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An innovative approach to better understand hot discomfort, based on the measurement of global human responses, including physiological and sensory indicators - application to end users of mixed mode cooled buildings under tropical climate conditions

Gwénaëlle Haese[*1], Maxime Boulinguez[2,3], Pierre Bernaud[4], Anthony Couzinet[1]

*1 **Technical and Scientific Centre for Building (CSTB), PULSE Laboratory**,*
11 rue Henri Picherit 44323 Nantes, France
**Corresponding author: gwenaelle.haese@cstb.fr*

*2 **Laboratoire Physique et Ingénierie Mathématique pour l'Énergie, l'environnemeNt et le bâtimenT (PIMENT)** University of la Réunion, Sainte-Clotilde 97715, La Réunion, France*

*[3] **Laboratoire d'Ecologie Urbaine Réunion** 137 rue Isautier, 97410 Saint Pierre, La Réunion, France*

*[4] **Univ. Grenoble Alpes, CEA, Liten, INES***
73375 Le Bourget du Lac
France

ABSTRACT

Comfort modelling is a critical scientific barrier to reaching better thermal satisfaction in buildings. It allows designers to combine different cooling systems better to target comfortable low-energy buildings in hot and tropical climates. Increasing computer performance offers new perspectives to use more refined thermo-physiological models against traditional normative ones. Also, new types of coupled cooling alternatives arise and set a need for adequate comfort assessment models. The proposed article presents a methodology for better understanding human discomfort based on sensory response in hot conditions. It is an entry point to develop better and calibrate more generic bio-heat models for comfort prediction in the building industry. This study is part of a 48-month project called *CoolDown* funded by the French Nation Research Agency. It presents the first four months of field measurement. Preliminary results already give first insights into how relative humidity is predominant in hot climates when overreaching 68% and how temperature range is significant in occupant satisfaction when relative humidity is on the high side.

KEYWORDS

Thermal comfort, field survey, tropical climate, mixed-mode cooling, thermo-physiological models, bioheat model.
NOMENCLATURE

1 INTRODUCTION

In the current context of global warming, severe problems of overheating buildings in hot and humid climates arise. As a result, when natural ventilation (NV) is insufficient to target comfort, these hot periods lead to an overuse of air conditioning (AC), increasing energy consumption and electricity demand globally. However, alternative and original solutions exist to answer both comfort performance and energy savings in hot seasons. They are known as mixed-mode or hybrid cooling solutions and are aimed at drastically reducing AC energy use. They use ceiling fans coupled with either natural ventilation or air conditioning depending on the extremeness of climatic conditions. Nevertheless, although these mixed-mode solutions are gaining popularity nowadays, their use remains marginal in the Architecture Engineering and

Construction (AEC) industry, especially in temperate and tropical climates. The lack of quantitative and qualitative user experience feedback and knowledge of the actual comfort performance of combined active and passive systems partly explains this lack of interest by designers. Indeed, the normative approach to building comfort modelling, based on 20th-century research, highlights the dichotomy between analytical models (resulting from laboratory studies) and empirical models, such as the adaptive model (resulting from on-site surveys). This thus opposes air-conditioned buildings to naturally ventilated buildings. These two typologies are respectively governed by Fanger's PMV-PPD and the Adaptive Model, without foreseeing any real possibility of combining the two systems, or at least, without giving any clear prerogative as to the use of this, or that model in mixed-mode cooled buildings. (Yao et al., 2022). Both models have their field of application, advantages and disadvantages. On the one hand, the analytical model is based on all the environmental and individual variables without considering the notion of adaptability, thus, considering a passive user in the face of his comfort. On the other hand, the adaptive model hides them by focusing on the outside temperature alone. The case of mixed cooling then raises the question of combining the best of both worlds of air-conditioned and naturally ventilated buildings. The choice of the comfort model then becomes the priority question for understanding the transitions between the coupled cooling modes and the adaptability of the end user in such buildings. This study focuses on a more detailed approach accounting for a more dynamic way to assess thermal comfort based on physiological measurements on subjects working in a mixed-mode (MM) cooled building in la Réunion, an outermost French territory in a tropical climate. The cooling solutions consist of naturally ventilated and air-conditioned spaces, both coupled with high-performance ceiling fans. It aims at presenting the deployed methodology and preliminary results of a first summer campaign. This study is part of a French National Agency (ANR) funded *CoolDown* project focusing on mixed-mode cooling alternatives.

