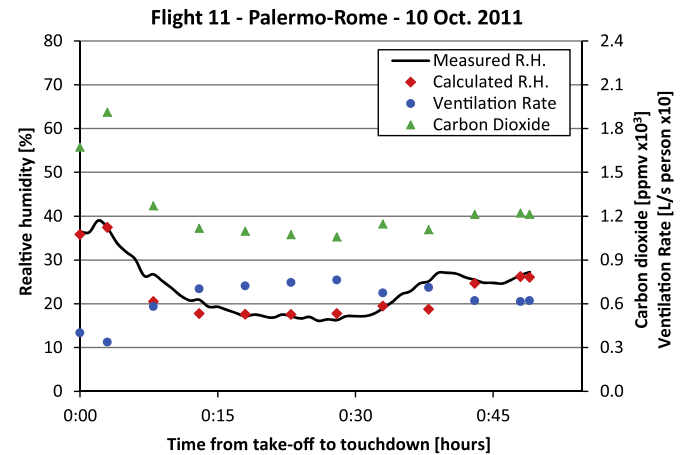


Fig. 14. Calculated and measured relative humidity, ventilation rate and CO<sub>2</sub> concentration during flight 11.

outside air, rate of metabolic heat production  $M$ , mechanical work supplied  $W$ , mass  $m$  and height  $l$  for each one of the crew and passengers. Moreover, to calculate water vapour pressure  $p_v$ , which is contained in Eqs. (5), (6) and (22), it is necessary to carry out the iterative calculation, which is described in the Appendix.

The outside airflow rate per person was determined by means of Eq. (1) using the measured CO<sub>2</sub> concentration; for the temperature in the cabin the measured data were used. The pressure in the cabin is an important parameter that directly affects the calculation of the relative humidity. During high-altitude flights the ECS changes the pressure in order to maintain the cabin pressurization according to the partial pressure of oxygen required for the crew and passengers. To allow the normal physiological functions without supplementary oxygen, the cabin trunk must be pressurized to an equivalent altitude that does not exceed 2400 m. The differential pressure control provides a cabin pressure based on the flight altitude of the aircraft. In order to consider the variation of the cabin pressure, in this paper it was assumed that the ambient pressure and the schedule cabin altitude changed with the aircraft altitude as it is shown in Figs. 4 and 5 [37].

The humidity ratio of the outside air is another relevant parameter of the problem. Actually, the value of the humidity ratio changes with the altitude and with weather conditions. Because it only was possible to get experimental data at ground level, the

variation of ambient moisture with the altitude proposed by ASHRAE [37], which is shown in Fig. 6, was adopted. Only the values of the diagram of Fig. 6 that are less than the ground level data were used for calculations. Moreover, to avoid using unrealistic values of the humidity ratio, also the effect of the outside air temperature was considered adopting the ambient temperature profile of Fig. 7 [37].

A value of the rate of metabolic heat production equal to 1.15 met was assumed, whereas the rate of the mechanical work supplied was considered negligible. To take into account the presence of both male and female passengers, a value of the body surface area of 1.75 m<sup>2</sup> was considered. The saturation pressure of water vapour was calculated using the polynomial equations provided by ASHRAE for saturation pressure over ice and over liquid water in the temperature range of  $-100\text{ }^{\circ}\text{C}$ – $200\text{ }^{\circ}\text{C}$  [37].

The calculations of the relative humidity were carried out for all flights of Table 1 and the results were compared with the measurements performed from take-off to landing. For the sake of brevity only the results of the most significant flights are depicted in Figs. 8–15.

Observing Figs. 8–15 it is possible to affirm that the used procedure permitted to reach an adequate level of accuracy in calculating the relative humidity in the cabin. The greater differences between calculated and measured data correspond to the lapses of

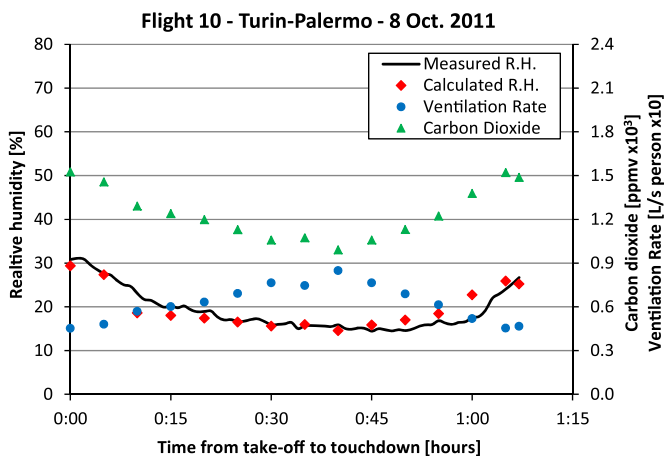


Fig. 13. Calculated and measured relative humidity, ventilation rate and CO<sub>2</sub> concentration during flight 10.

