IMPROVEMENT OF COMFORT AND ENERGY EFFICIENCY IN EXISTING BUILDINGS USING ADAPTIVE THERMAL COMFORT ALGORITHM

José Manuel Salmerón Lissén*[1], José Sánchez Ramos[2], Pablo Aparicio Ruiz[3], Javier García Ramos[1], Servando Álvarez Domínguez[1], José Luis Molina Félix[1], Elena Barbadilla Martín[3]

1 Grupo de Termotecnia. Seville University
Camino de los descubrimientos S/N
Escuela Técnica Superior de Ingenieros
Seville 41092, Spain
**Corresponding author: jms@us.es*

2 Cádiz University
C/Chile 11002
Cádiz, Spain

3 Grupo de Investigación Operativa. Seville University
Camino de los descubrimientos S/N
Escuela Técnica Superior de Ingenieros
Seville 41092, Spain

ABSTRACT

Comfort and energy saving are two important concepts treated in current buildings in order to maintain a good air quality reducing the energy consumption. According to International Energy Agency (IEA) buildings represent 32% of total final energy consumption, and the need for reduction of CO_2 emission leads to pay attention to the energy demand in buildings. On the other hand maintaining a good-quality environment helps to improve the productivity and effectiveness of workers. Thus thermal comfort models that optimize the consumption of energy guaranteeing the comfort of occupants are gaining importance in the building sector.

This is what adaptive thermal comfort theory pursues, being the aim of this paper to develop an adaptive thermal comfort algorithm for air conditioned buildings located in Seville. Two different buildings have been chosen to perform the experiments, two operator's room with about 15 people which are surveyed every day to carry out the field studies. Sensors have been placed around the room to measure the environmental parameters.

The main aspects treated in this paper are:

1. Instrumentation required to measure the environmental parameters and its location in the room are introduced,
2. The transversal and longitudinal questionnaires that are necessary to perform the field studies.
3. Description of the characterization method that is going to be used in order to evaluate the energy savings.

The experimental phase lasts until the end of August 2017.

KEYWORDS

Comfort, energy efficiency, Ventilation, Adaptative thermal comfort

1 INTRODUCTION

This paper is based on the works carried out in the ME4CA project. The objective of the project is to develop an adaptive thermal comfort algorithm (ACA) that guarantee comfort conditions leads to energy savings benefits and keeps an adequate indoor air quality.

In most of the existing buildings, the indoor air temperature is maintained between a relative narrow temperature limits –in practice, 22±2ºC-. International standards as EN ISO 7730 [1] and ASHRAE 55-92 [2] suggest the calculation of the comfort temperature as a function of the clothing levels and the methabolic rate of the occupants. Additionally, due to the need of reduce the CO2 emmissions the energy consumption of buildings have been tackled and both criteria have been considered together.

At the nearly 70s, Nicol and Humphreys developed an introduction to the adaptive comfort theory, where they show as the occupants could tolerate indoor conditions out of those recommended by the standards. Humphreys suggested that the comfort temperature could be related with the outdoor temperature in a given location, this is shown in the next figure and leads to what is known nowadays as ACA.

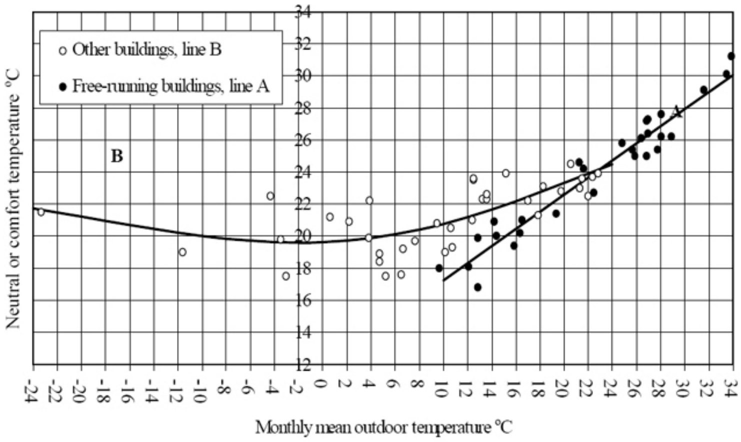

Figure 1: Comfort temperature as a function of the monthly mean outdoor temperature. Source Nicol, Humphreys and Nicol [8].

