

UNDERFLOOR AIR CONDITIONING SYSTEM – OPERATIONAL CONDITIONS FOR COMFORT IN OFFICE ENVIRONMENTS

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Abstract. *Comfort air conditioning systems are widely used in office buildings, particularly in big cities. Most of such systems, which uses ceiling air supply, do not present good comfort conditions, besides a lack of layout flexibility. Building performance evaluation applied to contemporary office buildings has shown that for most such buildings comfort and air quality users level satisfaction is low. About 30% of several national and international office building users demonstrate dissatisfaction with thermal conditions. These results are strong indicators that it is necessary to change design, operation and practice concepts about air conditioning systems. In order to solve these problems a laboratory facility was built at the Mechanical Engineering Department of Polytechnic School of University of São Paulo, supported by FAPESP and industries. This paper presents experimental results of this kind of system, emphasizing operational conditions to meet Fanger thermal comfort requirements adopted by ISO 7730. Measurements of thermal comfort and system conditions were done simultaneously. These data and results of users' evaluation were used to establish project reference values, in order to provide the more appropriate conditions using underfloor air supply for comfort in office environments.*

Keywords: *Air conditioning, thermal comfort, office buildings, underfloor air supply.*

1. Introduction

In offices buildings the general design concept of air conditioning systems contemplates air distribution done by means of ducts plant with diffusers uniformly distributed in the ceiling. This concept foresees a complete supplying air mixture with the air of the environment, keeping the volume to a desired temperature, assuring the minimum external air rate. In the practical one, the conventional system is operated to keep the internal environment conditions according to the NBR- 6401/1980 standards (ABNT, 1980).

Until the moment, the thermal comfort standards adopted as reference for the air conditioning systems designs are those of the Standard ASHRAE 55a (ASHRAE, 1995), which specifies a *comfort zone* defined for an excellent combination of physical factors (air temperature, mean radiant temperature, air velocity and air humidity) and personal factors (clothing and activity), with which, at least 80% of the occupants express satisfaction (ISO 7730, 1994). Despite this, results of international and Brazilian researches on work environments, where the air distribution is done by the ceiling, have indicated that the thermal comfort is not being well promoted (Schiller, 1988; Leite, 1997; Ornstein et al., 1999).

One assumes that this situation is mainly due to the changes in the dynamics of the work in offices because of the introduction of the landscape office concept in 1950's. Since this time, the type of occupation (lay out) started to be flexible, implying in variations and increase of thermal load due to the increment and/or work equipment changes (like computers, printers and task lighting), that generate conflicts between the proposals of occupation (flexible) and air distribution by diffusers in the ceiling (fixed), compromising substantially the performance of the installed system (Leite, 1997).

As the conventional mixing strategy for the environment air conditioning may be an unsuitable solution to solve this problem, the underfloor air supply system seems to be a more appropriate technology, as much for its characteristics of flexibility as much as the operational way. One system, introduced initially in Germany office buildings, in the 70's, supplies cooled air "low to top", by means of diffusers installed on the raised floor. The system has the following main characteristics: it promotes the exchange of heat with the environment more quickly, only the air volume of the effectively busy space is conditioned, it operates with higher air temperatures than the ones adopted in the conventional systems with ceiling air supply, and it promotes flexibility because allows changes of the air captation floor points due to the absence of ducts.

Until the end of 1990's, the use of this technology was limited to the data processing centers (CPD) areas and the greater contingent was found in the United States, South Africa, Japan, Germany, Sweden and Italy (Heinemeier, 1990).

Since its introduction, this type of system has aroused the interest of researchers, mainly in the United States, Europe, Japan and, more recently, in Brazil. Researches have been developed to define thermal comfort situations promoted by the underfloor air supply system in offices environments, which depend on the resultant thermal conditions in the environment and on the acceptance of these conditions by the users (Leite et al., 2000). These works are results of laboratory (climatic chambers) and field researches, including users. Indicators of the whole system performance or of part of the system are presented, mainly with focus in comfort and in the system operational conditions. Amongst the most recent works in this area published in 2002, they can be detached: Bielli, Cermak, Clarke, Jacobsen, Kaczemarczyk, Leite and Tribess, Naydenov, Pitchurov (2002).