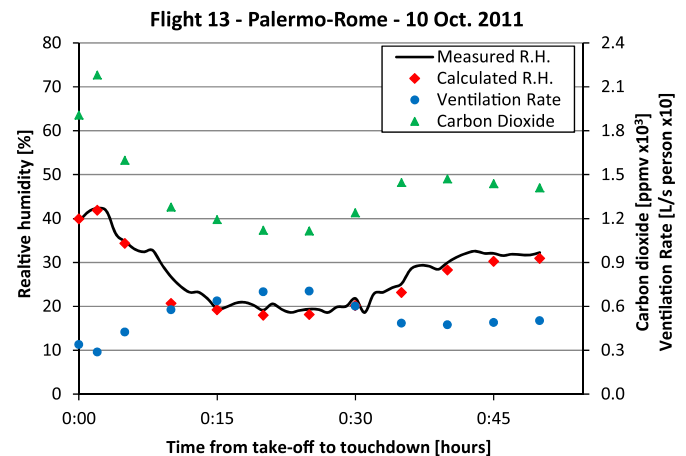


Fig. 15. Calculated and measured relative humidity, ventilation rate and CO<sub>2</sub> concentration during flight 13.



**Table 3**

Differences between calculated and measured relative humidity.

Flight no.	Relative humidity absolute difference [%]			Relative humidity difference [%]		
	Min.	Max.	Average	Min.	Max.	Average
1	0.02	5.84	2.16	−5.84	2.63	−0.66
2	0.15	5.47	2.08	−5.47	2.96	−0.86
3	0.15	5.74	2.41	−4.31	5.74	0.14
4	0.10	2.96	1.16	−2.19	2.96	0.22
5	0.28	6.76	2.25	−6.76	3.79	−1.43
6	0.02	3.81	1.41	−3.81	1.99	−0.58
7	0.11	5.15	2.81	−5.15	0.32	−2.74
8	0.04	5.07	1.99	−5.07	4.07	0.51
9	0.19	3.38	1.87	−3.11	3.38	−0.43
10	0.13	5.17	1.72	−4.48	5.17	−0.05
11	0.09	6.43	1.82	−6.43	1.48	−1.34
12	0.82	5.03	3.07	−5.03	−0.82	−3.07
13	0.32	6.07	2.00	−6.07	0.55	−1.48
14	0.37	5.34	2.31	−2.03	5.34	1.57

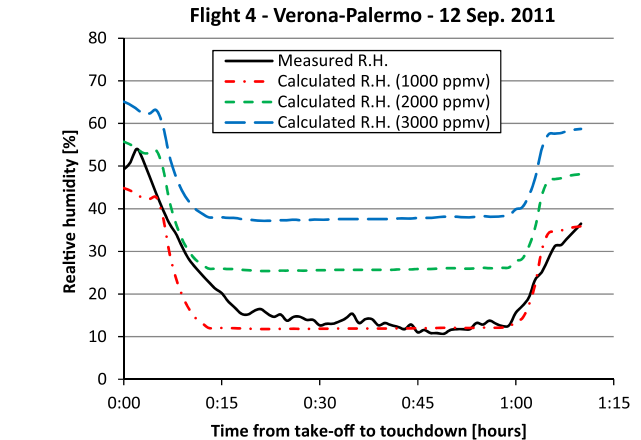
time after take-off and before touchdown when the greatest variations in the aircraft altitude are present. Actually, because the calculus is very sensitive to the ambient moisture, which in turn depends on the altitude, the accurate measurements of the aircraft altitude should have been necessary. Unfortunately, the safety-related rules obeyed during take-off and touchdown did not permit to ask the crew about the aircraft altitude. For this reason the calculations were performed taking account of the normal maximum rates of change of cabin pressure, which are 150 m/min for increasing altitude and 90 m/min for decreasing altitude. Table 3 lists some figures of the accuracy achieved in calculating the relative humidity in the cabin.

The average absolute difference between calculated and measured values of the relative humidity ranges from 1.16 to 3.07%, whereas the average difference is included between −3.07 and 1.57%.

The absolute maximum differences vary from 2.96 to 6.76%.

#### 4. Improvement of the relative humidity levels in the cabin

Because, on the basis of the comparison between measured and calculated data, it can be claimed that the above procedure is able to adequately represent the relationship between relative humidity, CO<sub>2</sub> concentration and rate of outside air during flights, such a procedure was used to predict the possibility of increasing the