In order to evaluate the energy savings due to the use of the new comfort techniques it is necessary to use a thermal characterization method that could forecast the energy consumption of buildings.

In the first section of the present paper we describe the variables that are required to develop the ACA and the characterization method, in the second section we describe the survey used to recover the information from the occupants; and finally in the third section we describe the thermal characterization methodology.

2 MEASUREMENTS OF ENVIRONMENTAL PARAMETERS

The studied building is a call center used for emergency purposes. There are air inlets on the floor symmetrically distributed, and air outlets on the floor and ceiling. The reason why we selected this building is that there are enough people to perform the field study, working during the night and changing the seats frequently. Figure 2 shows this room:

Figure 2: Call center selected to carry out the field study

The parameters that are going to be registered are the next:

- Air temperature (ºC)
- Globe temperature (ºC)
- Relative humidity (%)
- Air velocity (m/s)
- CO_2 concentration (ppm)
- Illuminance on the work plane (lux)

These are the general parameters that have also been measured in the SCATs project "Project controls and thermal comfort" [8]. CFD simulations have been developed in order to determine the required number of sensor and their location in the room.

2.1 Location of the air velocity sensors

The whole room is split in 5 sections. The sections 1 to 5 are represented in the next figure for the velocity field. According to the figure 3, there should be at least one sensor in each row, but keeping in mind that the workers are concentrated in the first 4 rows (section 1 and 2) and the price of the multidirectional velocity sensor is high, only one sensor has been placed at head level in the centre of the occupied area (section 2 in figure 3).

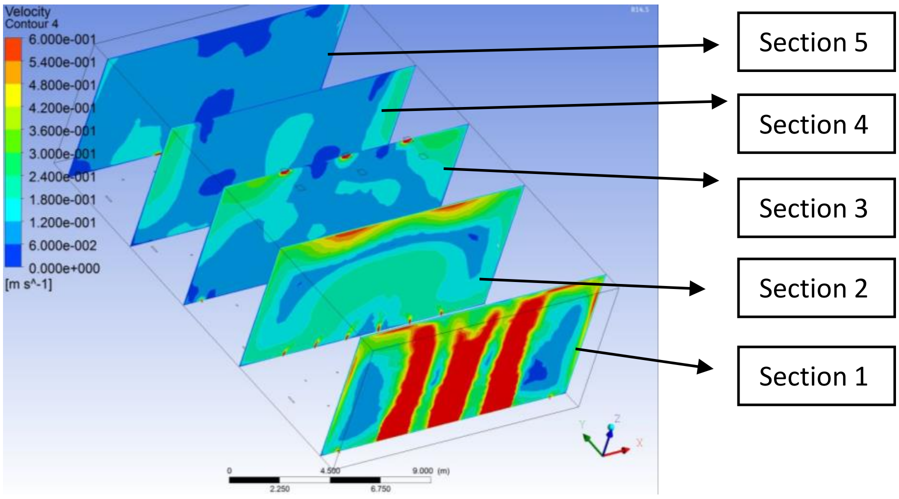

Figure 3: Velocity field in the five representative sections

2.2 Location of the air temperature sensors

As mentioned above, the whole room is split in 5 sections. The sections 1 to 5 are represented in the next figure for the temperature field. According to the figure 4, there should be at least three sensor in each row, but keeping in mind that the workers are concentrated in the first 4 rows (section 1 and 2), only three sensors has been placed at head level in the first 3 rows.