In Brazil, this technology begins to be applied for comfort, as much in new as old buildings, although still in a limited number of buildings. For instance, the following buildings can be cited: Spazio JK, GM, Serasa, Gazeta Mercantil and Votorantim, in São Paulo; Bemge - MG, Unimed - RS and Souza Cruz in Rio de Janeiro, being this last one a rebuilt building. The number is still low expressive because the fact that the underfloor air supply technology is not well known and the lack of information constitute an obstruction for its use in wide scale.

In order to solve these problems a laboratory facility was built at the Mechanical Engineering Department of Polytechnic School of University of São Paulo, supported by FAPESP and industries. This paper presents experimental results of this kind of system, emphasizing operational conditions to meet Fanger thermal comfort requirements adopted by ISO 7730. Measurements of thermal comfort and system conditions were done simultaneously. These data and results of users' evaluation were used to establish project reference values, in order to provide the more appropriate conditions using underfloor air supply for comfort in office environments.

2. Laboratory tests for the thermal comfort conditions evaluation

The prototype used for the tests represents, in a real scale, an office area rate, where the experimental procedures had been applied. This area, called "cell", means a typical floor fraction of an office building whose characteristics: layout, type of people occupation and equipment, besides being the most repetitive characteristics, represent the real conditions of this kind of buildings.

2.1. Characteristics of the laboratory

The laboratory, shown in the Fig. (1), is comprised by the following basic components:

- Test Chamber, with possibilities of underfloor air distribution (or optionally the ceiling air distribution);
- Air conditioning unit;
- Automation and control system;
- Data acquisition system in the environment.

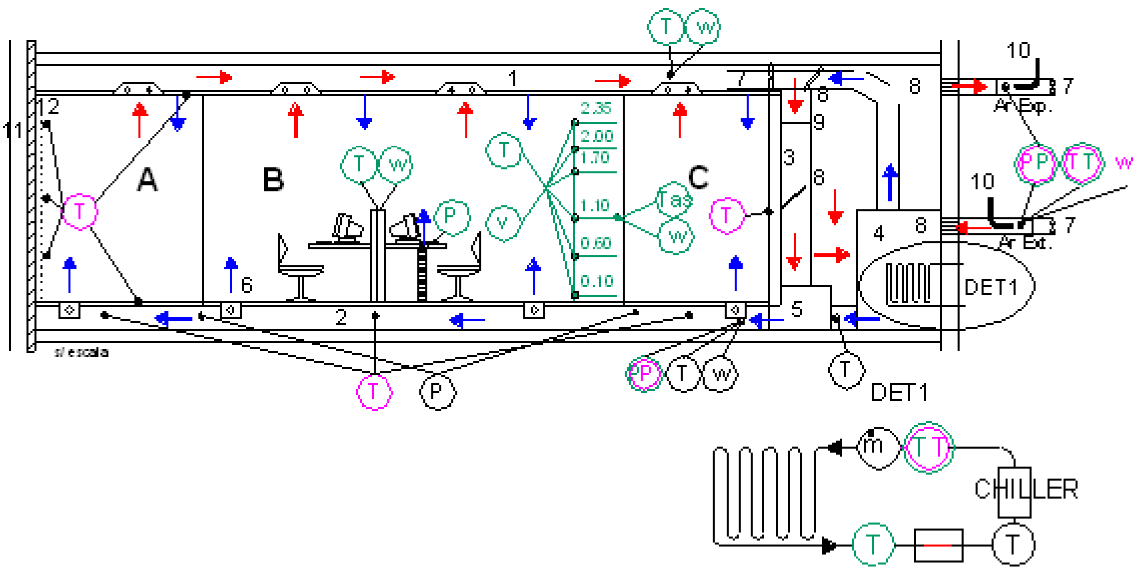

Figure 1. Laboratory scheme

The ***test chamber***, illustrated in Figs. (2 and 3), has a 34,8 m^2 area, and is isolated with polyurethane; all the walls and the door being thermically isolated minimize external loads or the loss of heat and the tests can be carried out in any season. There is a metallic lining in the ceiling that, with the superior slab, composes a plenum for the return air and ticket of ducts for the ceiling air supply. In one of the walls a lamp panel comprised by eight rows, each one with 20 incandescent lamps of 40 W distributed over the whole wall area - simulates the solar radiation in a single glass surface. Adjustable blinds with horizontal sheets to vary the radiation effect inside the chamber had been added.