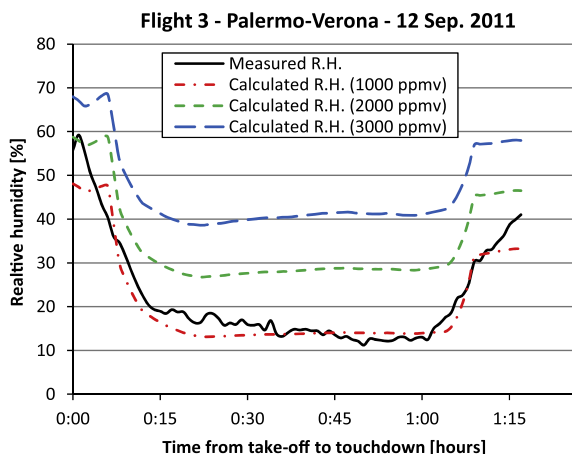


**Fig. 17.** Measured and simulated relative humidity, for fixed, concentrations of CO<sub>2</sub>, during flight 4.

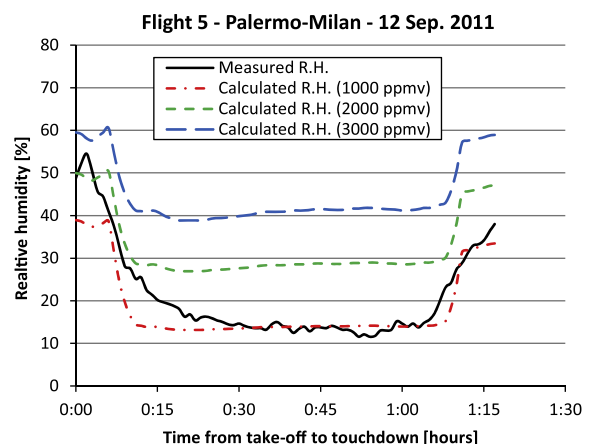
comfort of the crew and passengers in order to reach a compromise between low levels of CO<sub>2</sub> and sufficient values of relative humidity in an aircraft cabin. At first, to reach this purpose, it is necessary to define the limit values of carbon dioxide concentration and the relative humidity in the cabin than can be considered acceptable.

Even if they do not have toxic effects, relatively high values of CO<sub>2</sub> concentration are usually correlated to stuffy air for the lack of sufficient ventilation and the increased perception of the odours due to the presence of human bio-effluents. Many Authorities have set the limit of carbon dioxide in workplaces to 3500 ppmv [49] or to 5000 ppmv [50–53]. Carbon dioxide concentrations of 5000 ppmv, sea level equivalent, are also considered the upper limit by the Federal Aviation Administration and the European Joint Aviation Authorities [54,55].

The European Standard EN 4618 [56], which covers the aircraft internal air quality standards, criteria and determination methods, has confirmed the safety limit of 5000 ppmv and has set a comfort limit of 2000 ppmv. The comfort limit is assumed as the limit that, if exceeded, would not allow an acceptable cabin environment, which is defined as the one in which a significant majority of the exposed people would not express dissatisfaction with the air quality contaminants and/or environmental criteria. In the EN 4618 Standard it is claimed that such comfort limit was set on the basis of the data collected in the measurements programme carried out in the EC CabinAir Project [57], which consistently indicated an absolute



**Fig. 16.** Measured and simulated relative humidity, for fixed, concentrations of CO<sub>2</sub>, during flight 3.



**Fig. 18.** Measured and simulated relative humidity, for fixed, concentrations of CO<sub>2</sub>, during flight 5.

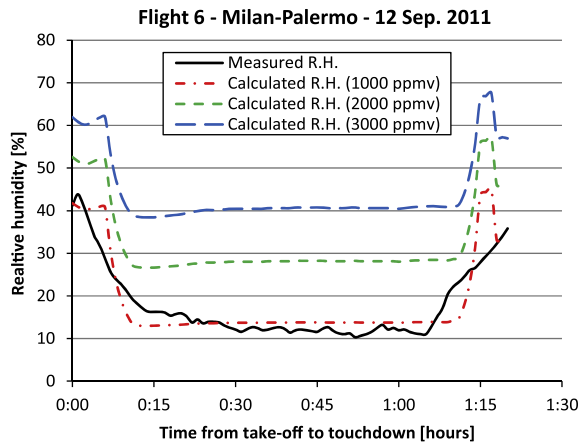


Fig. 19. Measured and simulated relative humidity, for fixed, concentrations of  $\text{CO}_2$ , during flight 6.

carbon dioxide level below 2000 ppmv. Moreover, the results of the analysis of the data collected with the subjective comfort questionnaire further demonstrated that such carbon dioxide levels did not affect comfort.

With the aim of verifying the effect of varying the rate of outside air to increase the level of the relative humidity in the cabin, calculations were performed assuming the ventilation rates necessary to keep the carbon dioxide concentration during flights at a constant value.

Figs. 16–23 show the simulations of the variation of the relative humidity that were carried out assuming the constant  $\text{CO}_2$  concentrations of 1000, 2000 and 3000 ppmv and the corresponding outside air rates of 8.33, 3.19 and 1.97 L/s per person.

Figs. 16–23 highlight the effect of the variation of the rate of outside air that is correlated to the different values of constant  $\text{CO}_2$  concentrations used in calculations. It easy to see that, with a carbon dioxide concentration of 2000 ppmv the relative humidity in the cabin comes close to 30% at cruising altitudes, whereas a value of about 40% is reached if the a  $\text{CO}_2$  concentration of 3000 ppmv is assumed. For all flights Table 4 lists some figures of the relative humidity in the cabin.

The average relative humidity in the cabin ranges from 29.9% to 36.0%, for a carbon dioxide concentration of 2000 ppmv, and from 42.1% to 47.7% with a  $\text{CO}_2$  concentration of 3000 ppmv.

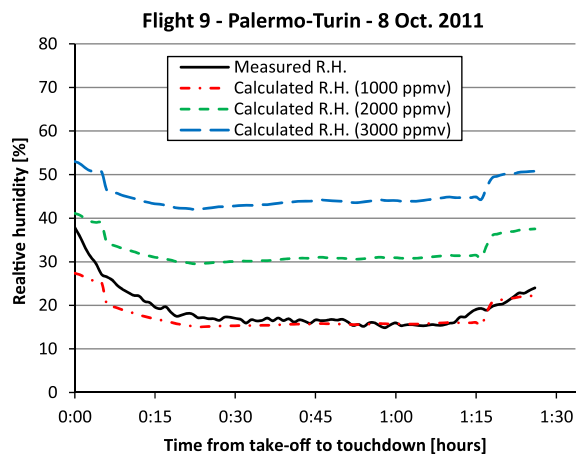


Fig. 20. Variation of measured and simulated relative humidity, for fixed, concentrations of  $\text{CO}_2$ , during flight 9.