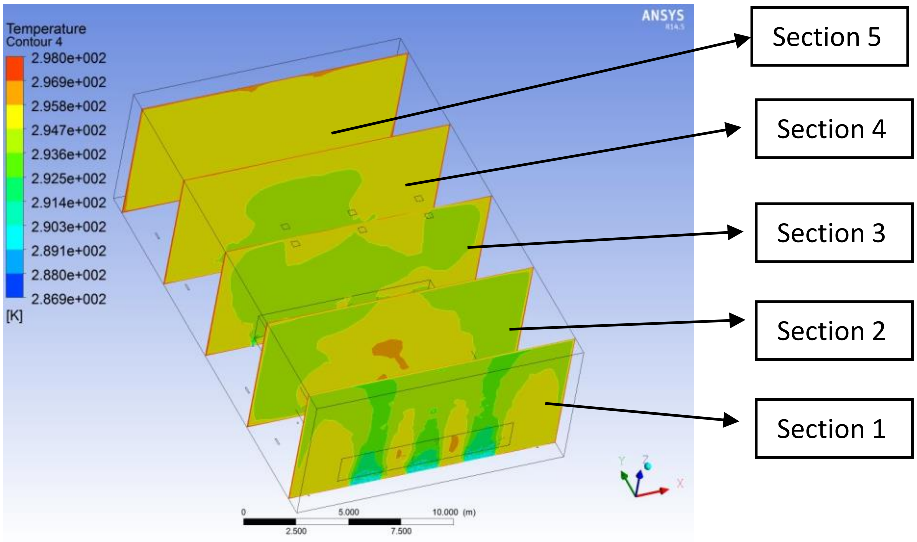

Figure 4: Temperature fields in the five representative sections

Note how the temperature profiles are symmetric in each room, but the occupants are not located symmetrically, so it cannot be used this property when deciding where to place the sensor.

2.3 Location of the CO_2 sensors

Qualitatively, the CO_2 profiles are similar to the air temperature profiles, thus the figure 4 can be taken into account to select the place where to locate the sensors. Since it is required the maximum value of CO_2 concentration, 1 sensor should be installed in each section of the occupied area.

2.4 Monitoring system

Among the sensors mentioned above, it has been located luxometers, relative humidity, globe temperature and surface temperature sensors. The number of sensors and their position are listed below:

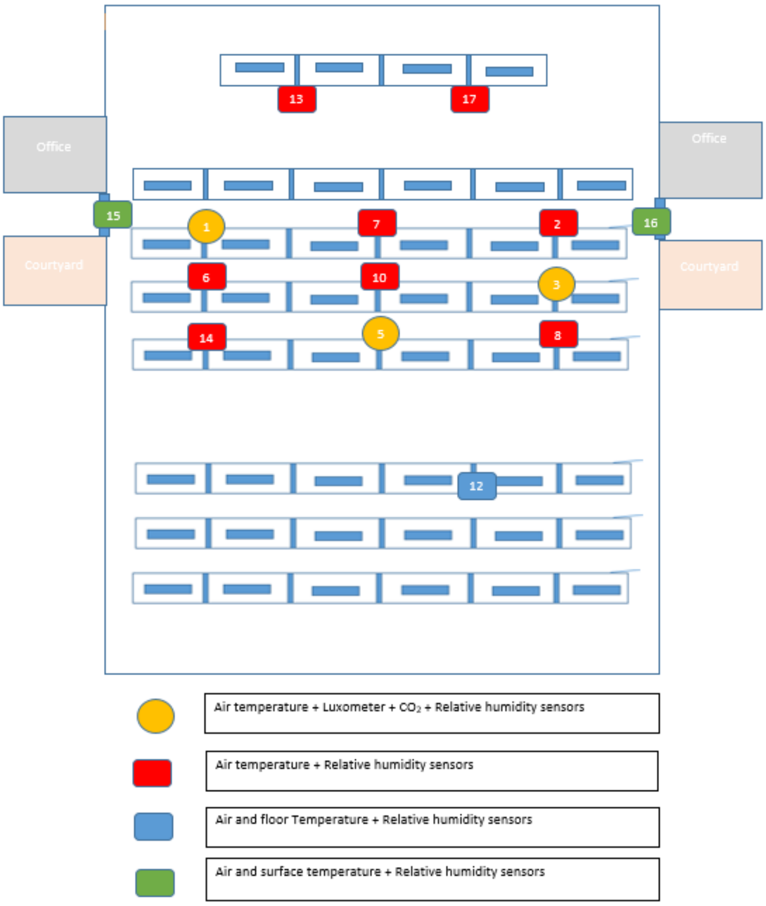

Figure 4: Location of each sensor of the monitoring system

3 THERMAL COMFORT EVALUATION THROUGH QUESTIONNAIRES

It has been shown that there is often an acute discrepancy between the comfort objective and subjective comfort [3]. The survey as a fundamental element of subjective data collection is presented by ASHRAE thermal comfort as a means to study the comfort [4]. The sampling of the users comfort, allows observing and predicting the level of comfort on the HVAC system. The development of online sampling systems assists in the recognition of the behavior patterns that occur in the offices [5].