2 COMFORT MODELING IN BUILDINGS: TOWARD A PHYSIOLOGICAL APPROACH

The most commonly used thermal comfort models in the AEC industry are dedicated to uniform static environments. They are based on a right-here/right-now approach of body exchanges with its environment. They consider the human body to be a one-time physical body that does not react to varying environmental conditions and accounts neither for short/long term acclimatisation nor energy storage and dissipation mechanisms or adaptation of any kind. This dynamic should be considered in comfort modelling in NV and MM buildings as indoor ambient conditions is non-steady by nature. Furthermore, the human body does not detect the environmental condition directly. It is only made possible by thermoreceptors located in the outer skin layer. This skin layer is a strategic part of most common thermo-physiological models composed of two systems. They generally consist of a passive system representing all the human body's tissues and is the site of heat exchanges in the body and an active system which simulates physiological mechanisms such as shivering, cutaneous blood flow and sweating. Therefore, it becomes necessary to calculate the skin temperature to estimate the thermal sensation perceived by an individual in a given environment. This can be established through a thermoregulation model of the human body. Several complex thermoregulatory models exist to simulate the physiological responses of the human body and predict its skin and core temperatures (Fiala et al., 1999; Stolwijk, 1971; Tanabe et al., 2002; Salloum et al., 2007; Wissler, 2018). Some more simplified ones can also be found in the literature and are partially used in the AEC industry for specific applications (Urban comfort, Ashrae Elevated Air Speed Method) (Gagge, 1986; Walther, 2018; Walther, 2018; Ashare Standard, 2020).

El Kadri (2020) developed a thermoregulation model based on neurophysiology, the NHTM (Neuro Human Thermal Model). Its passive system is based on Wissler's one developed for NASA (Wissler, 2018). The active system is based on signals from the skin and central thermoreceptors. Moreover, this model is individualisable; it can simulate several types of populations. The NHTM is coupled with Zhang's model (Zhang, 2003), which calculates sensation and thermal comfort in heterogeneous unsteady environments. In addition to calculating thermal comfort, the NHTM can estimate the health risks due to the exposure of individuals to thermal stress. This can be done by calculating core temperature and water loss through transpiration, sweating and evaporation.
Skin temperature plays an essential role in monitoring the thermoregulatory system of the human body. The skin is the physiological bridge between the human body and its environment. This sensory organ is therefore used as an indicator of thermal comfort.
Peripheral (skin) temperature was assessed as an index to estimate individual thermal sensation. The autonomic thermoregulation system uses peripheral blood vessels to maintain the temperature balance of the human body. In hot environments, cutaneous blood vessels dilate, allowing heat release. Thus, the skin temperature changes according to the blood flow. Field measurements must be carried out in labs or actual buildings to quantitatively estimate its influence on thermal sensation. Lan et al. (2014) reported thermal comfort levels during sleep for different air temperatures using mean skin temperature and responses to subjective thermal comfort questionnaires. Liu et al. (2013) studied the variations of mean skin temperature as a function of the skin surface in stable and unstable thermal environments.
A statistical analysis of the data collected according to different measurement methods, carried out by Yao et al. (2007), showed that the Burton model (3 points) obtains similar results for the average skin temperature compared to the other methods, for example, Colin/Houdas (10 points), Hardy/DuBois (12 points), Stolwijk/Hardy (10 unweighted points), and Mitchell/Wyndham (15 unweighted points). Due to its simplicity and convenience, Burton's model is quite suitable for in situ measurements for relatively long periods.
Burton minimises the number of sensors to three: on the heart chest side, the left forearm, and the right shin. He applies weighting coefficients to it to calculate the average skin temperature (T_{sk}), such as:

$$T_{sk} = 0.14*T_{forearm} + 0.5*T_{chest} + 0.36 + T_{shin} \quad (1)$$

Various technologies have recently been used to measure skin temperature, such as resistance thermometers, thermocouples applied to the skin's surface or infrared thermometers (Li et al., 2017). In the case of continuous measurements over a long period, the choice of thermocouples applied to the skin's surface is the least restrictive way to equip the participants.

3 MATERIALS AND METHODS

Three five days-long campaigns were organised during one working week from the 13th of February to the 31st of March 2023.