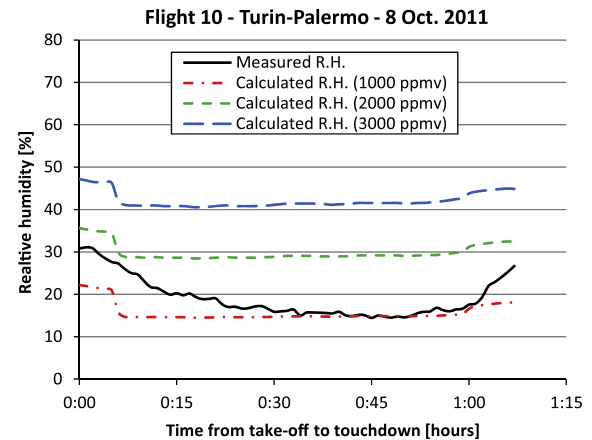


Fig. 21. Measured and simulated relative humidity, for fixed, concentrations of  $\text{CO}_2$ , during flight 10.

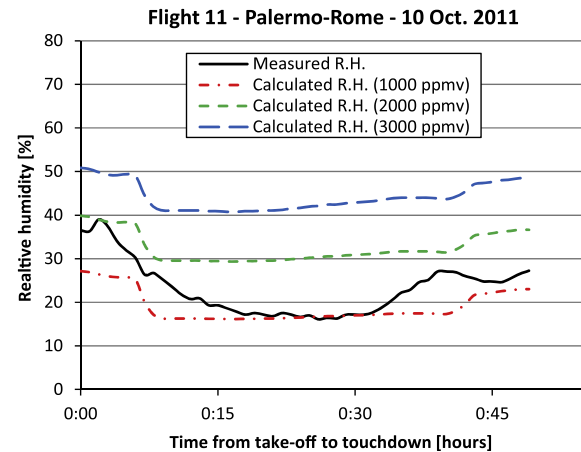


Fig. 22. Measured and simulated relative humidity, for fixed, concentrations of  $\text{CO}_2$ , during flight 11.

Such values of relative humidity are definitely more suited to reduce the discomfort caused by dryness of nose, eyes, throat and skin. On the other hand, the reduction of the ventilation rate may increase the number of persons who may be dissatisfied with the level of body odour in the cabin. The percentage of dissatisfied can be calculated by means of the following equation [58]:

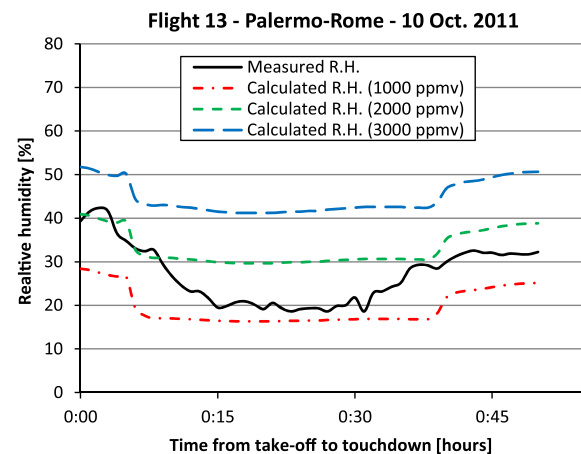


Fig. 23. Measured and simulated relative humidity, for fixed, concentrations of  $\text{CO}_2$ , during flight 13.

**Table 4**Figures of the relative humidity calculated for fixed values of CO<sub>2</sub> concentration.

Flight no.	Calculated relative humidity in the cabin [%]								
	CO <sub>2</sub> concentration 1000 ppmv			CO <sub>2</sub> concentration 2000 ppmv			CO <sub>2</sub> concentration 3000 ppmv		
	Min.	Max.	Average	Min.	Max.	Average	Min.	Max.	Average
1	12.5	43.9	18.7	25.6	55.1	31.8	37.0	64.9	43.1
2	13.4	46.4	21.9	27.3	57.5	35.6	39.4	67.1	47.5
3	13.1	48.1	20.4	26.7	58.8	34.1	38.6	68.5	46.0
4	11.8	44.9	18.1	25.4	55.7	31.4	37.2	65.1	43.0
5	13.2	38.9	18.4	26.9	50.4	32.4	38.9	60.6	44.5
6	13.0	45.1	18.7	26.7	57.2	32.4	38.4	67.6	44.3
7	16.3	34.1	19.7	29.6	46.5	33.2	41.1	57.2	44.8
8	15.9	26.8	18.4	29.5	39.6	32.3	41.4	50.7	44.3
9	15.0	27.4	17.4	29.5	41.1	32.2	42.0	53.0	45.0
10	14.5	22.2	15.7	28.4	35.6	29.9	40.5	47.2	42.1
11	16.2	27.1	19.0	29.4	39.9	32.5	40.8	50.9	44.2
12	14.1	23.0	16.9	27.9	36.3	30.7	39.8	47.8	42.6
13	16.3	28.4	19.6	29.7	40.9	33.1	41.2	51.8	44.7
14	16.6	33.0	22.5	30.1	46.4	36.0	41.8	58.0	47.7