The layout contemplates three workstations, being two individual and one for two people, which are separated by partition walls of 1.20 and 1.60 m height. On the tables there are microcomputers and printers. Also, diffusers for manual airflow adjustments and direction were installed on the table, as option for personalized comfort. In the four workstations, black cylinders (simulators), that dissipate a seating person's equivalent heat, had been placed - in Fig. (4).

Metallic modulated plates that form a plenum for cold air storage compose the floor of the test chamber -raised floor. The cold air is supplied to the environment through 23 diffusers that were installed in previously determined positions and quantified for maximum thermal load, being nine circular diffusers of Ø 200 mm near to the lamp panel and 14 of Ø 150 mm distributed in the circulation and occupation areas. The chamber still account with five diffusers installed on the workstation tables for personal comfort. The diffusers are of swirl jet type and admit as maximum airflow the following values: for Ø 150 mm, up to 20 l/s and for Ø 200 mm, up to 40 l/s.

The ***air conditioning system*** is composed by a chiller with 5 TR nominal capacity, a fan coil with nominal capacity of 3420 m^3/h airflow - in Fig (5) and a three way valve installed in the chilled water line to guarantee constant discharge air temperature at the fan coil outlet - in Fig. (6).



Figure 2. Test chamber perspective Figure 3. Lamp panel Figure 4. Simulator


Figure 5. Chiller Figure 6. Fan coil

Referring to the air circuit the underfloor air supply system has some characteristics in common to the ceiling air supply, however, it requires some modifications with the objective to promote the desired thermal comfort conditions in the environment.

For instance, a mixture box was installed to allow the increase of the supplied air temperature by mixing fan coil cooled air with a percentage of the hot return air. The cold and hot mixture air volumes are determined by two micro-processed control dampers installed in one of the branches of the air return duct.

The plenum is pressurized and operates with differential pressure values (from plenum to the environment) between 5 and 20 Pa; these values are kept constant for each certain operation condition. When the airflow demand varies in the environment the pressure in the plenum modifies and a previously established set point varies the fan frequency. The air returns through 11 grids installed in the ceiling, which are distributed and placed in a way to prevent at the maximum short circuits.

The ***automation system*** applied to the air conditioning system is composed by a supervision software and by the following transducers: *temperature sensors* installed in the air and water circuits; *air humidity sensors*; d*ynamic* and *static pressure sensors* for airflow determination, and a *water flow device*.

The ***control strategy*** is based on four loops: a) the first acts on the refrigeration unit to control the inlet water temperature; b) the second refers to the control on the chilled water flow in the fan coil by the acting on a three way valve; c) the third consists in the acting on the fan frequency controlled by the pressure difference between the plenum and the environment; d) the fourth loop acts on the opening of the damper installed in the air return flow line controlled by the air temperature supplied to the plenum.

The laboratory counts on two ***data acquisition systems*** for environmental variables measurement. The systems are composed by sensors, and data acquisition modules (signals receiving and converting) and software, which are mounted on an IBM/PC base. For the measurement of the superficial temperatures, there are nine units of thermocouples. The other system, named SENSU, contains the following transducers: 6 sensors for air velocity (hot sphere anemometer); 6 air temperature sensors; 1 globe thermometer; 1 relative humidity sensor and 1 radiant temperature asymmetry sensor.

2.2. Method for the evaluation of the environment thermal comfort conditions

The evaluation of the environment thermal comfort conditions was based on local measurements of the thermal comfort variables and on the level of the users' satisfaction included in the tests. The experimental method is composed by techniques used by Fanger (1972), and in procedures indicated in the following norms: ISO 7730 (1994), ISO 7726 (1985), ASHRAE Standard 55a (1995) and Post Occupancy Evaluation techniques and procedures (Leite, 1997), consisting of a specific method for this application.

The tests were accomplished in two stages:

1st stage – measurements of the environment thermal comfort variables and of the system variables - in six different thermal conditions (**C1** to **C6**, for which, the air temperature values are 26°C to 21°C respectively). Simulators were used to dissipate the equivalent heat as people in light activity. The steady state condition was established, and the thermal conditions, **C1** to **C6**, were based on the air temperatures and relative humidity values measured in the medium point of the test chamber (relatively to the floor plan and height).

