A PMV CONTROL STRATEGY MODEL FOR AIRCRAFT AIR CONDITIONING SYSTEM

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Abstract. *During cruise flight, aircraft cabin environmental conditions are different from that found in a building. The relative humidity, mean radiant temperature and air density are lower than that found in a building environment. The low relative humidity provides a higher evaporation and heat loss while the low mean radiant temperature imposes higher radiation heat loss. Besides, low air density implies a reduction of the convection heat loss due to lower heat transfer coefficients. Traditionally, the control strategy for aircraft air conditioning system is based on the cabin dry bulb temperature as feedback signal, similar to building air conditioning systems. These paper analyses the use of the Predicted Mean Value (PMV), which combines the effect of the relative humidity, mean radiant temperature and air density, as an alternative feedback signal for the control system of air craft air conditioning system. For the simulation, a mock flight composed of a 5 minute taxi, 20 minute climb from sea level to 35000 ft, a cruise flight of one hour and 30 minutes, a 20 minute descent and a 5 minute taxi to the gate was considered. The results showed that the combination of the effects of low relative humidity, low mean radiant temperature and low air density required higher cabin air temperature than that for building environments for thermal neutrality.*

Keywords*. air conditioning, aircraft, control system, thermal comfort, simulation*

1. Introduction

During cruise flight, aircraft cabin environmental conditions are different from that found in a building. The relative humidity, mean radiant temperature and air density are lower than that found in a building environment. The relative humidity is around 15 to 20 %, the mean radiant temperature is lower than air temperature and the air density is lower than 1,18 kg/m^3. The low relative humidity provides a higher evaporation and heat loss while the low mean radiant temperature imposes higher radiation heat loss. Besides, low air density implies a reduction of the convection heat loss due to lower heat transfer coefficients. The combination of these three factors requires different air temperature settings, compared to the ones usually applied in building environments.

The purpose of this paper is to evaluate two environmental control systems controlling methodologies. The first one is based on controlling the air conditioning system using the predicted mean vote (PMV) index as feedback signal, where the effects of air temperature, relative humidity, and mean radiant temperature while the second methodology considers the cabin temperature as a feedback signal to the system.

2. Thermal Comfort

In the modern society, due to the higher exposition to conditioned environments, researchers are interested in the effects of these ambient in the human body and conditioning requirements for occupied environments have being established. The idea of these requirements is to guarantee thermal comfort, that is not a function only of the temperature, but of several factors as activity level, clothing thermal insulation, air temperature, ambient mean radiant temperature, air relative humidity and air speed. These factors have influence in the thermal neutrality of the body, that is a necessary condition for thermal comfort. Thermal neutrality, as defined by Fanger (Fanger, 1972), is that condition in that the human being is not able to define if he would prefer a warmer or a colder ambient. As per ISO 7730 (ISO, 1994) and ASHRAE 55-95 (ASHRAE, 1995), “thermal comfort is that condition in that a human being is satisfied with the thermal environment”.

The human body has an approximately constant temperature (37 ºC) and it can only be maintained if there is thermal neutrality, or, if the heat produced by the body is equal to the heat dissipated to ambient.

Considering the heat balance presented in Eq. (1) below:

$$S = M - W - E_p - (E_R + C_R) - (C + R) \tag{1}$$

Where:

S	Energy accumulated
M	Level of activity
W	Work developed by the person
C	Heat exchanged by convection
R	Heat exchanged by radiation

E_p Heat dissipated by transpiration and water vapor diffusion though the skin
E_R Heat exchanged by evaporation due to the respiration
C_R Heat exchanged by convection due to respiration

Thermal neutrality is obtained by S=0, therefore:

$$M - W - E_p - (E_R + C_R) = (C + R) \tag{2}$$

The comfort equation (Eq. (2)) does not satisfy all human beings, but there are combinations of the variables that will satisfy a greater number of persons. Fanger (Fanger, 1972) showed that the best combination will present a number of 5 % of dissatisfied persons and that changing this combination would increase the number of dissatisfied persons. This thermal comfort condition is established by the comfort equation (Eq. (2)).

In order to quantify the thermal comfort sensation, Fanger proposed the Predicted Mean Vote (PMV) index in accordance to Tab. (1):

Table 1. PMV index and related thermal comfort sensation.