$$PD = 395 e^{-15.15C_{CO_2}^{-0.25}} \quad (24)$$

where  $C_{CO_2}$  is the above carbon dioxide concentration outdoors, in ppmv. Actually, Eq. (24), which was defined on the basis of experiments involving office workers and university students with modern habits of personal hygiene [30,59,60], may yields to results not corresponding to the reality dealing with occupants that have different frequency of bathing and societal expectations. Anyway, assuming a value of 380 ppmv and of 2000 ppmv for the concentrations of carbon dioxide in the atmosphere and in the cabin, respectively, Eq. (24) yields a percentage of dissatisfied equal to 36.3%, which permits to claim that a substantial majority of the people exposed would not be expected to express dissatisfaction. With a CO<sub>2</sub> concentration in the cabin of 3000 ppmv the percentage of dissatisfied would rise to 47.5%, which may be considered too high. As a conclusion, keeping a carbon dioxide concentration of 2000 ppmv during flight, which is not an issue for the modern ECS technology, can be considered an effective way to reach adequate levels of air quality and hygrometric comfort.

Even if the results of the study seem to be significant, a caveat has to be provided. Table 1 shows that the flight durations ranged from 37 min to 1 h and 26 min. Such lapses of time, especially the shorter ones, may be too small to allow the crew and passengers to adapt themselves to the airliner cabin that is an environment quite different from the places, such as the waiting areas of the airport terminal, where people stayed for long before boarding. For this reason, the used steady-state conditions might be considered unrealistic and it would be sensible to adopt a dynamic approach to assess the effects of CO<sub>2</sub> and water vapour concentrations especially during the initial part of flights. Unfortunately, because the data describing the variation of the water vapour and CO<sub>2</sub> emitted by the human body in transient conditions were not available, the study was carried out assuming the steady-state conditions. Obviously such hypotheses limit the field of validity of the present study to the parts of each flight that are sufficiently far from the take-off. For this reason, as longer the flight durations are, so more reliable the global results should be. In our opinion the conclusions of the present study should be fair valid for long-haul flights, whose duration is greater than 5 h, and transoceanic flights.

## 5. Conclusions

With the aim of assessing the possibility of improving the hygrometric conditions in the aircraft cabins by means of a suitable reduction of the outside airflow rate, a relationship between the

relative humidity and carbon dioxide concentration was set. The reliability of the relationship was tested by comparison with the data collected in the passenger cabin of an Airbus A319 during 14 short-haul domestic flights during which the measured values of the relative humidity ranged from 17.9% to 27.0%.

The relationship was used to predict the possibility of increasing the comfort of the crew and passengers reaching a suitable compromise between low levels of CO<sub>2</sub> and sufficient values of relative humidity in the aircraft cabin. The results of calculations showed that, slightly increasing the carbon dioxide concentration up to 2000 ppmv, the relative humidity in the cabin comes close to a satisfactory value of 30% at cruising altitudes, whereas a value of about 40% can be reached if the a CO<sub>2</sub> concentration of 3000 ppmv is assumed as a possible level. If the cabin ventilation rate was controlled by a CO<sub>2</sub> detector, the energy cost of the aircraft ECS would decrease and the crew and passengers would feel more comfortable.

## Acknowledgments

The Authors are pleased to thank the WindJet Airline Company and the Commander D. Catalisano for their valuable support, as well as the PHD students M. Ariolo and D. Giurintano who have carried out the measurement campaign onboard the WindJet Aircrafts.

## Appendix

Calculation flow chart for the relative humidity in the cabin.

Input data:

$C_{O,CO_2}$	CO <sub>2</sub> concentration in the outside air, from Eq. (19) [ppmv]
$M$	rate of metabolic heat production [W/m <sup>2</sup> ]
$p_a$	ambient pressure [Pa]
$S_b$	body surface area [m <sup>2</sup> ]
$t_a$	ambient temperature [°C]
$T_a$	absolute ambient temperature [K]
$\nu_{H_2O}$	water vapour specific volume at $t_a$ and $p_a$ [m <sup>3</sup> /kg]
$V_0$	outside airflow rate per person [L/s]
$W$	rate of mechanical work accomplished [W/m <sup>2</sup> ]
$\omega$	humidity ratio of the outside air [kg water vapour/kg dry air]
$p_{v,sat@t_a}$	saturation pressure of water vapour at temperature $t_a$
$N_{H_2O} = 0$	set first attempt value of the water vapour generation rate per person

