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Improved Thermal Comfort in Cabin Aircraft with in-seat Microclimate Conditioning Module

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ABSTRACT

Climate control of cabin aircraft is traditionally conditioned as a single unit by the environmental control system. Cabin temperature is controlled by the crew while passengers of the aircrafts have the control on the gaspers providing fresh air from the above head area. The small nozzles are difficult to reach and adjust to meet the passenger's needs in terms of flow and direction. A more dedicated control over the near environment of each passenger can be beneficial in many situations. The European project COCOON, funded under Clean Sky 2, aims at developing and demonstrating a Microclimate Conditioning Module (MCM) integrated to a standard economy 3-seat row. The system developed will lead to improved passenger comfort with more control on their personal thermal area. This study focuses on the assessment of thermal comfort of passengers in the cabin aircraft through simulation. A first analysis investigates thermal comfort and sensation of passengers in varying cabin environmental conditions: from cold to very hot scenarios, with and without MCM installed in the seats. The modelling platform is also used to evaluate the impact of different physiologies of passengers on their thermal comfort as well as different seat locations. Under the current cabin conditions, a passenger of a 50th percentile body size is feeling uncomfortably cool due to the high velocity cabin air ventilation. The simulation shows that the in-seat MCM developed in COCOON project improves the thermal comfort of the passenger.

INTRODUCTION

Automotive seating has improved significantly in recent years in terms of passenger comfort and experience. Heating systems integrated to the seat of the vehicle were once limited to luxury class but are now becoming standard across all vehicle ranges. Manufacturers then added in-seat air distribution through the seat fabric to provide ventilation and air-conditioning capabilities for improved passenger comfort. Improvements in aircraft seating have not kept pace with these developments and the passenger's experience presents space for enhancement in terms of comfort. Transitioning automotive level seating quality to the aerospace market is already being targeted by a US joint venture with an automotive manufacturer (Fraunhofer. 2018). The European project COCOON aims at developing an in-seat heating, ventilation and air-conditioning module that will create a personalized microclimate around the passenger improving the flight experience. The system consists of a thermoelectric solid-state heat pumping device to provide heating and cooling, a ventilation module to provide air circulation and an advanced control system for the passenger via a tablet or smart phone capable of integrating personal thermal preferences.

The assessment of thermal comfort of passengers is of main interest in the automotive and aviation industries for an improved experience in the vehicle. In (Karimi et al. 2002; Karimi et al. 2003), the transient response, in terms of local and overall thermal comfort levels, of a car passenger seating on a heated, ventilated seat in a highly non-uniform thermal environment is assessed through simulations and experiments. The human body is modelled with 21 distinct segments and three layers, as defined in (Burch et al. 1991); the human thermal response simulated by the model is

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validated during experiments through questionnaires. The experiments and simulations show that a heated seat greatly reduces the time needed to reach a local thermal comfort at the contact areas and improves the overall thermal comfort. In-seat ventilation can quickly and efficiently lower the seat temperature, leading to an increased thermal comfort for the passenger. (Kaushik et al. 2011) investigated different micro-cooling strategies for automotive application: ventilated seat, front nozzles, back nozzle for the neck and cheek and a seatbelt capable of delivering conditioned air to the chest and laps. The thermal comfort achieved with each micro-cooling strategy was assessed through CFD simulation and human subject tests. Significant thermal comfort gains are attained with the use of ventilated seat: all the micro-cooling strategies include a combination of in-seat ventilation with dedicated nozzles for specific body parts. (Wolfe et al. 2007) reviewed three main types of heating and cooling technologies integrated to automotive car seats for close-to-passenger air delivery: 1) thermo-electric devices with embedded fan, 2) air pulling and 3) air pushing systems. The Virtual Thermal Comfort Engineering tool, developed by Delphi Harrison Thermal Systems jointly with the University of California, Berkeley (Han et al. 2001), was used to predict the thermal environment of the passenger and his/her thermal comfort. To the authors' knowledge, the assessment of the thermal comfort of passengers in cabin aircraft environment has not been fully investigated and presents some additional challenges compared to the automotive application.