PMV index	Thermal comfort sensation
+3	Very Hot
+2	Hot
+1	Slightly Hot
0	Neutrality
-1	Slightly Cold
-2	Cold
-3	Very Cold

Fanger (Fanger, 1972) defined the index of thermal activity (IAT) based on the heat balance of human body as:

$$IAT = M - W - E_p - (E_R + C_R) - (C + R) \tag{2}$$

Based on the IAT index, Fanger (Fanger, 1972) defined the PMV index as:

$$PMV = (0{,}303\ e^{-0{,}036M} + 0{,}028)\ IAT \tag{3}$$

Fanger (Fanger, 1982 apud ASHRAE, 2001) defined the percentage of dissatisfied person index (PPD) as follows:

$$PPD = 100 - 95e^{-0{,}03353PMV^4 - 0{,}2179PMV^2} \tag{4}$$

According to ISO 7730 (ISO, 1994), it is considered acceptable PMV index values between –0,5 e 0,5 and the PPD index shall be lower than 10 %.

2.1. Aircraft Cabin Thermal Comfort Evaluation

Several aspects make an aircraft cabin an environment different from a building office such as number of occupants per volume, low relative humidity, mean radiant temperature different from ambient air temperature, lower air density, etc.

The relative humidity is around 15 to 20 %, the mean radiant temperature is lower than air temperature and the air density is lower than 1,18 kg/m^3. The low relative humidity leads to a higher evaporation and heat loss while the low mean radiant temperature imposes higher radiation heat loss. Besides, low air density implies a reduction of the convection heat loss due to lower heat transfer coefficients. The combination of these three factors requires different air temperature settings, compared to the ones usually applied in building environments.

Fig (1) presents the differences between the curves of percentage of dissatisfied persons as a function of air temperature considering the characteristics of a typical office and aircraft cabin. Fig (1) was obtained calculating IAT, PMV and PPD as per Eqs (2), (3) and (4) considering a level of activity of 58,2 W/m^2 ^{o}C, clothing insulation equivalent to 0,6 clo and an additional insulation of 0,17 clo due to the seat. The calculations considered also a person of 70 kg and 1,70 m. The additional insulation was estimated based on the estimation of the body surface covered by the seat following the concept proposed in ISO 9920 (ISO, 1995).

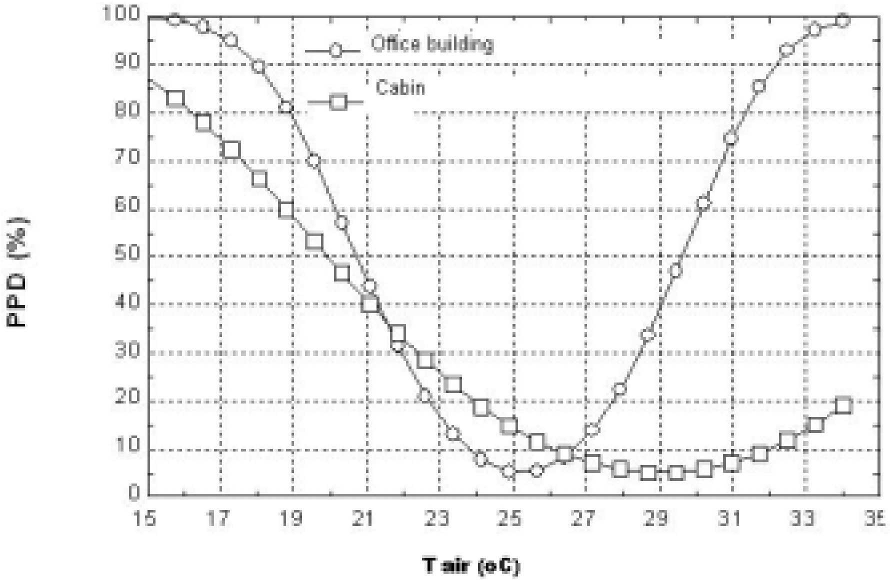

Figure 1. Differences in percentage of dissatisfied persons for typical cabin and office environments.

3. Literature Review

Pierce et all. (Pierce, 1999) in their paper about cabin air quality presented a research of the ASHRAE technical committee 9.3 (Transportation Air Conditioning) that supports the development of the ASHRAE 161P (Air Quality Within Commercial Aircraft). The research consisted of revising the available bibliography, preparation of a questionnaire and preparation of an air quality measurement protocol. The results of a survey performed during 8 Boeing 777 commercial flights are published. The paper presents information about dissatisfaction factors elected among the passengers and among the flight attendants as for example noise, seat, space for legs, etc. In Tab. (2) the opinion of passengers and flight attendants about cabin thermal sensation on that study is presented.