The survey allows knowing the different perceptions of the users about indoors comfort levels. The system stores information relating to the comfort related to the temperature and humidity at the moment when the survey data are collected. It is selected the international standard ISO 10551:1995 [6] which looks at the ergonomics of the thermal environment as a basis employing subjective judgment scales. Even so, in spite of the requests of those surveyed, all systems must be limited to certain norms whether determined by the ergonomics expert or by the laws or regulations of a country.

The experiment look at such things as the difference between individuals and the effect of time series on comfort. The problem with this method is period of study, because if the survey period is completed in a short time, say a day then the variety of environmental conditions you investigate with any group of subjects is generally small, since the variation of temperature in a single day may be limited. The method need to study the reactions of a different sample to each value of temperature.

In general, this studies take weeks to complete the enough result to study the adaptive model. The comfort characteristics alter its character over time and space. So whilst the conditions may vary, you are in effect measuring the user with each temperature. For this reason, this project works through a long-term experiment. This is an experimental procedure that runs through a long period of time, although the number of subjects in this group is not strictly limited, only a relatively small sample will be possible with a view to maintaining continuity in the survey answers.

An interesting example was presented by Humphreys and Nicol (1970) [7] who carried out a wide-ranging survey based on monthly records collected from a small group of subjects over a period of 15 months. In 2010, the SCATs project were collected 4655 sets of environmental and subjective data, and 1449 of these were collected in buildings which were free-running at the time of the measurements [8]. Many surveys have been conducted using subjects in a tropical context and relate observed sensation on the ASHRAE scale (or the similar Bedford scale) to the physical environment. Examples of authors are: Webb, Sharma and Ali, Busch, Matthews, Nicol, Taki, Bouden and many others are quoted in the literature e.g. (Nicol, 2004) [9]. They found that subjects differed from themselves from month to month by as much as they did from each other. In this way a relatively small group can be representative of a much larger population.

This sample of users chosen are familiar with their surroundings and the climate they are living in and the experiment allow them to go about their usual routine and use their own clothes.

In our case the particular group of individuals for the study are workers in a big office. The individuals in the sample are willing to devote the effort needed for taking part in the survey and their Trades Union was contacted for the approval.

To make a sample representative of the population, the project select user with different sex, age and body dimensions and they are registered in the system.

The survey is divided in three questionnaires:

1. Clothing questionnaire
2. Transversal questionnaire
3. Longitudinal questionnaire

The clothing survey, this questionnaire is filled every week and include different clothes aspects like:

- Q: Shoes (A: Sandals, Shoes, Boots)
- Q: Sock (A: Thin socks, Nylon stockings, Thick socks or none)
- Q: Pants (A: Shorts, Trousers, Corduroys or none)
- Q: Dresses – Skirts (A: Summer skirt, Skirt winter, Light Dress, Winter dress or none)
- Q: Shirts - Blouses - T-shirt (A: Short sleeves, Long sleeved, Long sleeve winter or none)

- Q: Vest – Sweater (A: Sleeveless, Lightweight, Thick, Thick gooseneck or none)
- Q: Jacket (A: Summer Jacket, Winter Jacket, Coat, anorak or none).

The transversal questionnaire is filled every week, but three days after the clothing survey. This questionnaire only has five questions.