This paper investigates the current thermal comfort of passengers of the economy class of commercial aircrafts, through simulation, ant its potential improvement via the implementation of in-seat MCMs. The first section describes the thermal modelling and simulation of the passenger and its environment used for thermal comfort assessment. The second section presents the results from Computational Fluid Dynamics (CFD) simulations of the cabin air ventilation system and its impact on the passengers. The thermal comfort and sensation assessment of the passengers through simulation is presented in section three, in different environmental conditions of the cabin: from cold to various hot scenarios, without MCM installed in the seats. The impact of the seat location of the passenger (aisle, centre or window) on their thermal comfort and their physiology is also studied. The last section shows the improvement in thermal comfort with the implementation of in-seat MCM.

THERMAL COMFORT AND SENSATION ASSESSMENT THROUGH SIMULATION

This study uses the software TAITherm, developed by (ThermoAnalytics 2019), as a thermal modelling and simulation platform for comprehensive Computer-Aided Engineering analysis of both steady-state and transient-heat transfer conditions. The thermal modelling software computes transient conduction, convection, and both thermal and solar radiation. The TAITherm Human Thermal Module (HTM) can simulate the thermo-physiological response of the human body and predict the local and overall thermal comfort and thermal sensation in complex transient and asymmetrical environmental conditions. All thermoregulatory responses are computed based on environmental conditions, clothing, body percentile, and activity level. The HTM considers heat storage, three-dimensional conduction, and heat transfers due to changes in blood flow, metabolism and sweating at the skin surface. The major physiological responses (metabolic heating, shivering, respiration, sweating and peripheral vasomotion, etc.) are modelled in the HTM to simulate a human body attempting to maintain a constant core temperature.

The thermoregulation model computes the physiology-based skin and core temperature predictions, which are then inputted to the University of California Berkeley sensation and comfort models (Arens et al. 2006; Arens et al. 2006). The Berkeley models provide overall and localized sensation and comfort assessment for each body segment; nineteen models are provided for each body segment. The definition of human thermal comfort is very complex: it involves both physiological and psychological states of a person under specific conditions. In uniform thermal conditions, sensation and comfort are well correlated: a neutral thermal sensation corresponds to the most comfortable situation. In transient environment, the relationship between sensation and comfort is more complex.

The thermal sensation and comfort predicted by the Berkeley models are reported on a nine-point scale from -4 to +4. The sensation scale has the same interpretation as the ASHRAE seven point scale (ASHRAE Standard 55 2010) but it includes two additional points for extreme sensations (very hot and very cold). Positive comfort values indicate an increasing level of comfort with a "just comfortable" state being represented with a value just above zero and inversely with negative values for uncomfortable states.

The HTM takes as inputs the geometry of the human body, the activity level, clothing insulation and the environmental conditions of the surroundings of the human body. The HTM simulates the dynamic thermoregulation behaviour of the human body and predicts the core, skin and clothing temperatures of the different body segments; the local and overall body heat fluxes are estimated as well as the thermal comfort and sensation of the body using physiology-based metrics. The human body geometry is defined in the 3D CAD model with 19 body segments, from which 9 body parts are in-contact with the seat (back head, upper/mid back, upper/lower lumbar, left/right butt and left/right thigh). An activity level of 1 met is considered, corresponding to a person seating at rest. Appropriate clothing insulation is applied to the HTM according to the summer (0.41 clo) or winter (0.69 clo) season. The environmental conditions, specified in the thermal model, cover the cabin air temperature, humidity level, air velocity. The model considers the non-uniform air distribution from the cabin air ventilation system (inputted from CFD simulation) and the asymmetry in the surface temperatures of the floor, ceiling and fuselage for the different scenarios.

The thermal sensation and comfort of the passenger are assessed in different cabin environmental conditions varying from cold to very hot (Table 1). The cold (21C) and hot (24C) scenarios correspond to the usual range of variation of the temperature in the cabin aircraft. The thermal comfort in the two hotter scenarios is investigated due to the high energy-consuming process for cabin air conditioning. The in-seat MCM developed in COCOON project delivers a conditioned airflow to the 9 body segments in contact with the seat, while the other body segments are impacted by the surrounding conditions set by the cabin air ventilation system. The controller unit of the MCM modulates the fan and thermoelectric device to set the supplied airflow rate and temperature for the different body segments.