Table 2. Passengers and flight attendants cabin thermal sensation evaluation.

	Hot (%)	Acceptable (%)	Cold (%)
Passengers	2,0	73,7	24,3
Flight Attendants	11,1	81,5	7,4

Haghighat et all. (Haghighat, 1999) in their paper presented the data obtained during thermal comfort and air quality measurements aboard 43 commercial flights. During this campaign cabin temperature, relative humidity and CO2 concentrator were measured in commercial flights performed in Airbus 320, DC9, Boeing 767 and Airbus 340. The measurements were performed in the first class using a portable registrator for ambient temperature, relative humidity and CO2 concentration. The results show that the temperature is a stable variable while the relative humidity increases in the beginning of the flight, during the flight it is reduced to very low values (sometimes 5 %) and in the end of the flight increases to values around 30 %. The low relative humidity values observed could be related to the higher ventilation and lower occupation of the first class but this aspect is not discussed in the paper. The CO2 concentration increases in the beginning of the flight but during the flight its values assume stable and acceptable values.

In the thermal analysis presented in the paper by Haghighat et all. (Haghighat, 1999), the temperature were below the range recommended by ASHRAE 55-92 (ASHRAE, 1992) (21 to 24 ºC). In the analysis it is assumed an activity level of 1,2 met (70 W/m^2) and clothing insulation values of 0,5 and 1,0 clo. It could be inferred that the PMV is calculated based in the mean temperature and minimum relative humidity. For clothing insulation of 0,5 clo, PMV values between –1,19 and –2,49 were obtained corresponding to a PPD range of 35 to 93 % while for clothing insulation of 1,0 clo PMV values obtained were between –0,21 and –1,12 corresponding to PPD range of 6 to 31 %. Haghighat et all. (Haghighat, 1999) conclude that the thermal comfort was not acceptable and it should be pointed out that the ASHRAE 55-92 (ASHRAE, 1992) is valid for ambient pressures of 1 bar. This may limit the use of this standard for aircraft cabins and that the requirements established shall be re-examined before being applied to cabin.

Hunt-Space (Hunt-Space, 1995) focused on aircraft cabin environment and presented a survey answers on perceptions about cabin air quality. An evolution of stressors is presented by listing the stressors predominant in the past (vibration and noise, turbulence, cabin altitude, pressure changes, temperature control and drafts) and in the present (flight duration, cabin altitude, jet lag, low relative humidity and workload). The relative humidity is one of the new stressors and Hunt-Space (Hunt-Space, 1995) considered that the low relative humidity is caused by the frequent air change and due to the low ambient humidity and it is evaluated that the mean relative humidity in aircraft cabins is between 15 and 20%.

Wai L. Tse (Wai, 2000) proposes the use of the predicted mean vote (PMV) in the control of an office air conditioning system. In the paper it is presented an historical of the evolution of the use of PMV in the control of air conditioning systems. Kaya et all (Kaya, 1982 apud Wai, 2000) proposed to control the temperature, humidity and air speed. Although the idea was supportable, the mathematics details in the paper were not realistic and the paper lacked the discussion about control algorithms. They also concluded that the concept of PMV was still not practical to implement. MacArthur (MacArthur, 1986 apud Wai, 2000) brought comfort control into the concept of PMV but an excessively simplified model on the air-conditioned space was used, making it impractical for implementation. Scheatzle (Scheatzle, 1991 apud Wai, 2000) proposed the use of a microprocessor to calculate the PMV conditioned space. The author did not use PMV as a control parameter but as a criterion to exercise appropriate actions, e.g., switching on and off a fan or closing and opening a window and the PMV could be only "controlled" within a desirable range, say from –0.1 to +0.5. The author presented a very favorable view of the utilization of the PMV comfort index for environmental control. Henderson et all (Henderson et all, 1992 apud Wai, 2000) assessed the impact of controlling an air conditioning to maintain constant comfort instead of temperature using 3 different indexes, i.e.: effective temperature, PMV and modified PMV. Models simulating typical residences showed that sometimes energy consumption reduction could be obtained while a better PMV could be maintained. Simmonds (Simmonds, 1993 apud Wai, 2000) verified that the utilization of PMV can achieved energy saving. Tanabe and Kimura (Tanabe, 1994 apud Wai, 2000) reported that under hot and humid conditions, air movement might be one of the least expensive methods of providing thermal comfort. The authors pondered that, under high levels of air movement or high relative humidity, the PMV might not be the best index to describe thermal sensation but argued that there was no still better index than it. Wai L. Tse (Wai, 2000) acknowledges that, thanks to the advance in control electronics, comfort sensors were available in the marketplace at low price providing information about PMV avoiding the use of a number of expensive sensors.