3.1 Buildings

Two buildings in Saint-Pierre in La Réunion, France, were selected to serve as demonstrators in this study. La Réunion is an outermost French territory in the Indian Ocean, governed by tropical climate conditions (Type Aw and As as from the Köppen Geiger classification). The average annual daytime temperatures [7 a.m. to 6 p.m.] do not drop below 23°C for Saint-Pierre. During the hot period, a daily temperature amplitude of 24 to 34 degrees Celsius with a relative humidity higher than 75% is expected. The design of buildings is thought to provide comfort, avoiding space overheating. The first demonstrator “Ilet du Centre” building (IDC), is a large double floor open space office building built in 2008. As an experimental construction operation in a dense urban context, it was subject to a bioclimatic design primarily based on natural cross ventilation with louvres openings and double protection facades acting as fixed shadow devices. It is described by Payet et al. (2022). The second demonstrator, “CoArchitectes” (COA), is the first floor of an old basic concrete residential house on the city’s seaside. It has been recently renewed and extended as an office building. It does not benefit from natural cross ventilation in all spaces, and two third of the building has indeed single-sided openings. Those spaces are therefore equipped with AC units and ceiling fans for the hottest period of the year. May it be poorly insulated, solar impact on this building is limited by a second floor and very dense nearby vegetation.

3.2 Subjects

Twenty-one subjects (named SUi with i϶[1:21]) (eleven females, ten males), aged from 25 to 52 (age mean: 35.2 ± 9.1), participated in the experiments. Their sensibility to cold and hot conditions was auto-evaluated by answering a questionnaire developed by CSTB; a sensitivity score was calculated to describe the panel. Based on the scores obtained from this group of participants, half can be considered “sensitive” to hot conditions, and the other half is “not very sensitive”. For the sensitivity to cold conditions, three categories can be defined: “not very sensitive” (2 participants), “moderately sensitive” (7 participants) and “very sensitive” (11 participants). These sensitivity levels can be used to analyse the results by sensitivity groups.
The subjects are office workers. The studied population comprises architects, engineers and landscape designers working in their profession to reduce the impact of the AEC industry. By that means, they are sensitised to the AEC industry’s environmental impact and have a basic-to-good understanding of comfort components and their impact on energy use and carbon emission in buildings. SU1-8 were located in the IDC building, whereas SU9-21 was in the COA building.

3.3 Physiological measures

The physiological responses measured were skin temperatures and core temperature.
Skin temperatures were measured by using stainless steel thermo buttons data logger 22L (ProgesPlus, France) at three localisations on the body (chest side of the heart, on the left forearm and on the right shin). Core temperature was measured using the same materials and placed under the armpit. The temperature acquisitions were made with a time step of 5 minutes. The average skin temperature (T_{sk}) was calculated according to Equation 1.

3.4 Comfort surveys

During the surveys, subjects were prompted to report their comfort status every 2 hours through a local executable written in French (Figure 1). The right side of the questionnaire concerns subject clothing and essential operable building elements such as sunshade deployment, doors and windows opening. Subjects could report any additional nuisance, such as noise, dust or glare and provide any comment in a free field. The left side of the questionnaire concerns comfort and air movement evaluation, such as thermal sensation (7-point scale), thermal comfort (6-point scale), satisfaction (4-point scale), acceptability (4-point scale), and preference (3-point scale). All results are gathered in tabulated format to speed up the data process and avoid transcription mistakes.