Beginning of iterative calculation:

$$C_{C,H_2O} = \frac{N_{H_2O}}{V_0} 10^6 + C_{0,H_2O} \quad (1a)$$

$$\phi = \frac{p_a C_{C,H_2O}}{p_{v,sat@t_a}} 10^8 \quad (2a)$$

$$p_v = p_{v,sat@t_a} \frac{\phi}{100} \quad (3a)$$

$$h_v(t_a) = (2501 + 1.86t_a) 10^3 \quad (4a)$$

$$t_{sk} = 37.5 - 0.0275(M - W) \quad (5a)$$

$$h_l(t_{sk}) = 4179(t_{sk} - 0.01) \quad (6a)$$

$$\Delta h = h_v(t_a) - h_l(t_{sk}) \quad (7a)$$

$$E_{rsW} = 0.42(M - W - 58.15) \quad (8a)$$

$$E_{dif} = 3.05[5.73 - 0.007(M - W) - p_v] \quad (9a)$$

$$E_{res} = 0.0173M(5.87 - p_v) \quad (10a)$$

$$E = E_{rsW} + E_{dif} + E_{res} \quad (11a)$$

$$M_{H_2O} = \frac{ES_b}{\Delta h} \quad (12a)$$

$$N_{H_2O}^* = M_{H_2O} \nu_{H_2O} 10^3 \quad (13a)$$

IF  $N_{H_2O}^* - N_{H_2O} > \text{Calculation Accuracy}$ .  
THEN.

Adequately change the value of  $N_{H_2O}$  and repeat the iteration  
ELSE

$$C_{C,H_2O} = \frac{N_{H_2O}^*}{V_0} 10^6 + C_{0,H_2O} \quad (14a)$$

$$\phi = \frac{p_a C_{C,H_2O}}{p_{v,sat@t_a}} 10^8 \quad (2b)$$

## Nomenclature

$C_{C,H_2O}$	water vapour concentration in the cabin [ppmv]
$C_{CO_2}$	CO <sub>2</sub> concentration above outdoors [ppmv]
$C_{S,CO_2}$	CO <sub>2</sub> concentration in the cabin [ppmv]
$C_{0,CO_2}$	CO <sub>2</sub> concentration in the outside air [ppmv]
$C_{0,H_2O}$	water vapour concentration in the outside air [ppmv]
$E$	rate of evaporative heat loss of the body [W/m <sup>2</sup> ]
$E_{dif}$	rate of heat loss due to water diffusion through the skin [W/m <sup>2</sup> ]
$E_{res}$	rate of heat loss due to respiration [W/m <sup>2</sup> ]
$E_{rsW}$	rate of heat loss due to sweating [W/m <sup>2</sup> ]
$h_l$	specific enthalpy of the liquid water [J/kg]
$h_v$	specific enthalpy of the water vapour [J/kg]
$l$	body height [m]
$M$	rate of metabolic heat production [W/m <sup>2</sup> ]
$M_{H_2O}$	water vapour emitted by the body [kg/s]
$m$	body mass [kg]
$m_a$	mass of dry air in the outside air [kg]
$m_w$	mass of water vapour in the outside air [kg]
$N_{CO_2}$	CO <sub>2</sub> generation rate per person [L/s]

$N_{H_2O}$	water vapour generation rate per person [L/s]
$n_a$	air molar mass, 28.96
$n_{H_2O}$	water molar mass, 18.02
$p_a$	ambient pressure [Pa]
$p_v$	vapour pressure in the cabin [kPa]
$R_u$	universal gas constant, 8.31447 kJ/kmol K
$S_b$	body surface area [m <sup>2</sup> ]
$T_a$	absolute ambient temperature [K]
$t_a$	air temperature [°C]
$t_{sk}$	skin temperature [°C]
$V_{a,0}$	volume of dry air in the outside air [m <sup>3</sup> ]
$V_{a,C}$	volume of dry air in the cabin [m <sup>3</sup> ]
$V_{w,0}$	volume of water vapour in the outside air [m <sup>3</sup> ]
$V_{w,C}$	volume of water vapour in the cabin [m <sup>3</sup> ]
$V_0$	outside airflow rate per person [L/s]
$\nu_a$	dry air specific volume [kg/m <sup>3</sup> ]
$\nu_{H_2O}$	water vapour specific volume [m <sup>3</sup> /kg]
$W$	rate of mechanical work accomplished [W/m <sup>2</sup> ]
$\phi$	relative humidity [%]
$\omega$	humidity ratio of the outside air [kg water vapour/kg dry air]