Considering summer weather, Wai L. Tse (Wai, 2000) verified that for a PMV system controlled, the PMV index was lower than 0,8 and the temperature changed to compensate the effect of higher mean radiant temperature. For the conventional control (dry bulb temperature as feedback signal), due to the increase of mean radiant temperature induced by the radiation through a window, this index achieved values around 2,5 (76.8 % of dissatisfied persons) and the temperature was kept constant. Similarly for the winter, Wai L. Tse (Wai, 2000) verified that for the PMV system controlled, the PMV index was lower than 0,5, while for the conventional control this index achieved values around 1,5 and the temperature was maintained constant.

Kolokotsa et all (Kolokotsa, 1999) studied the integration of a man-machine-interface system, that registers the preferences of the users and adapt the control strategies. An energy management system is used that monitors and controls the environment parameters and minimizes the energy consumption. The control strategies were developed using fuzzy logic and the index PMV based on the air temperature, air relative humidity, mean radiant temperature, air speed, level of activity and clothing insulation was selected to represent thermal comfort. The first four parameters were measured and the others were calculated.

Egilegor et all (Egilegor, 1997) analyzed the PMV index control actuating in the air temperature using a fuzzy control adapted by a neural network. The program that simulates the ambient sends information about air temperature, air relative humidity and external conditions and the program responsible for the control calculates the PMV as defined by Fanger (Fanger, 1972 apud Egilegor, 1997). In the analysis it was considered the level of activity and air speed as constants, 75 W/m^2 and 1,0 m/s respectively. The mean radiant temperature was adopted as being equal to air temperature and for the refrigeration conditions it was adopted clothes insulation as being 0,5 clo and for heating condition as being 1,5 clo.

Lam (Lam, 1995) evaluated the use of a genetic algorithm to permit that the controller, based in the PMV index learns the best strategy based on its experience. The results showed that the utilization of genetic algorithm is applicable in the control of an air conditioning system without the use of system model.

3. Case Study Description

In this study the characteristics of a short duration flight aircraft are adopted and information as flight profile, number of passengers, cabin volume and areas, heat load and capacity of air conditioning system are considered. This aircraft model here applied studied only the main characteristics once, without jeopardizing the quality of the analysis, simplifications such as: considering only the volume representing the passenger cabin and adopting a simplified model for the air conditioning machine.

Short duration flight aircraft performs several short flights during the day, with a mean duration of one hour and a half, the air conditioning system and the cabin are totally dynamic systems and disturbed by external variables with a large range of variations, therefore the transient should be considered. This is a challenging scenario to implement a control system and evaluate its performance in transient conditions.

The use of short duration flight aircraft characteristics is based on the availability of information and in its dynamic characteristics. The transient condition analysis allows the thermal comfort evaluation for take-off and landing that together represents almost half of whole flight.

This aircraft is generally equipped with two air conditioning machines and two controllers. Cabin and cockpit temperatures are controlled by separated machine. The main purpose of this study is to verify the contribution of the use of the PMV as feedback signal in the control of the air conditioning system. A simplified configuration for this study was considered where the influence of the cockpit conditioning system in the cabin conditioning system will not be considered and it will be assumed the operation of these systems as being independent. Only the volume of the passenger cabin will be considered which is conditioned by one air conditioning machine, as shown in Fig. (2) where:

TC	Passenger cabin air temperature
TMR	Passenger cabin mean radiant temperature
RH	Passenger cabin relative humidity