Table 1. Cabin environmental conditions for four scenarios simulated.

	Cold	Hot	Hot+	Hot++
Activity level [met]	1	1	1	1
Clothing [clo]	0.69	0.41	0.41	0.41
Cabin temperature [C]	21	24	26	28
Cabin relative humidity [%]	5	20	20	20
Average air velocity at passenger level from cabin air ventilation [m/s]	0.25	0.25	0.25	0.25

CABIN AIR VENTILATION SYSTEM MODELLING

The cabin conditions considered in this model correspond to the aircraft in cruise flight phase; these thermal conditions are maintained by the cabin air ventilation system. The cabin airflow patterns, air velocity and temperature are captured through CFD modelling and its impact on the passengers is imported to the HTM by inputting the heat transfer coefficients (HTCs) for each body segment. In this study, the cabin environmental conditions defined in Table 1, for hot and cold scenarios, are considered as standard conditions used by airliners. These conditions are set constant during the simulation for thermal comfort assessment.

Figure 1 presents the CFD results of the distribution of the air velocity and Figure 2, the air temperature in the cabin, at a given time step in the simulation, when controlled by the environmental control system. The conditioned air is supplied from four outlets in the ceiling, above and below the luggage compartments in the above-head area. The supply air outlets are clearly visible in purple on Figure 2 with the coldest temperatures around 13.5C. The air patterns can be observed on Figure 1 where the two streams of air supplied from the ceiling are crossing in the aisle and directed towards the legs of the passengers in the aisle, followed by the centre and window passengers. The air stream rises up following the fuselage and mixing with the second air outlet below the luggage compartment. The air stream remains in a cross-section of the cabin avoiding any spread of air contaminant from one row of seats to another. Figure 2 highlights the stratification of the air temperature in the cabin. Two sections are observable: the lower volume (in green) from the feet to the chest of the passengers, at about 20.4C and the upper volume (in orange), for the passengers head, around 22.7C. The HTCs at the passenger level are extracted during the 5-min transient simulation. Temperature boundary conditions are applied to the passenger body segments, instead of internal heat generation rate of the passengers. The

HTCs are calculated based on the velocity field near the wall, turbulence parameters and gas properties. A time-average is calculated for the HTCs of several body segments after the initialization period (Table 2). The HTCs are imported in the HTM for a representative model of the cabin air ventilation.

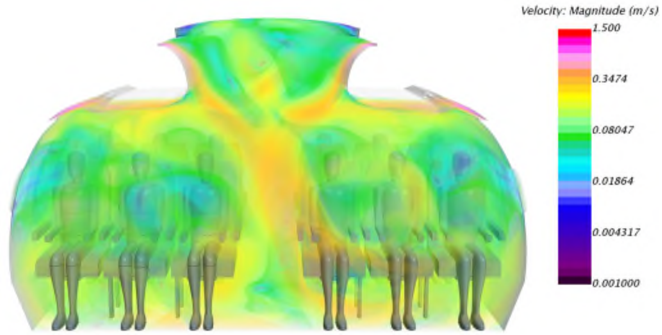

Figure 1 Cabin air velocity distribution at a given simulation time.

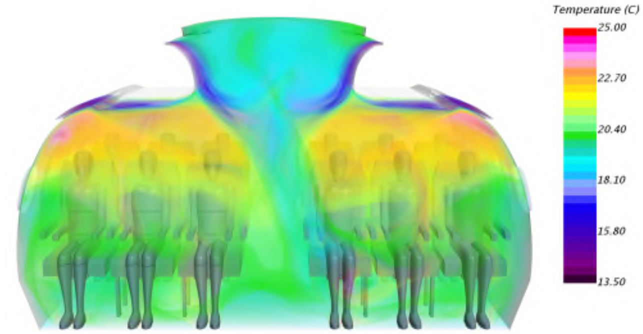

Figure 2 Cabin air temperature distribution at a given simulation time.

Table 2. Time-averaged HTCs at the passenger level for different seating locations.