- Q: How would you describe the quality of the natural lighting in your work area? (A: Clearly acceptable, Acceptable, Unacceptable, Clearly unacceptable)
- Q: How would you describe the quality of the artificial lighting in your work area? (A: Clearly acceptable, Acceptable, Unacceptable, Clearly unacceptable)
- Q: How do you find the air quality right now? (A: Clearly acceptable, Acceptable, Unacceptable, Clearly unacceptable)
- Q: How strong do you find the smell to be right now? (A: No smell, Weak smell, Moderate smell, Strong smell, Very strong smell, Overwhelming smell)
- Q: At the moment you are... (A: Happy, Optimistic, Excited, Normal, Uninterested, Depressed, Sad)

The longitudinal questionnaire is filled every day and contain 8 questions:

- Q: How do you feel just now? (A: Cool , Slightly cool, Neutral, Slightly warm, Warm)
- Q: How do you find the temperature right now? (A: Acceptable, Unacceptable)
- Q: How do you want the temperature to be? (A: Higher, Slightly higher, Unchanged, Slightly lower, Lower)
- Q: The activity that you are carrying out... (A: Is stressful, Is normal, Is relaxing)
- Q: Have you eaten or drunk anything in the last 30 minutes? (A: Nothing, I have drunk something or I have eaten and drunk something)
- Q: You are wearing at this moment a shirt, blouse or t-shirt ... (A: Short sleeves, Long sleeved, Long sleeve winter or none)
- Q: You are wearing at this moment a vest or sweater... (A: Sleeveless, Lightweight, Thick, Thick gooseneck or none)
- Q: You are wearing at this moment... (A: Summer Jacket, Winter Jacket, Coat, anorak or none)

The personal thermal condition (perceptual and emotional evaluation and temperature preferences) is incorporated as in the UNE-EN ISO 10551:2002, the thermal environment (personal acceptance and tolerance) is included in the longitudinal questionnaire and about the emotional state, the level of stress appear in the longitudinal questionnaire and the worker's mood in the transversal survey.

A Web application has been made under an Apache server and developed in PHP language, the data is stored in a MySQL database. The answers to the questionnaires are stored on the web-server. PMV (Predicted Mean Vote) is calculated in real time after the user answers the survey, the value CLO (Clothing insulation) is based on the responses to the questionnaire, the PMV is calculated in general (with the clothing survey) or a second CLO changes the clothing survey with the last three questions in the longitudinal questionnaire. All the process is carried out with the survey and sensors data through other program, this program is used to calculate the body mass index, or other important and necessary information.

4 CHARACTERIZATION METHOD FOR THE EVALUATION OF THE ENERGY SAVINGS

To develop a method to characterize the energy savings is necessary in order to evaluate the benefit of the implementation of the adaptive comfort algorithm (ACA) due to the fact that we cannot compare simultaneously the building with and without this kind of control. It is necessary to carry out a base line period without the ACA, and then characterize the consumption in order to compare the data with those obtained after the implementation of the ACA.

The characterization model described below is based on transfer functions [10], [11], so it requires an instantaneous relation between input data and output, but not at other way. Transfer functions are used in many applications to evaluate dynamics variables; because, this models can be too easy but very efficiency.

The main objective of the model is defining tool for characterizing energy consumption of existing building. In addition, the main requirements for the model are:

- Identify their coefficients through experimental data
- Adaptable to different time steps: small (hour) or big (days).
- Enough accuracy to be a tool to evaluated energy savings.

So, mathematical and basic formulation results:

$$f(t) = \sum_{i=1}^{m} \sum_{j=0}^{n} a_{ij} \; Y_i(t-j) - \sum_{k=1}^{d} d_k \; f(t-j) \qquad (1)$$

Where:

- f(t) objetive variable
- Y_i excitations (i=1,..,m)
- a_{ij} coefficients for each independent variable Y_i
- d_k coefficients of inertia effect.

Equation (1) is a general formulation of the model that it is possible to specify for the application studied. For this one, it is necessary to know:

- Temperature of outdoor air [ºC]
- Global radiation [W/m^2]
- Temperature of indoor air [ºC]
- Schedule of operation
- Energy consumption of HVAC.

Hence the basic model for characterize sum energy consumption of HVAC for term z is:

$$CI(Z) = \sum_{i=0}^{m} a_i \cdot T_{SA}(z-i) + \sum_{i=1}^{m} b_i \cdot T_{INT}(z-i) + \sum_{i=1}^{n} d_i \cdot CI(z-i) \qquad (2)$$

It should be noted that, CI(Z) has a double correlation, because the model needs temperature of indoor air but this temperatures is depends on energy consumption of HVAC.