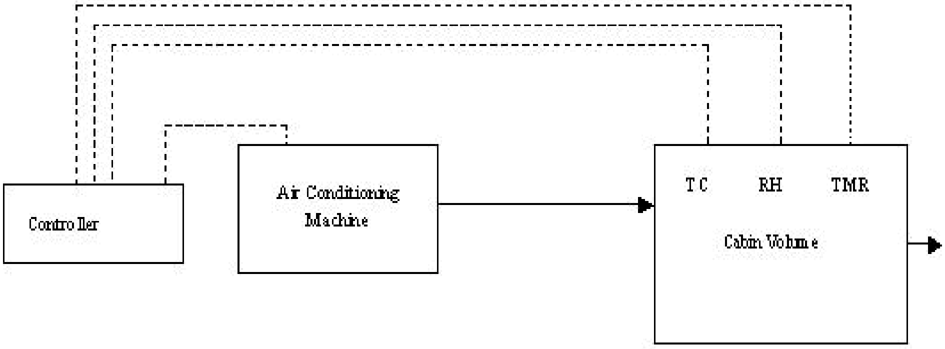

Figure 2. Sketch of the simplified system.

4. Mathematical Model

It is assumed that the cabin air density is constant and this hypothesis is adequate and does not harm the quality of the analysis considering the main influences are low relative humidity and mean radiant temperature.

A sketch of the thermal cabin model is shown in Fig. (3) where:

m1	cabin inlet airflow
T1	cabin inlet air temperature
ϕ1	inlet air relative humidity
w1	inlet air absolute humidity
Tc	cabin air temperature
ϕc	cabin air relative humidity
wc	cabin air absolute humidity
UA	Global heat transfer coefficient (considering skin temperature)
hi	internal convection heat transfer coefficient
Ts	skin temperature (outside surface cabin temperature)
Tw	internal superficial temperatures
Tamb	ambient temperature (outside)
Tref	reference temperature
Q	heat load due to passengers and electrical equipment dissipation
A	cabin structure internal surface area
Am	furniture and seats surface area
Tm	temperature of furniture and seats
V	cabin volume
ρ	cabin air density
cp	specific heat (constant pressure)
cv	specific heat (constant volume)

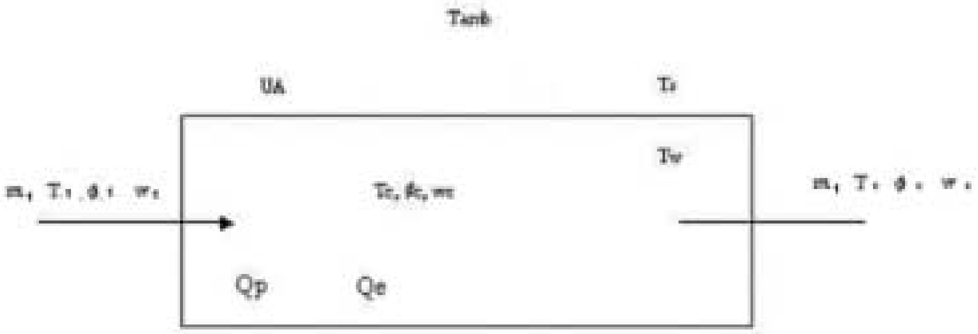

Figure 3. Cabin thermal model.

By applying the first law of thermodynamic:

$$\begin{aligned}&\dot{Q}\ (t)+h_i A(T_w(t)-T_c(t)) + h_i A_m(T_m(t)-T_c(t)) + \\ &+ \dot{m}_1(t)\ c_p(T_1(t)-T_{ref}) = \\ &= \dot{m}_1(t)\ c_p\ (T_c(t)-T_{ref}) + V\rho\, c_v \frac{dT_c}{dt}\end{aligned} \tag{5}$$

The fuselage will be modeled as a uniform mass characterized by an equivalent mass (m_{eq}) and equivalent specific heat (c_{eq}). This model is simple but allows the evaluation of the contribution of the internal surfaces temperatures in the mean radiant temperature. Therefore, applying the first law of thermodynamic one can established:

$$\begin{aligned}&UA\ (T_s(t)-T_c(t)) = \\ &= h_i A\ (T_w(t)-T_c(t)) + m_{eq} c_{eq} \frac{dT_w(t)}{dt}\end{aligned} \tag{6}$$

It will be assumed that the skin temperature is a function of ambient temperature and Mach number as proposed by SAE (SAE, 1969). Those variables are a function of flight profile and it will be used as model perturbations.