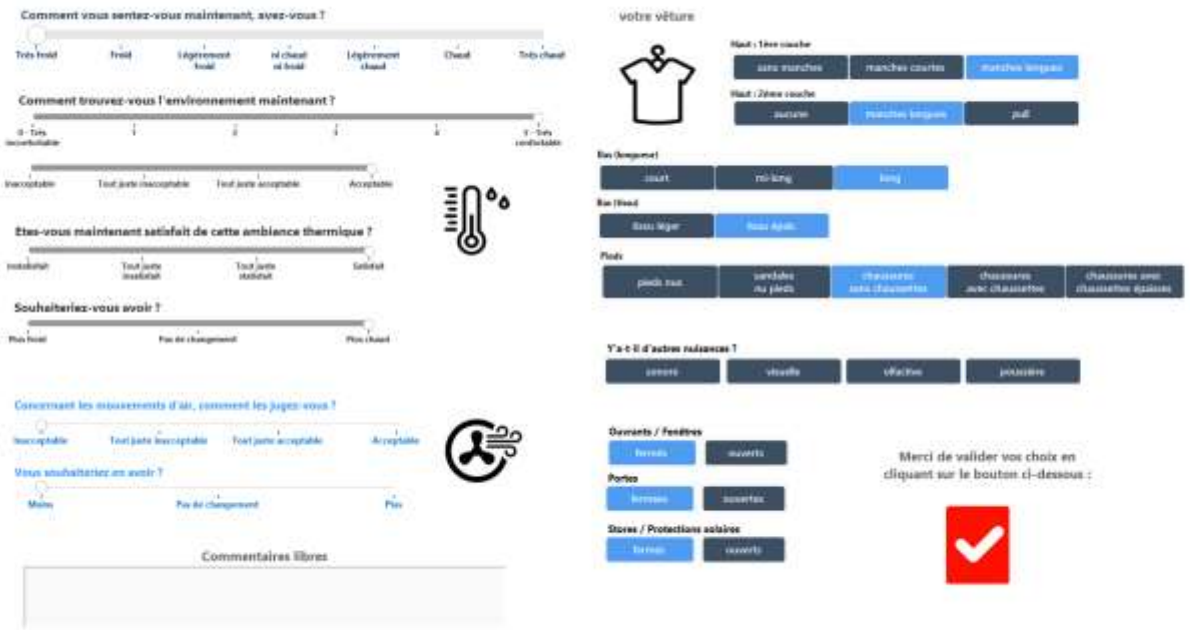

Figure 1: Screenshot of the Cooldown project comfort application for comfort survey(in French)

3.5 Environmental measures

Indoor climatic conditions were recorded at two different levels, at the space level and the subject level.
The micro-climate around the participants was monitored using one hygro-button data logger for the air temperature (MC_T) and relative humidity (MC_RH). This sensor was pinned on the subject's top piece of the garment (at the chest level). These acquisitions were made with a time step of 5 minutes.
Air temperature and relative humidity were acquired with the PULSE box developed by CSTB every 10 minutes.
Environmental parameters for all spaces, such as dry bulb temperature, globe temperature, air velocity, and relative humidity, were recorded with various equipment, as in Table 1. All environmental parameters data are pre-processed to obtain a mean at 5 minutes time-step. For example, the environmental data from the PULSE box being acquired at a time step of 10 minutes, the value lying between two measured values corresponds to the average between these two values.

The meteorological data were extracted from the Mereen platform developed by CSTB, which combines solar radiation from satellite observations with classical weather station data, all at an hourly time step base. Results presented in this paper do not yet consider all granulometry of measurement at this early stage of the study.

Table 1: List of environmental parameters measure equipment

Supplier	Model	Probes	Measurements	Timestep

DeltaOhm	HD32.1 – Thermal Microclimate Data Logger	Combined temperature and relative humidity probe. Globe temperature probe Ø 150mm Omnidirectional hot wire probe (0°C…80°C)	Tdb, Tg, Va, RH	15 s
Testo	400	$C0_2$ probe with Temperature and relative humidity sensors Globe temperature probe Ø 150mm TC type K Hotwire thermo-anemometer	Tdb, Tg, Va, RH	15 s
Kimo	VT 110 / VT 115	Hotwire thermo-anemometer	Va, Tdb	15 s
Campbell Scientific + Testo	CR1000	Combined temperature and relative humidity probe. Globe temperature probe Ø 152mm Thermal anemometer	Tdb, Tg, Va, RH	1 s

4 RESULTS & DISCUSSION

4.1 Quality of the data

The database was obtained by synchronising the data from the different sources of measurements. It contains 935 lines, corresponding to the 935 questionnaires obtained from the 20 participants over the three campaigns, and allowing the statistical analysis of the data to correlate all the environmental data, physiological and declarative data.
Due to the constraints of *in-situ* experimentation, some missing values exist in the database, depending on the sensors. The temperatures measured by the PULSE box showed a mean difference of 0.5°C with the temperature acquired with the comfort stations. The relative humidity recorded with the PULSE box showed a mean difference of 3.6% with the measures made with the comfort stations. These mean differences being sufficiently low compared to the uncertainty of the sensors, the missing values from the comfort stations were completed with the values of the PULSE boxes.
The number of missing values remaining after the database cleaning is 55 for the indoor temperature and indoor relative humidity measurements and 30 for the skin temperatures.