## References

- [1] Dechow M, Sohn H, Steinhanses J. Concentrations of selected contaminants in cabin air of airbus aircrafts. *Chemosphere* 1997;35(1/2):21–31.
- [2] Lee S, Poon C, Li X, Luk F. Indoor air quality investigation on commercial aircraft. *Indoor Air* 1999;9:180–7.
- [3] 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 Environment* 1999;8:58–66.
- [4] Wang A, Zhang Y, Sun Y, Wang X. Experimental study of ventilation effectiveness and air velocity distribution in an aircraft cabin mockup. *Building and Environment* 2008;43:337–43.
- [5] Kühn M, Bosbach J, Wagner C. Experimental parametric study of forced and mixed convection in a passenger aircraft cabin mock-up. *Building and Environment* 2009;44:961–70.
- [6] Chen Q, Jones BW, Loo SM, Nazaroff WW, Overfelt RA, Spengler JD, et al. Report to the FAA on the Airliner Cabin Environment. Report No. RITE-ACER-CoE-2010-1. National Air Transportation Center of Excellence for Research in the Intermodal Transport Environment (RITE) - Airliner Cabin Environmental Research (ACER) Program; 2010.
- [7] Spengler JD, Vallarino J, McNeely E, Estephan H, Sumner AL. In-flight/onboard monitoring: ACER's component for ASHRAE 1262, Part 2. Report No. RITE-ACER-CoE-2012-6. National Air Transportation Center of Excellence for Research in the Intermodal Transport Environment (RITE) - Airliner Cabin Environmental Research (ACER) Program; 2012.
- [8] Gladyszewska-Fiedoruk K. Indoor air quality in the cabin of an airliner. *Journal of Air Transport Management* 2012;20:28–30.
- [9] Chen Q, McDevitt JJ, Gupta JK, Jones BW, Mazumdar S, Poussou SB, et al. Infectious disease transmission in airliner cabins. Report No. RITE-ACER-CoE-2012-01. National Air Transportation Center of Excellence for Research in the Intermodal Transport Environment (RITE) - Airliner Cabin Environmental Research (ACER) Program; 2012.
- [10] Chen Q, Zhang Z. Prediction of particle transport in enclosed environment. *China Particuology* 2005;3(6):364–72.
- [11] Zhang Z, Chen Q. Experimental measurements and numerical simulations of particle transport and distribution in ventilated rooms. *Atmospheric Environment* 2006;40:3396–408.
- [12] Zhang Z, Chen Q. Comparison of the Eulerian and Lagrangian methods for predicting particle transport in enclosed spaces. *Atmospheric Environment* 2007;41:5236–48.
- [13] Zhang TF, Chen Q. Identification of contaminant sources in enclosed environments by inverse CFD modeling. *Indoor Air* 2007;17:167–77.
- [14] Mazumdar S, Chen Q. A one-dimensional analytical model for airborne contaminant transport in airliner cabins. *Indoor Air* 2009;19:3–13.
- [15] Zhang T, Chen Q. Novel air distribution systems for commercial aircraft cabins. *Building and Environment* 2007;42:1675–84.
- [16] Poussou SB, Mazumdar S, Plesniak MW, Sojka PE, Chen Q. Flow and contaminant transport in an airliner cabin induced by a moving body: model experiments and CFD predictions. *Atmospheric Environment* 2010;44:2830–9.
- [17] Mazumdar S, Poussou SB, Lin CH, Isukapalli SS, Plesniak MW, Chen Q. Impact of scaling and body movement on contaminant transport in airliner cabins. *Atmospheric Environment* 2011;45:6019–28.
- [18] Gupta JK, Lin CH, Chen Q. Inhalation of expiratory droplets in aircraft cabins. *Indoor Air* 2011;21(4):341–50.
- [19] Gupta JK, Lin CH, Chen Q. Transport of expiratory droplets in an aircraft cabin. *Indoor Air* 2011;21(1):3–11.