Similarly to the fuselage, the furniture and seats will be modeled as a uniform mass with equivalent mass (m_{eq2}) and equivalent specific heat (c_{eq2}) where, by applying the first law of thermodynamic, one can evaluated:

$$0 = h_i A_m (T_m(t) - T_c(t)) + m_{eq2} c_{eq2} \frac{dT_m(t)}{dt} \tag{7}$$

Part of the cabin air is re-circulated and part is provided by the environmental control system (fresh airflow). Follows the energy and mass balance implemented for the mixture chamber:

$$m(t)c_p T(t) + m_r(t)c_p T_c(t) = (m(t) + m_r(t))c_p T_1(t) \tag{8}$$

$$m(t)w(t) + m_r(t)w_c(t) = (m(t) + m_r(t))w_1(t) \tag{9}$$

Where:

m_r	re-circulated airflow
m	fresh airflow

The main source of water vapor in the cabin is passengers' respiration and evaporation. In this analysis only the respiration is being considered in the mass transfer of the cabin. Evaporation is being considered in the human body heat balance and in the evaluation of the effect of humidity in the thermal comfort.

The water vapor mass balance in the cabin is defined by the following equation:

$$\frac{dm_v(t)}{dt} = \dot{m}_{vap}(t) + m_1(t)\,w_1(t) - m_1(t)\,w_C(t) \tag{10}$$

where the cabin air absolute humidity is defined as:

$$w_C = \frac{m_V}{m_a} \tag{11}$$

Where:

m_{vap}	water vapor generation rate
m_v	water vapor mass in the cabin
m_a	dry air mass in the cabin

For a constant cabin pressure, the sum of air and water vapor partial pressures is constant. The changes in water vapor mass in the cabin would cause a variation of dry air partial pressure and mass but even for high absolute humidity the mass of water vapor is very low compared to dry air mass. In order to simplify the model the mass of dry air will be assumed as constant. The water vapor mass balance in the cabin can be defined as:

$$m_a\frac{dw_c(t)}{dt} = \dot{m}_{vap}(t) + m_1(t)\,w_1(t) - m_1(t)\,w_C(t) \tag{12}$$

The heat balance for the human body gives the predicted mean vote (PMV) defined by the following equation:

$$PMV = (C1 + C2\, w_c + C3\, T_c + C4\, TMR) \tag{13}$$

Where C1, C2, C3 and C4 are constants based on the values of the level of activity, clothing insulation, air speed and radiation heat transfer coefficient and TMR is the mean radiant temperature.

5. Simulation Results and Discussions

A regional jet flight profile composed by the following phases was adopted in the analysis:

- Taxi (5 minutes)
- Take-off and climb to 35000 ft (20 minutes)
- Cruise flight (90 minutes)
- Descent and landing (20 minutes)
- Taxi (5 minutes)

The following disturbances were considered in the analysis:

- Ambient temperature variation causing variation of skin temperature
- Cabin inlet airflow variation due to altitude changes
- External humidity variation

The controller design uses classic control techniques, the air conditioning system was represented by transfer functions provided by the manufacturer, the aircraft cabin was modeled and its equations linearized and converted to frequency domain where the root locus method was applied. In order to obtain a better performance, pre-compensators were used. The controllers and pre-compensators obtained by both methodologies were used in the simulation of a non-linear plant. The evaluation was performed for clothing insulation equivalent to 0,6 e 1,0 clo and considering sedentary activities (58,2 W/m^2).

Figs. (4) and (5) present the simulation results (cabin air temperature and predicted mean vote) for clothing insulation equivalent to 0,6 considering also an additional insulation of 0,17 clo due to the seat.