Therefore, it can do another model for correlation average temperature of indoor air. This new model has two formulation: (3) when HVAC is turned off and indoor air is in free-floating, and (4) when HVAC is on, average indoor air temperature is the objective variable and CI(Z) is a input of the model.

$$T_{INT}(Z) = \sum_{i=0}^{m} e_i \cdot T_{SA}(z-i) + \sum_{i=1}^{n} d_i \cdot T_{INT}(z-i) \quad (3)$$
$$T_{INT}(Z) = \sum_{i=0}^{m} g_i \cdot T_{SA}(z-i) + \sum_{i=0}^{m} h_i \cdot CI(z-i) + \sum_{i=1}^{n} d_i \cdot T_{INT}(z-i) \quad (4)$$

Where:

- $T_{INT}(Z)$: Average temperature of indoor air [ºC].
- $GI(z)$: average of internal gains for term z [W/m^2]
- $T_{SA}(z)$: Equivalent temperature sun-air.
- a_i, b_i, e_i, g_i and h_i : coefficients of the model
- d_i: Coefficients depends on the time constants of the system. ASHRAE [12]–[14] and UNE 13790 [15].

The double model, energy consumption vs temperature of indoor air can be know

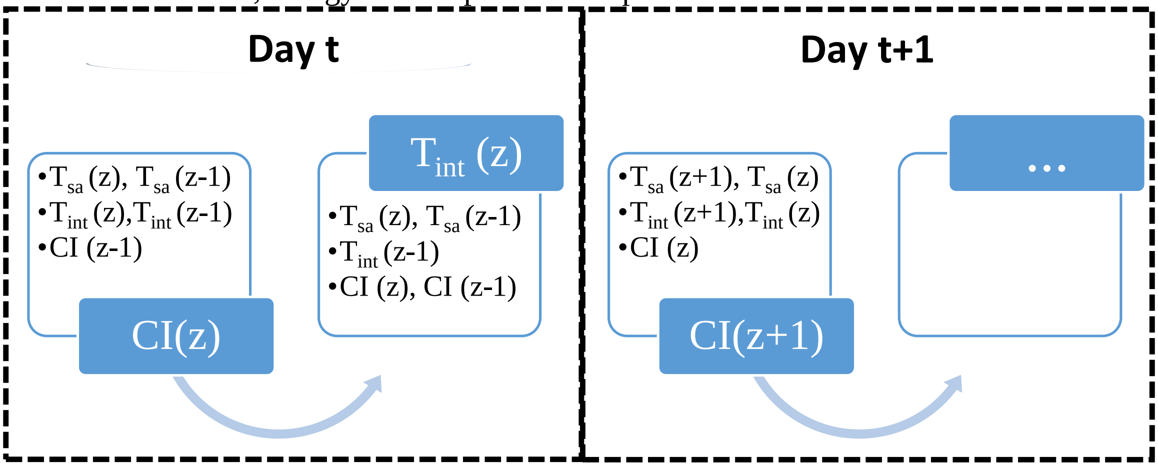

Figure. Simplified diagram of double model CI(z)-T$_{INT}$(z).

Equivalent temperature sun-air is combination of global radiation [Wh/m^2] and temperature of outdoor air [ºC]. For calculating, it is necessary to make an experiment in free-floating of the buildings (without internal gains: people, lights… and with HVAC turns off). The model of indoor temperature in this conditions results:

$$T_{INT}(Z) = \sum_{i=0}^{m} aa_i \cdot T_{EXT}(z-i) + \sum_{i=o}^{m} bb_i \cdot RAD(z-i) + \sum_{i=1}^{n} d_i \cdot T_{INT}(z-i) \quad (5)$$

Where: $\mathrm{T_{EXT}}(z)$ is an average temperature of outdoor air for term z, and $RAD(z)$ is the sum of global radiation incident. So, temperature sun-air is defined as:

$$T_{SA}(z) = \mathrm{T_{EXT}}(z) + k \cdot RAD(z) \quad (6)$$

Where k [ºC/Wh/m^2] is obtained in steady state of expression (5).