Body segment	Heat transfer coefficient [$W/m^2.K$]		
	Aisle	**Center**	**Window**
Head/Neck	6.45	5.24	5.10
Chest	5.00	4.34	4.41
Abdomen	5.54	4.95	5.06
Pelvis	6.16	5.75	5.81
Left arm	7.18	6.23	6.06
Right arm	6.38	6.04	6.65
Left leg	9.23	8.86	8.36
Right leg	8.88	8.31	8.24
Left thigh	7.98	5.92	5.72
Right thigh	6.45	5.24	5.10

THERMAL COMFORT ASSESSMENT WITHOUT IN-SEAT MCM

Impact of cabin temperature on passenger thermal comfort

This section presents the assessment of passenger thermal comfort using the HTM model in different cabin conditions presented in Table 1, without MCM installed in the seat. The HTM representative of the physiology of a white 50th percentile western male is modelled in a hot cabin environment with an average temperature of 24C and relative humidity of 20%. The HTM is wearing a summer clothing ensemble with trousers and short-sleeve shirt (0.41 clo). The HTCs of the centre passenger in the three-seat row (Table 2) are applied to the body segments of the HTM for the first set of results.

A summary of the thermal comfort and sensation assessment for the simulation is presented in Table 3 for different cabin environmental conditions varying from cold (21C) to very hot (28C). For each environmental condition in the cabin, the overall sensation and comfort of the passenger outputted by the model at the end of the 60-min simulation is presented. The body segments presenting the worst local sensations (too warm or too cool) and the worst local comforts are reported as well to give some insights on the estimation of the overall human thermal state. The ideal local sensation should tend towards a neutral state (value of 0, above 1 would be too warm and below -1 too cool); while the ideal local comfort should be above 1 and tending towards 4. The results show that in the cold scenario, the overall comfort tends towards just uncomfortable (-0.5) with a cool overall sensation (-2.2). The body segments affecting the overall comfort are the head, hands, feet and lower legs showing a cool local sensation. In the very hot scenarios, the model shows an overall comfortable state (1.3-1.5) with a neutral overall sensation (-0.4-0.6). The back segment of the

HTM shows a warm sensation (1.2), while the head and chest body segments are still presenting a slightly cool sensation (-1). Note that the "slightly cool" to "cool" sensation on the head, chest and upper arms body segments is due to the elevated air speed (0.25 m/s) from the cabin ventilation system. Some limitations must be considered: the HTCs were assumed constants during the simulation and computed with a reference temperature of 300K. The impact of varying the cabin air temperature on the HTCs is assumed negligible due to the small variation in magnitude while the cabin airflow is not changed.

Table 3 Summary of overall and local thermal comfort and sensation for different cabin conditions with a passenger in the centre seat location.

	Hot	Cold
Cabin temperature [C]	24	21
Overall Sensation	-1.4	-2.2
Overall Comfort	0.2	-0.5
Worst local sensation	Head (-2.17), Chest (-1.54), Right Hand (-1.31), Left Hand (-1.15), Right Upper Arm (-1.11)	Head (-2.69), Left Hand (-1.94), Right Hand (-1.88), Left Lower Leg (-1.42), Right Lower Leg (-1.38)
Worst local comfort	Head (-0.98), Right Hand (-0.50), Right Lower Arm (-0.39), Right Upper Arm (-0.32), Left Hand (-0.30)	Head (-1.92), Left Hand (-1.48), Right Hand (-1.41), Left Foot (-0.15), Right Foot (-0.11)
	Hot+	**Hot++**
Cabin temperature [C]	26	28
Overall Sensation	-0.4	0.6
Overall Comfort	1.3	1.5
Worst local sensation	Head (-1.29), Chest (-0.89), Left Upper Arm (-0.36), Right Upper Arm (-0.33), Pelvis (-0.32)	Back (1.19), Chest (-1.04), Head (-0.98), Left Lower Leg (-0.95), Right Lower Leg (-0.89)
Worst local comfort	Head (0.67), Chest (0.88), Pelvis (1.03), Left Upper Arm (1.15), Right Upper Arm (1.22)	Back (0.04), Left Lower Leg (1.08), Right Lower Leg (1.19), Chest (1.45), Right Foot (1.75)

Impact of seat location on passenger thermal comfort

The impact of the seat location (aisle, centre and window) on the thermal comfort and sensation perceived by the passenger is summarized in Table 4. The seat locations differ in terms of HTCs at the level of the passenger (Table 2) representative of the cabin air ventilation system. The simulation is performed with a 50th percentile HTM in a hot cabin environment of 24C. The results from simulation show an overall state of the passenger between just comfortable (1) and just uncomfortable (-1) for the different seat locations, while the overall sensation is between slightly cool (-1) and cool (-2).