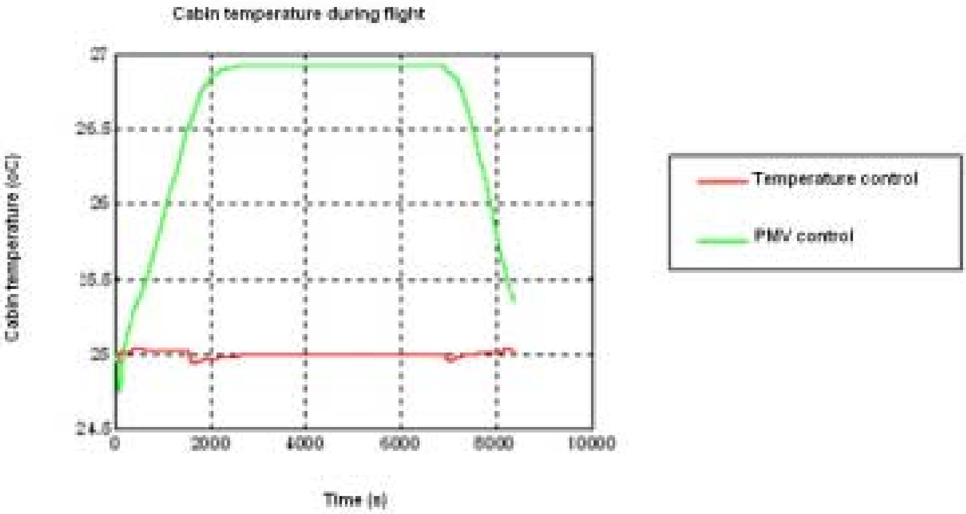

Figure 4. Cabin air temperature – 0,6 clo.

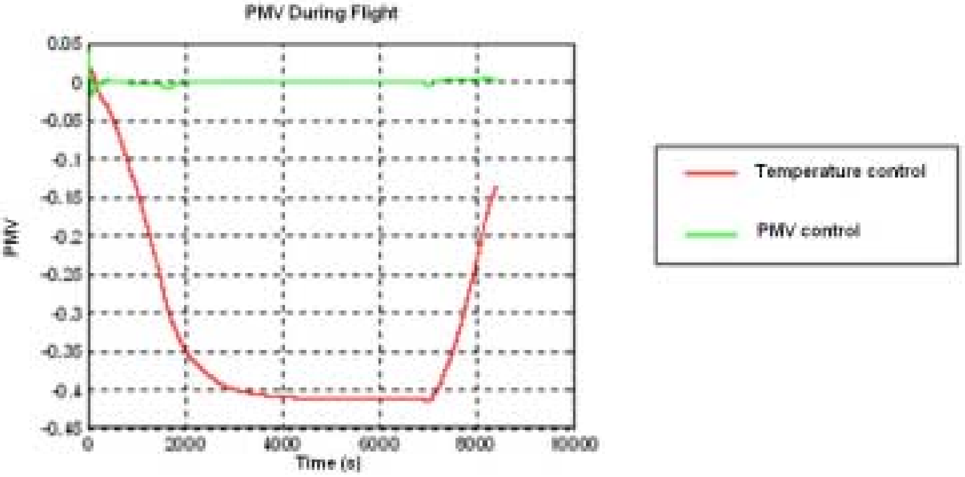

Figure 5. Predicted mean vote (PMV) – 0,6 clo.

As expected, comparing to a building environment, lower relative humidity and mean radiant temperature lower than air temperature requires higher temperature to guarantee a minimum of dissatisfied persons maintaining PMV equal to zero. These results are equivalent to that verified in literature review.

The system controlled by temperature signal maintain the temperature in the reference desired but allowed PMV to be lower than zero but still within the range recommended by ISO 7730 (ISO, 1994) (-0,5 to +0,5).

The system controlled by PMV signal maintained this index equal to zero guaranteeing a minimum of dissatisfied persons by increasing cabin air temperature in order to compensate the effects of lower relative humidity and mean radiant temperature.

Figs. (6) and (7) present the simulation results (cabin air temperature and predicted mean vote) for clothing insulation equivalent to 1,0 considering also an additional insulation of 0,17 clo due to the seat.