- [20] Gupta JK, Lin CH, Chen Q. Risk assessment for airborne infectious diseases in aircraft cabins. *Indoor Air* 2012;22(5):388–95.
- [21] Rankin WL, Space DR, Nagda NL. Passenger comfort and the effect of air quality. In: Nagda NL, editor. *Air quality and comfort in airliner cabins*. Conshohocken, PA: American Society for Testing and Materials (ASTM); 2000. p. 269–89.
- [22] Lee SC, Poon CS, Li D, Luk F, Chang M. Questionnaire survey to evaluate the health and comfort of cabin crew. In: Nagda NL, editor. *Air quality and comfort in airliner cabins*. Conshohocken, PA: American Society for Testing and Materials (ASTM); 2000. p. 259–66.
- [23] Lindgren T, Norbäck D, Andersson K, Dammstrom BG. Cabin environment and perception of cabin air quality among commercial aircrew. *Aviation Space and Environmental Medicine* 2000;71(8):774–82.
- [24] Lindgren T, Norbäck D. Health and perception of cabin air quality among Swedish commercial airline crew. *Indoor Air* 2005;15(s10):65–72.
- [25] Nagda NL, Hodgson M. Low relative humidity and aircraft cabin air quality. *Indoor Air* 2001;11(3):200–14.
- [26] Lindgren T, Norbäck D, Wieslander G. Perception of cabin air quality in airline crew related to air humidification, on Intercontinental flights. *Indoor Air* 2007;17(3):204–10.
- [27] Strøm-Tejsten P, Wyon DP, Lagercrantz L, Fang L. Occupant evaluation of 7-hour exposures in a simulated aircraft cabin – Part 1: Optimum balance between fresh air and supply and humidity. *Indoor Air* 2005;40–5.
- [28] Grün G, Trimmel M, Holm A. Low humidity in the aircraft cabin environment and its impact on well-being – results from laboratory study. *Building and Environment* 2012;47:23–31.
- [29] ASHRAE Standard 62.1-2007. Ventilation for acceptable indoor air quality 2007.
- [30] Berg-Munch B, Clausen G, Fanger PO. Ventilation requirements for the control of body odour in spaces occupied by women. *Environment International* 1986;12:195–9.
- [31] Cain WS, Leaderer BP, Isseroff R, Berglund LG, Huey RJ, Lipsitt ED, et al. Ventilation requirements in buildings – I. Control of occupancy odor and tobacco smoke odor. *Atmospheric Environment* 1983;17(6):1183–97.
- [32] Fanger PO, Berg-Munch B. Ventilation and body odor. In: *Proceedings of Engineering Foundation Conference on Management of atmospheres in tightly enclosed spaces*. Atlanta: ASHRAE; 1983. p. 45–50.
- [33] Catalisano D, Giaconia C, Grillo C, Montano F. An experimental investigation on air quality inside WindJet aircraft. In: *4th International Conference on Applied human factors and Ergonomics 2012 (AHFE 2012)* San Francisco, California, USA, July 21–25 2012.
- [34] Zhang T, Chen Q, Lin CH. Optimal sensor placement for airborne contaminant detection in an aircraft cabin. *HVAC&R Research* 2007;13(5):683–96.
- [35] Mazumdar S, Chen Q. Influence of cabin conditions on placement and response of contaminant detection sensors in a commercial aircraft. *Journal of Environmental Monitoring* 2008;10:71–81.
- [36] Loo SM, Jones B, Kiepert J, Pook M, Anderson M. Bleed-air sensing: wireless sensor networks in mock-up cabin. Report No. RITE-ACER-CoE-2012-4. National Air Transportation Center of Excellence for Research in the Intermodal Transport Environment (RITE), Airliner Cabin Environment Research Program; 2012.
- [37] ASHRAE. Hvac application 2007.
- [38] Machida T, Kita K, Kondo Y, Blake D, Kawakami S, Inoue G, et al. Vertical and meridional distributions of the atmospheric CO<sub>2</sub> mixing ratio between northern midlatitudes and southern subtropics. *Journal of Geophysical Research* 2003;108(d3).
- [39] Sawa Y, Matsueda H, Makino Y, Inoue HY, Murayama S, Hirota M, et al. Aircraft Observation of CO<sub>2</sub>, CO, O<sub>3</sub> and H<sub>2</sub> over the North Pacific during the PACE-7 Campaign. *Tellus* 2004;56B:2–20.
- [40] Foucher PY, Chédin A, Armante R, Boone C, Crevoisier C, Bernath P. Carbon dioxide atmospheric vertical profiles retrieved from space observation using ACE-FTS solar occultation instrument. *Atmospheric Chemistry and Physics* 2011;11:2455–70.
- [41] Tuzson B, Henne S, Brunner D, Steinbacher M, Mohn J, Buchmann B, et al. continuous isotopic composition measurements of tropospheric CO<sub>2</sub> at Jungfraujoch (3580 m a.s.l.), Switzerland: real-time observation of regional pollution events. *Atmospheric Chemistry and Physics* 2011;11:1685–96.
- [42] Hocking MB. Passenger aircraft cabin air quality: trends, effects, societal costs, proposals. *Chemosphere* 2000;41:603–15.
- [43] Fanger PO. Calculation of thermal comfort: Introduction of a basic comfort equation. *ASHRAE Transactions* 196; 773(2): III.4.1.
- [44] Fanger PO. Thermal comfort analysis and applications in environmental engineering. New York: McGraw-Hill; 1970.
- [45] Rohles Jr FH, Nevins RG. The nature of thermal comfort for sedentary man. *ASHRAE Transactions* 1971;77(1):239.
- [46] Fanger PO. Thermal comfort. Malabar, FL: Robert E. Krieger; 1982.
- [47] ASHRAE. Fundamentals 2009.
- [48] DuBois D, DuBois F. A formula to estimate approximate surface area, if height and weight are known. *Archives of Internal Medicine* 1916;17:863–71.
- [49] Exposure guidelines for residential indoor air quality: a report of the Federal-Provincial Advisory Committee on Environmental and Occupational Health. Health Canada; 1995.
- [50] Code of federal regulations, Title 29, part 1910-1000. U.S. Department of labour, occupational safety and health administration.
- [51] Maximum concentrations at the workplace and biological tolerance values for working materials. Commission for the Investigation of Health Hazard of Chemical Compounds in the Work Area, Federal Republic of Germany; 2000.
- [52] NIOSH pocket guide to chemical hazards (NPC). National Institute for Occupational Safety and Health; 2004.
- [53] Threshold limit values for chemical substances and physical agents and biological exposure indices. In: *American Conference of Governmental Industrial Hygienists* 2001.
- [54] Federal Aviation Administration. FAR 25. Airworthiness standards – transport category.
- [55] European Joint Aviation Authorities. JAR 25. Large Aeroplanes.
- [56] Aerospace series – aircraft internal air quality standards, criteria and determination methods.
- [57] Ross D, Crump D, Hunter C, Perera E, Sheridan A. Client report: extending cabin air measurements to include older aircraft types utilised in high volume short haul operation. BRE Environment; 2003.
- [58] ECA, European Collaborative Action, Indoor air quality and its impact on man. Guideline for ventilation requirements in building. Report No. 11, EUR1449EN.
- [59] Fanger PO, Bergh-Munch B. Ventilation requirements for the control of body odour. In: *Proceedings of an Engineering Foundation Conference on Management of atmospheres in tightly enclosed spaces*. ASHRAE; 1983. p. 45–60.
- [60] Rasmussen C, Clausen GH, Bergh-Munch B, Fanger PO. The influence of human activity on ventilation requirements for the control of body odour. In: *Proceedings of CLIMA 2000 World Congress on heating, ventilating and air-conditioning*, Copenhagen 1985;4. p. 357–63.