The main differences between the three seat locations are listed in the followings. The passenger in the aisle presents a cool to cold (-2.5) sensation to the head compared to cool (-2.2) for window and centre, due to the direct airflow from the cabin ventilation. The passenger at the window has a cooler sensation on the left hand and upper arm (close to the window), due to surface temperature of the fuselage (18C). The passenger in the centre location presents a better overall comfort than the ones in the aisle and window. In terms of overall sensation and comfort the difference between the seat locations is very small due all comprehensive effect.

Table 4. Summary of overall and local thermal comfort and sensation for different seat locations, in a hot cabin environment.

Seat location	Aisle	Center	Window
Overall Sensation	-1.5	-1.4	-1.6
Overall Comfort	0.1	0.2	0.0
Worst local sensation	Head (-2.48), Chest (-1.59), Left Hand (-1.16), Left Upper Arm (-1.13), Right Upper Arm (-1.01)	Head (-2.17), Chest (-1.54), Right Hand (-1.31), Left Hand (-1.15), Right Upper Arm (-1.11)	Head (-2.28), Chest (-1.66), Left Hand (-1.58), Left Upper Arm (-1.23), Right Hand (-1.21)

Worst local comfort	Head (-1.50), Left Upper Arm (-0.36), Left Hand (-0.34), Left Lower Arm (-0.32), Right Upper Arm (-0.20)	Head (-0.98), Right Hand (-0.50), Right Lower Arm (-0.39), Right Upper Arm (-0.32), Left Hand (-0.30)	Head (-1.20), Left Hand (-0.90), Left Lower Arm (-0.53), Left Upper Arm (-0.51), Right Hand (-0.43)

Impact of physiology on passenger thermal comfort

Passengers of different physiologies will perceive differently a given thermal environment in the cabin. The modelling platform gives the ability to assess the thermal comfort and sensation of passengers of different physiologies. Three physiologies of varying body height (1.54, 1.70 and 1.84 m) and weight (51.7, 73.5 and 95.3 kg), respectively for the 5th, 50th and 95th percentiles are simulated. Different physiologies involve different metabolic rates (increasing from 0.7 to 0.9 met with the body size) and different Berkeley temperature setpoints to reach local comfortable conditions for each body segment, also increasing with the body size.

The simulation is performed for a passenger in the centre seat location, in a hot cabin environment of 24C; the results are summarized in Table 5. The results show that the 95th percentile HTM presents a discomfort in the back (-0.98) due to a warm sensation (1.85). The other body segments are comfortable and hence the HTM is overall comfortable (1.2) with a slightly warm overall sensation (0.8). The results for the 50th percentile HTM are the same as presented in Table 3 and Table 4 for the hot cabin conditions (24C) in the centre seat location. The 50th percentile HTM shows an overall slightly cool sensation (-1.4) with an overall state between just comfortable and just uncomfortable (0.2). The fifth percentile HTM presents a cool overall sensation (-1.9) and an overall state between just comfortable and just uncomfortable (0.1) similar to the 50th percentile. This cool overall sensation of the body is driven by the head, hands and lower legs segments with cool sensations (from -1.6 to -2.7).

Table 5. Summary of overall and local thermal comfort and sensation for passengers of different physiologies seating in centre location of a hot cabin environment.