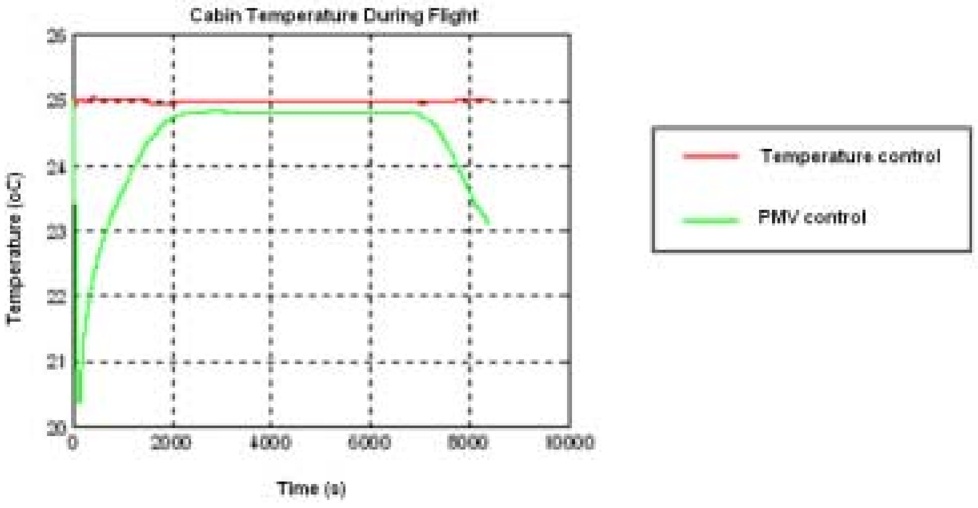

Figure 6. Cabin air temperature – 1,0 clo.

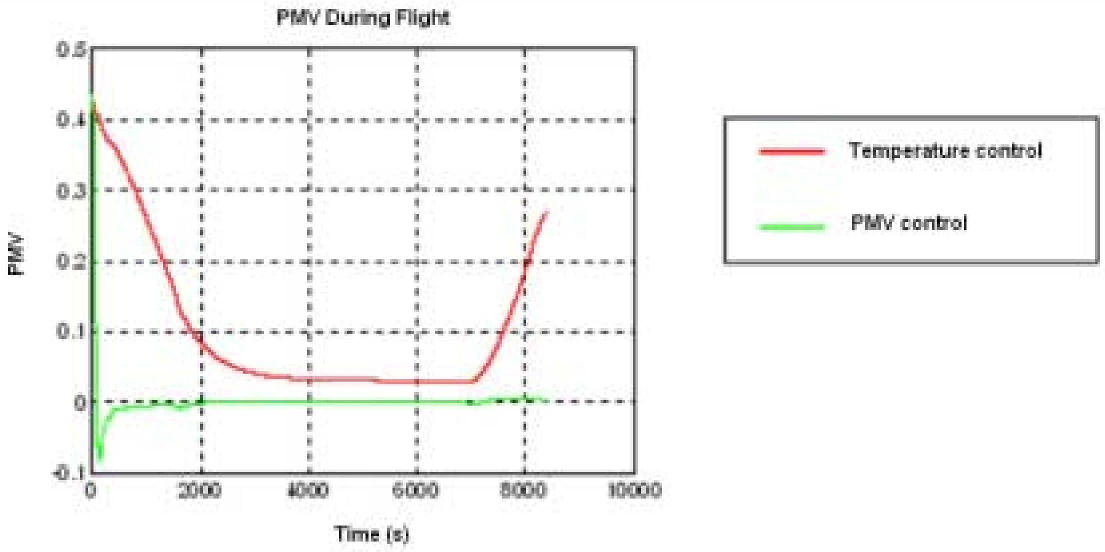

Figure 7. Predicted mean vote (PMV) – 1,0 clo.

Due to higher clothing insulation, the cabin temperature and PMV curves in both control system (PMV and dry bulb temperature feedback signal) are similar .

The system controlled by temperature signal maintained the temperature in the reference desired but permits that the PMV to be higher than zero but still within the range recommended by ISO 7730 (ISO, 1994) (-0,5 to +0,5).

The system controlled by PMV signal maintained this index equal to zero guaranteeing a minimum of dissatisfied persons by decreasing a little bit cabin air temperature.

6. Conclusions

Lower relative humidity and mean radiant temperature found during flight lead to a higher heat exchange between human body and environment increasing the possibility of occurrence of cold sensation. These effects can be mitigated using the predicted mean vote (PMV) as feedback signal in the control of the air conditioning system. By using the PMV as a control parameter the cabin air temperature would be maintained at higher values compensating the higher heat exchange by evaporation and radiation decreasing that amount exchanged by convection. This compensation depends on the clothing insulation once higher insulation decreases the influence of lower relative humidity and mean radiant temperature and also decreases convection.

Using the PMV as feedback signal requires the correct specification of passengers' typical clothes and permits to maintain this index equal to zero guaranteeing a minimum of dissatisfied persons. For light clothes (0,6 clo), the cabin air temperature should be increased, while for heavier clothes (1,0 clo) the temperature should slightly decreased.

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