4.2 First results

The meteorological data indicate that the mean outside temperature during the three campaigns and the hours of response to the questionnaires was 28.5°C (min: 23°C, max: 31°C), and the mean relative humidity was 64.7% (min: 44.8%, max: 88.84%). Most of the time, the wind came from the southeast at a mean speed of 6.5 m/s (min: 0 m/s, max: 13.4 m/s).
The indoor temperatures in the IDC building were between 25.4°C and 29.4°C (mean: 28.3°C), and in the COA building, between 23.9°C and 31.3°C (mean 29.3°C) during the campaigns. The indoor relative humidity in the IDC building was between 51.5% and 81.8% (mean: 59.8%), and in the COA building, between 50% and 82.5% (mean of 67.1%). Windows were opened 85% of the time.
Regarding the responses to the questionnaire, 50% of the time, the subjects had a neutral thermal sensation, 30% slightly warm, 11% warm, and around 3% for the other choices. Only subjects in the COA building were declared "hot" when none of the subjects in the IDC building did.
The respondents declared they were satisfied 62% of the time, just satisfied 29%, just unsatisfied 7% and unsatisfied 2%. As for the thermal sensation, only occupants of the COA building chose the "unsatisfied" response. The same analysis can be made for comfort and

acceptability. This result is consistent with the indoor conditions, which were hotter and more humid in the COA building than in the IDC one. The exact number of responses for each subject and each category of thermal sensation, comfort, acceptability and satisfaction is shown in Figure 2.

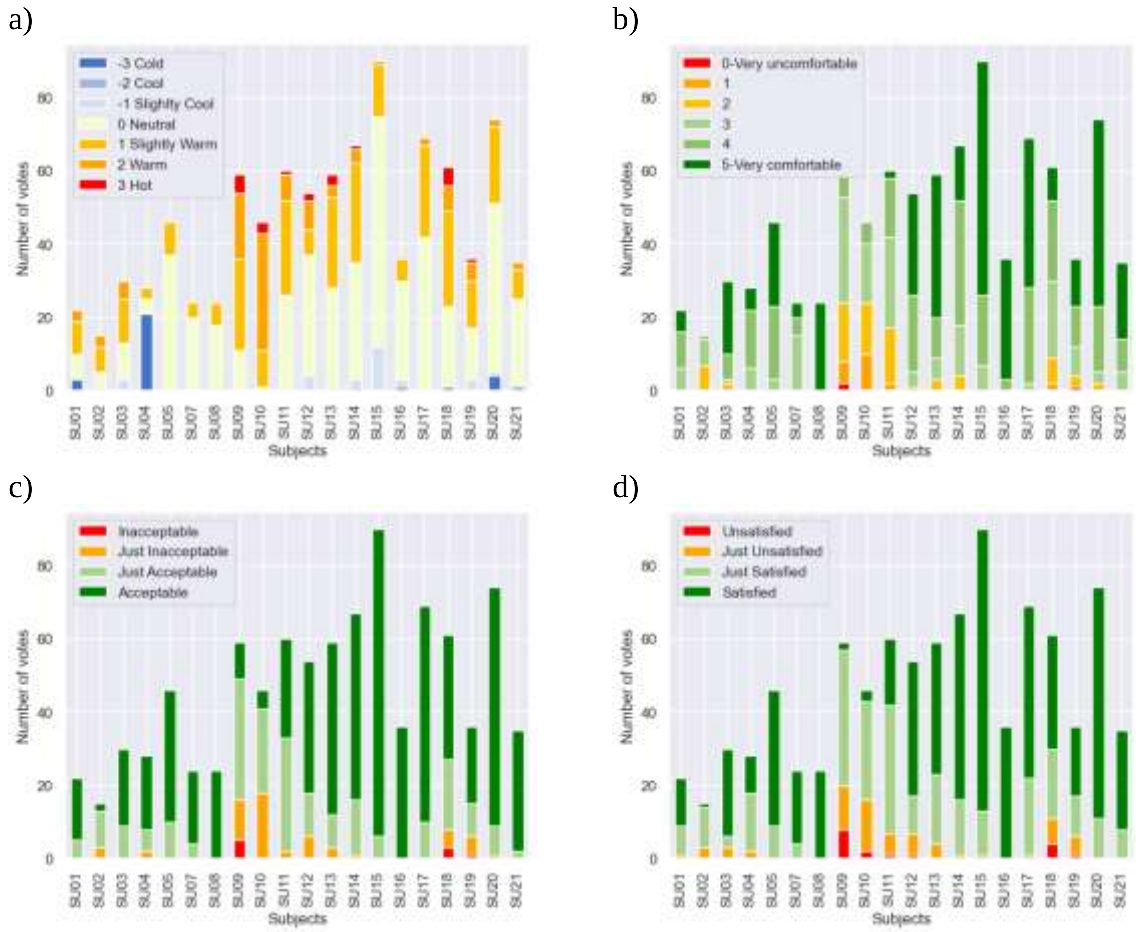

Figure 1: Number of votes for each subject and for each category of thermal sensation (a), comfort (b), acceptability (c) and satisfaction (d)