$$k = \frac{\sum_{i=o}^{m} bb_i}{1-\sum_{i=1}^{n} d_i} \quad (7)$$

This parameter k refers increment of indoor temperature due to effect of radiation.
Similar study, it is feasible to do with internal gains. For it, it has to do an experiment in normal operation of the building but HVAC has turn off. In this case, the model of average temperature of indoor air results:

$$T_{INT}(Z) = \sum_{i=0}^{m} cc_i \cdot T_{SA}(z-i) + \sum_{i=o}^{m} gg_i \cdot GI(z-i) + \sum_{i=1}^{n} d_i \cdot T_{INT}(z-i) \quad (8)$$

Therefore, steady-state parameter associated to internal gains is:

$$P_{GI} = \frac{\sum_{i=o}^{m} gg_i}{1-\sum_{i=1}^{n} d_i} / (V \cdot \rho \cdot C_P) \quad (9)$$

This parameter refers to increment of indoor temperature due to effect of internal gains. Finally, it has developed a double model to characterize energy building consumption and average temperature of indoor air. The combination of these models allows solve the main objective and the final application in the project.

5 FUTURE DEVELOPMENTS

We are currently measuring the parameters inside the room to be able to characterize the consumption before implementing the algorithm, and the questionnaires is being filling in by occupants to evaluate the comfort. Thus this summer and winter we will be collecting measures to be able to create the thermal comfort algorithm. Next summer and winter, this algorithm will be implemented and evaluated to determine the improvements in comfort and energy consumption.

REFERENCES

[1] EN ISO 7730 (2006). *Ergonomics of the thermal environment - Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria.*

[2] ASHRAE 55-2013. *Thermal Environmental Conditions for Human Occupancy*

[3] Meir, I.A., Garb, Y., Jiao, D., Cicelsky, A. (2009). Post Occupancy Evaluation: An Inevitable Step Toward Sustainability. *Advances in Building Energy Research*, 3, 189-220.

[4] ASHRAE (1997). *Ashrae handbook-fundamentals*. American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta.

[5] Aparicio, P., Guadix, J., Onieva, L., & Escudero, A. (2014). Methodology for analysis and decision making by sampling in buildings. *Dirección y Organización*, (53), 65-74.

[6] ISO 10551 (1995). Ergonomics of the thermal environment - Assessment of the influence of the thermal environment using subjective judgement scales. International Organization for Standardization, Geneva.

[7] Humphreys, M. A., Nicol, J. F. (1970). An investigation into thermal comfort of office workers. *Journal of the Institution of Heating and Ventilating Engineers*, 38, 181-189.

[8] Nicol, F., Humphreys, M. (2010). Derivation of the adaptive equations for thermal comfort in free-running buildings in European standard EN15251. *Building and Environment*, 45 (1), 11-17.

[9] Nicol, F. (2004). Adaptive thermal comfort standards in the hot–humid tropics, *Energy and Buildings*, 36 (7), 628-637.

[10] D. G. Stephenson and G. P. Mitalas, “CALCULATION OF HEAT CONDUCTION TRANSFER FUNCTIONS FOR MULTI-LAYER SLABS.,” ASHRAE Trans., vol. 77, no. Pt 2, pp. 117–126, 1971.

[11] E. Ponsoda, S. Blanes, and P. Bader, “New efficient numerical methods to describe the heat transfer in a solid medium,” Math. Comput. Model., vol. 54, no. 7–8, pp. 1858–1862, 2011.

[12] T. J. R. Cooper, “1986 ASHRAE handbook: Refrigeration systems and applications: ASHRAE, Inc., USA 1986, ISSN 82 64 3223, US$100,” Int. J. Refrig., vol. 10, no. 4, p. 243, 1987.

[13] “96/00806 1995, ASHRAE Handbook, HVAC applications, Si edition,” Fuel Energy Abstr., vol. 37, no. 1, p. 49, 1996.

[14] ASHRAE, “HANDBOOK FUNDAMENTALS 2009.” 2009.

[15] AENOR, “Eficiencia energética de los edificios. Consumo global de energía y definición de las evaluaciones energéticas,” UNE-EN 15603. 2008.