2nd stage – Subjective thermal comfort evaluation - where simulators were substituted by people (users) submitted at the same environment thermal conditions as of the *1st* stage.

In the first stage the environment thermal conditions had been evaluated to identify comfort and local discomfort situations, considering Fanger’s thermal comfort parameters as reference. Local measurements of the environmental variables of thermal comfort: air temperature; air relative humidity; air velocity; globe temperature; asymmetry of the radiant temperature and floor superficial temperatures, were accomplished.

The personal aspects and environmental conditions for the tests were the following:

- metabolic rate M = 1.2 met (69.6 W/m^2)
- clothing isolation $0.5 \leq Icl \leq 1.0$ clo (0.078 to 0.155 m2 ºC/W);
- operative temperature 21 ºC $\leq t_o \leq$ 26 ºC
- mean air velocity $0.10 \leq V \leq 0.30$ m/s
- relative air humidity RH ≅ 50%.

It is important to point out that the operative temperature, defined as “the uniform temperature of an imaginary black enclosure in which an occupant would exchange the same amount of radiant heat as in the actual nonuniform space” (ASHRAE, 2001), under the tests conditions was considered equal to the air temperature because the measured values of mean radiant temperature were very close to the air temperature ones.

Typical office equipment and sun shining on glass surfaces (with a condition of maximum insolation for the city of São Paulo) had been considered, which amounted to 4,200 W (121 W/m^2) of thermal load.

The measurements carried out over the twenty points illustrated in Fig. (7), which cover the test chamber area as a whole; that is, occupation zones (workstations with the **S1** to **S4** simulators, being three points around each simulator), peripheral zone (next to the lamp panel - P16), circulation zones (P13 to P15) and in the axis of the other four diffusers (P17 to P20). In each point, the variables had been measured in the following heights (levels): 0.10; 0.60; 1.10; 1.70; 2.00 and 2.35 m, being: 0.10; 0.60 and 1.10 m, recommended for thermal comfort evaluation of seated people and 0.10; 1.10 and 1.70m, for standing people - in Fig. (8). The rest of the upper levels had been added with the purpose of the verification of the air temperature stratification through the overall heigh of the room.

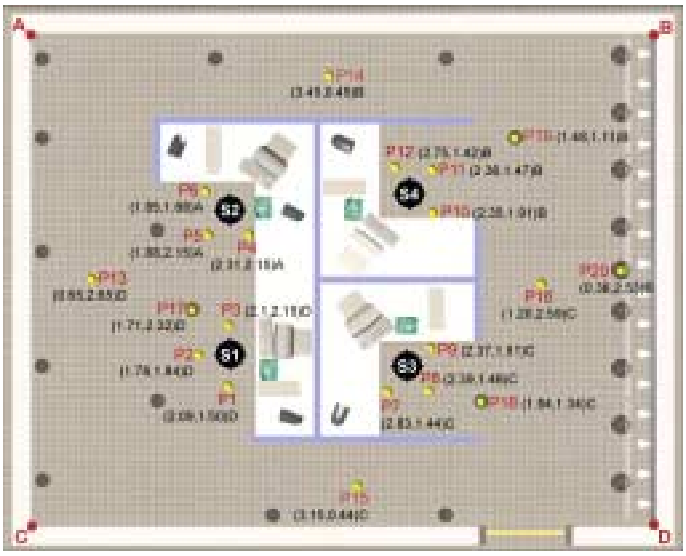

Figure 7. Measurement points

Figure 8. Environment data acquisition

Parallel to the thermal comfort variables measurements, others referring to the system operation had been continuously measured and monitored during each test. Some of the parameters used for the system operation during the tests displayed in Tab. 1.