Body size	5th percentile	50th percentile	95th percentile
Overall Sensation	-1.9	-1.4	0.8
Overall Comfort	0.1	0.2	1.2
Worst local sensation	Head (-2.66), Left Hand (-1.85), Right Hand (-1.65), Left Lower Leg (-1.60), Right Lower Leg (-1.54)	Head (-2.17), Chest (-1.54), Right Hand (-1.31), Left Hand (-1.15), Right Upper Arm (-1.11)	Back (1.85), Head (-1.53), Left Lower Leg (-0.93), Right Lower Leg (-0.90), Chest (-0.74)
Worst local comfort	Head (-1.85), Left Hand (-1.32), Right Hand (-1.07), Left Lower Arm (-0.90), Right Lower Arm (-0.74)	Head (-0.98), Right Hand (-0.50), Right Lower Arm (-0.39), Right Upper Arm (-0.32), Left Hand (-0.30)	Back (-0.98), Head (0.96), Left Lower Leg (1.35), Right Lower Leg (1.39), Right Foot (1.68)

THERMAL COMFORT ASSESSMENT WITH IN-SEAT MCM

This section presents the assessment of thermal comfort and sensation of the passenger in very hot (26C) and cold (21C) cabin conditions. In these scenarios, the seat is equipped with an MCM, which conditions the human body segments in contact with the seat. The analysis presents the dynamic thermal response of the body segments affected by the MCM (back, pelvis, thighs and back of the head and neck area). A Single-Input-Single-Output controller configuration is considered, which acts on the manipulated variable (seat air velocity or seat air temperature) to maintain the controllable variable (back temperature) at a given setpoint. The back temperature set point is determined using the Berkeley comfort setpoint for a given activity level and clothing insulation of the human body. The back temperature is selected as the controllable variable since the back body segment presents the largest surface area. The impact of the conditioned air distributed by the MCM on the other body segments in contact with the seat are also presented.

In the cold scenario, the HTM is initialized in a cold cabin environment (21C) without in-seat MCM and reaches a cool initial sensation. The simulation results present the evolution of the manipulated variable and skin temperature of the body parts in contact with the seat (Figure 3), and their local comfort and sensation (Figure 4). The manipulated variable is the temperature of the air supplied through the seat (displayed in red on Figure 3). The supply air temperature gradually decreases from 60C to reach 30C after 18 min, while the supply airflow is kept constant at 26 L/min through the back support and 16L/min through the bottom cushion. The MCM improves the local comfort of the back, pelvis and head from the initially uncomfortable conditions (red, green and blue circles on Figure 4). The local sensation of the back and pelvis start from a cool sensation with the 21C cabin temperature and reach a neutral sensation after about 20 min (dots on Figure 4). The head remains impacted by the cabin air ventilation system with a slightly cool sensation and between just uncomfortable and comfortable.

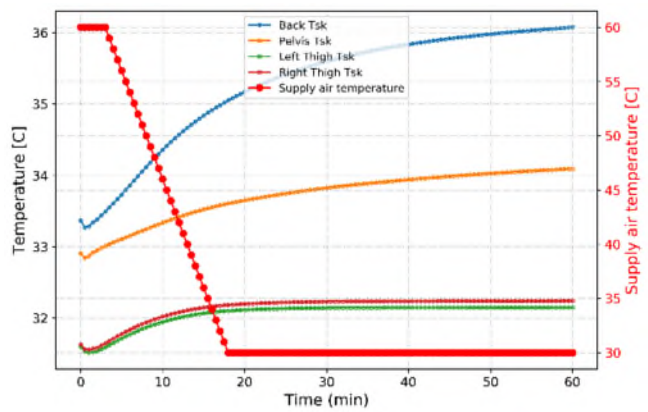

Figure 3 Skin temperature of body segments in contact with the seat with modulated seat air temperature in cold scenario.

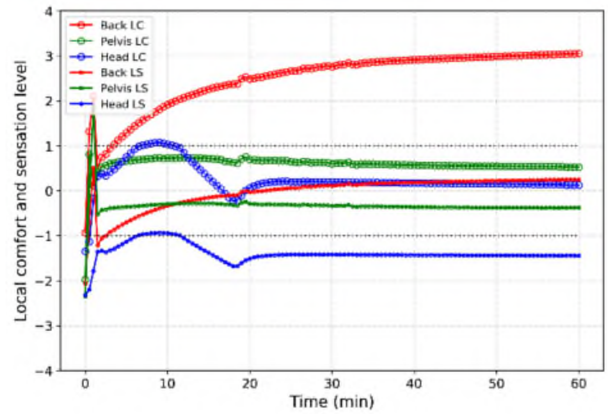

Figure 4 Local comfort and sensation of body segments in contact with the seat in cold scenario.