The four levels of satisfaction with the thermal environment are shown in Figure 3 as a function of the average values of air temperature and relative humidity. For each level, dissatisfaction increases with relative humidity. Confidence ellipses for the extreme satisfaction and dissatisfaction levels are constructed using the values of standard deviations of temperature and relative humidity. The correlation coefficient between temperature and relative humidity is used to calculate the angle of the confidence ellipse.

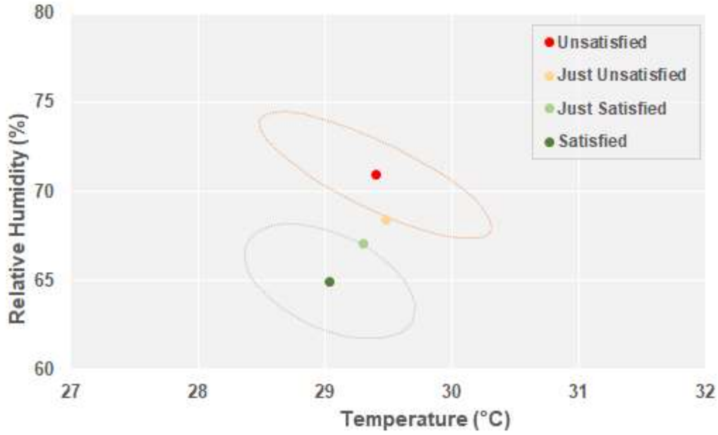

Figure 3: Evolution of the satisfaction level as a function of the temperature and relative humidity inside the buildings

Figure 3 shows that as dry as the air remains, the air temperature does not influence the level of satisfaction itself. On the contrary, a threshold value for relative humidity (68%) seems to condition the panel's dissatisfaction index.
Figure 4 shows the evolution of the skin temperature as a function of the microclimate temperatures and relative humidity. The results show that the main parameter influencing the skin temperature is the air temperature around the participants. The relative humidity is less linked to the skin temperature.

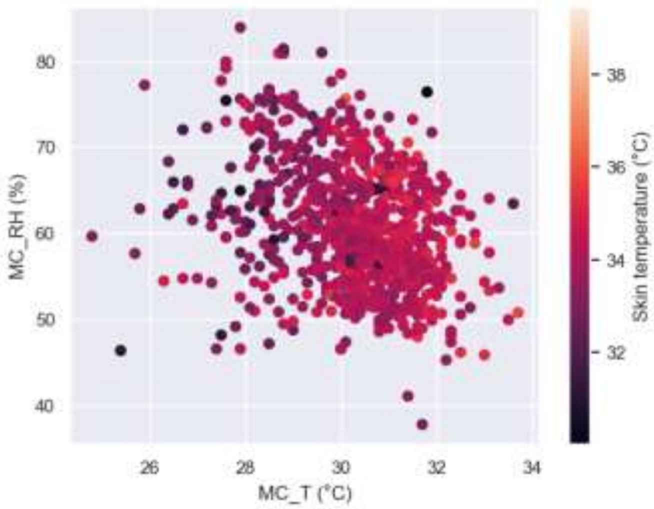

Figure 2: Evolution of the skin temperature as a function of the temperature and relative humidity given by the individual microclimate

5 CONCLUSIONS

This paper aims to present an overview of the methodology used in the ANR project CoolDown. Thus, the results presented in this paper are preliminary and do not show the whole set of data acquired.
These first results allow us to identify a trend regarding the strong influence of relative humidity on thermal satisfaction. A threshold value for relative humidity (68%) in this range of air temperatures seems to condition the panel's dissatisfaction index.
The skin temperature measurement is a good indicator of the ambient temperature around the subjects. This first set of declarative, physiological and environmental data constituted from the three campaigns will serve as entry data to build and optimise a thermal comfort prediction

model, which will be validated with the data from a second set of experimental campaigns while testing the optimised hybrid cooling solutions, identified during the CoolDown project.

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