Table 1. Parameters for system operation in the six tests conditions (C1 to C6)

Variables	***Tests conditions***					
	C 1	**C 2**	**C 3**	**C 4**	**C 5**	**C 6**
Air temperature - environment (^oC)	25.8	25.2	24.1	23.2	22.1	20.8
Relative humidity - environment (%)	42.0	45.0	43.0	48.0	57.0	63.0
Return air temperature (^oC)	27.2	26.6	24.5	24.4	23.4	22.4
Return air humidity (%)	40.0	42.0	40.0	45.0	52.0	57.0
Discharge air temperature - fan coil (^oC)	13.9	14.2	13.1	13.9	14.8	15.0
Plenum air supply temperature: mixture box (^oC)	19.9	19.5	19.0	17.9	16.3	15.4
Plenum air supply humidity: mixture box (%)	63.0	65.0	62.0	70.0	81.0	86.0
Chilled water supply temperature – (^oC)	9.0	9.0	8.0	8.9	9.1	9.0
Chilled water return temperature – (^oC)	13.8	14.1	12.9	14.1	14.0	14.2
Static pressure - plenum (Pa)	9.0	9.6	11.2	13.7	18.1	18.9

In the second stage, the subjective evaluation of the environment was carried out under the same six thermal conditions adopted in the previous one. The evaluation was based on the opinion of the users included in the tests - Figs (10 and 11), who had expressed their satisfaction with the thermal conditions answering to a questionnaire. The answers, represented by the Predicted Mean Vote (PMV), define the more adequate comfort parameters for users of Brazilian buildings offices with the same characteristics of the evaluated environment.

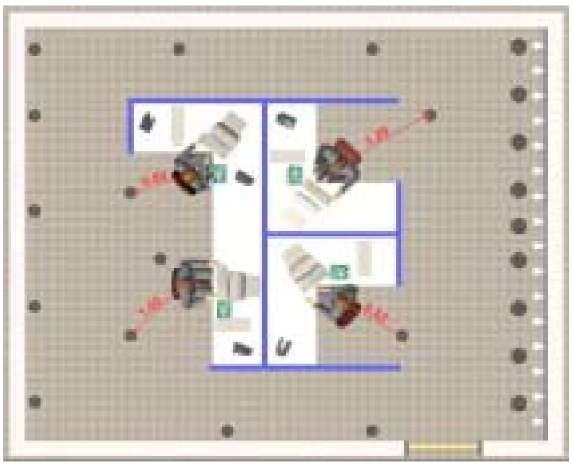

Figure 10 – Tests with users

Figure 11 – Workstations occupied by the users

3. Evaluation results

3.1. 1st stage

The analysis was accomplished with base on the results of the air temperature and air velocity profiles shown in Fig. (12) and on the other measurement data related to the six tests conditions shown in Tab. (2). The following profiles and data refer to the C1 test condition. The results referring to the other five tests conditions can be found in Leite (2003).