In the very hot scenario, the HTM is initialized with hot initial sensations, representative of a hot day on ground in a poorly conditioned airport. In this case, the controller modulates the airflow supplied through the seat and the supply air temperate is kept constant at 20C. The supply airflow rate is gradually reduced from 170L/min through the back support, respectively 105 L/min through the seat cushion, to nothing after 20 min (red line on Figure 5). The local sensation of the back, head and pelvis body segments affected by the MCM goes from initially hot to neutral and the corresponding local comfort reach comfortable conditions (Figure 6). Both local comfort and sensation of the body segments affected by the MCM are improved in the hot scenario.

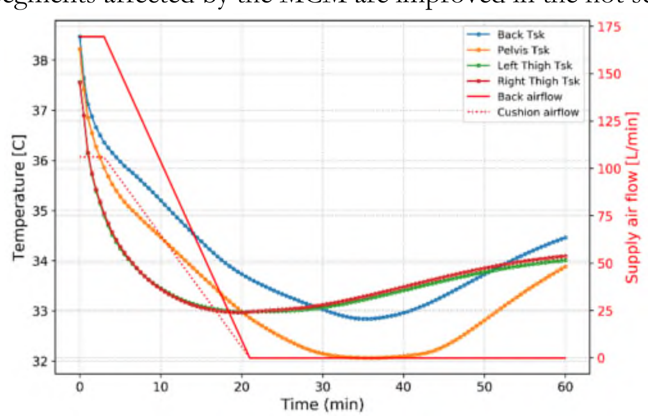

Figure 5 Skin temperature of body segments in contact with the seat with modulated seat air velocity in hot scenario.

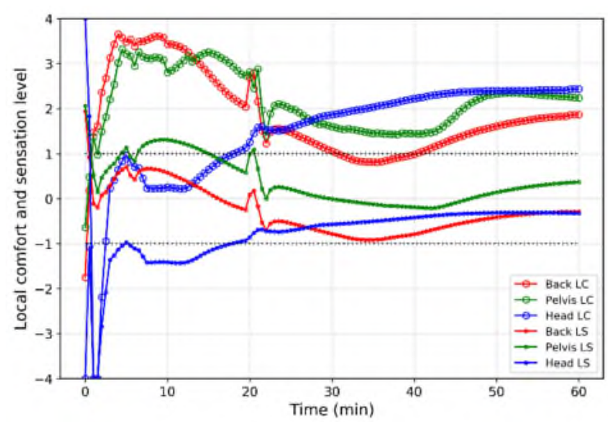

Figure 6 Local comfort and sensation of body segments in contact with the seat in hot scenario.

CONCLUSION

This paper investigates through simulation the thermal comfort and sensation of passengers in different environmental conditions of the cabin aircraft, with and without MCM installed in the seats. The impact of the seat location of the passenger (aisle, centre or window) and their physiology on their thermal comfort is also analysed. The simulation results show an overall state of the passenger between just comfortable and just uncomfortable for the different seat locations in a cabin environment of 24C, while the overall sensation is between slightly cool and cool. The impact of different physiologies of passengers on their thermal comfort is also evaluated through simulation. Three physiologies of different body size varying the 5th to 95th percentile are simulated in a cabin environment of 24C. The results show that the 95th percentile HTM presents a discomfort in the back (-0.98) because of a warm sensation (1.85) and is overall comfortable (1.2) with a slightly warm overall sensation (0.8). The fifth percentile HTM presents a cool overall sensation of the body (-1.9), driven by the head, hands and lower legs segments with cool sensations (from -1.6 to -2.7).

The MCM developed in COCOON project presents the capability to improve the thermal comfort conditions of the passengers in varying cabin environmental conditions, at varying seat locations, for varying body physiologies. The MCM has a direct impact on the head, back, pelvis and thighs body segments. It improves the thermal comfort of the passengers by bringing hot or cold air through the seat depending on their preferences and giving more control on their personal thermal area.

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