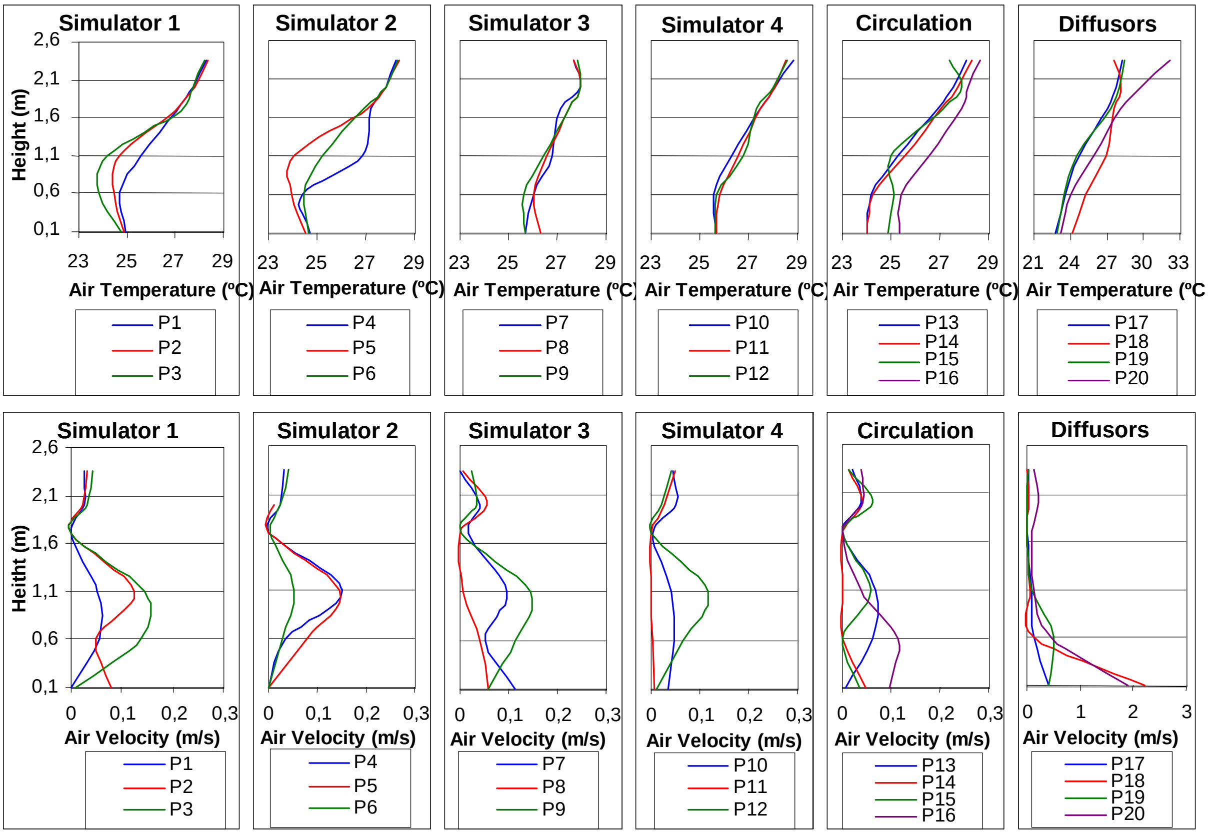

Figure 12. Air temperature and air velocity profiles – Test condition C1

Table 2.Variables used for thermal comfort analysis – mean values on 0.60m level – C1

	Condition 1 (26°C)							
	Simulator1	**Simulator2**	**Simulator3**	**Simulator4**	**P13**	**P14**	**P15**	**P16**
t_a	24.3	24.3	25.9	25.7	25.3	25.5	25.0	26.6
t_g	24.8	24.7	26.0	26.1	24.6	24.8	25.2	26.4
h_{cg}	1.58	1.55	1.07	1.50	1.3	1.75	1.27	1.23
$\overline{t_r}$	25.0	24.9	26.0	26.2	24.4	24.5	25.2	26.3
t_o	24.7	24.6	26.0	26.0	24.8	25.0	25.1	26.4
V_a	0.08	0.05	0.07	0.04	0.07	0.00	0.06	0.04
RH	39.0	39.6	36.3	36.5	39.6	39.2	37.2	36.8

Note: the values referring to simulators S1 to S4 are the averages values of the three points measured around each simulator and T_a = air temperature (°C); t_g = globe temperature (°C); h_{cg} = convective heat transfer; t_o = operative temperature (°C); $\overline{t_r}$ = mean radiant temperature (°C); V_a = mean air velocity (m/s); RH = relative humidity (%).

In accordance with the collected data the following considerations can be performed about the thermal conditions in the environment:

- In the majority of the thermal environment conditions the air temperature profiles show that the stratification of the temperature practically initiated at the level 0.60m, on account of this is the level where the main heat sources are placed. From the level 1.70m to up all the profiles had converged to the same value, with constant increase in the direction of the ceiling. Therefore, in the highest level (2.35m), the air temperature was practically equal in the overall room area. Referring to the lowest level (0.10m), that is, at the level of the people feet, the air temperature in the areas occupied by the simulators S1 and S2 was slightly lower than ones of the rest of simulators, with difference around 1°C, due to influence of the distances of the measurement points to the diffusers.

- The stratification of the air temperature is a foreseen phenomenon in environments where the underfloor air supply is installed. However, the air temperature profiles had shown that the vertical differences (Δt_a) between the measured values at the levels 0.10m and 1.10m (for seated people) had not exceeded to 1.5°C, and they had been less than 1°C in the majority of the points.
- Referring to the air velocity, in all the measured points and in the six tests conditions, the maximum values found around the simulators had been less than 0.20 m/s (around 0.10 m/s in the great majority of the cases). The representative profiles indicate greater displacement at the level 1.10m (the head level of the seated person). As the installed system air distribution is a "displacement flow" type, these data are coherent with the expected one (Skistad et al., 2002) and the thermal comfort requirements considered by norm ISO 7730 (1994) are satisfied.
- All the occupation zones had presented conditions of natural convection.
- In the tests conditions the superficial temperatures measured in the room floor had presented values from 19°C to 24° approximately, meaning that there are no discomfort situations.
- To verify the radiant temperature asymmetry the influence of a hot wall was considered, since the main source of radiation is the lamp panel installed in one of the walls of the test chamber. The collected data in all the measurement points had pointed differences around 3K. Considering that the measured values are quite inferior to limits for discomfort due to hot vertical surfaces (23K for predicted percentage of dissatisfaction – PPD = 5%) (ISO 7730, 1994 and ASHRAE Standard 55a, 1995) and that measurement uncertainties exist, does not justify a prompt evaluation, where the order of magnitude of the data is relatively small.

Considering the present results and the fact that environments which underfloor air supply system present air temperature stratification and low air velocity, the environment present satisfactory conditions for the thermal acceptance according to the Fanger's thermal comfort requirements (Fanger, 1972), adopted by ISO 7730 (1994). Moreover, the PMV indexes that were calculated by means of the Fanger's equation had varied from -0,35 to +0,47, with predicted percentage of dissatisfied indexes (PPD) less than 10%.

The collected data had allowed to verify that the analyzed environment did not present situation of local thermal discomfort due to vertical difference of air temperature since the maximum values had not exceeded 1.5°C between the levels 0.10m and 1.10m. Also, the measured data had not pointed discomfort due to draught. In the same way, discomfort due to the radiant temperature asymmetry and floor superficial temperature does not occur too.

3.2. 2nd stage

In this stage, in a subjective way a sample of 33 people evaluated the environment thermal comfort conditions expressing his/her sensation about the established thermal conditions (the same of the first stage – C1 to C6). They had to vote in Ashrae's "Thermal Sensation Scale" (ASHRAE, 1995), in which the values: -3, -2, -1, 0, 1, 2, 3 signify, respectively, *cold*, *cool*, *slightly cool*, *neutral*, *slightly warm*, *warm and hot*.

In accordance with the results related in the first stage, it can be observed that the majority of the thermal conditions created in the environment are acceptable (ISO 7730, 1994), without significant general thermal discomfort (for the body as a whole). However, in the test condition C6 (21°C), the majority of the users had declared unsatisfied, voting to the value -2 of the thermal sensation scale. It means that this temperature is not suitable (cold) for the users of this type of environment comfort. On the other hand, the thermal condition preferred by the people is the C1 (about 26°C), which got the major number of votes for the value zero of the referred scale – in Tab. (3).

Table 3. Percentages of votes for the thermal sensation scale values

Tests	**Percentage of people that had voted in:**						
	0	**-1**	**+1**	**-1, 0 e +1 (total)**	**-2**	**+2**	**-2, -1, 0, +1 e +2 (total)**
Fanger (25.6°C)*	55	20.0	20.0	95	2.5	2.5	100.0
C1 (26.0°C)	62.5	12.5	12.5	87.5	3.1	9.4	100.0
C2 (25.0°C)	59.4	25.0	12.5	96.9	3.1	0.0	100.0
C3 (24.0°C)	38.7	25.8	32.5	96.8	3.2	0.0	100.0
C4 (23.0°C)	41.9	51.6	0.0	93.5	6.5	0.0	100.0
C5 (22.0°C)	58.1	25.8	9.7	93.6	3.2	3.2	100.0
C6 (21.0°C)	25.8	48.4	6.5	80.7	19.3	0.0	100.0

Note: the Fanger's data refer to the comfortable situation ($-0.5 \leq PMV \leq +0.5$) and they were used as reference for the comparisons.

4. Concluding remarks

On the basis of the results of this work the following considerations can be made:

- The thermal conditions promoted by the underfloor air supply system satisfy the requirements of thermal comfort adopted by ISO 7730 (ISO, 1994) and have a good acceptance by the users. Although this type of supplying provokes stratification of air temperature, it was evidenced that this fact does not offer risk for the thermal comfort because the temperature differences between the occupation levels (from 0.10 to 1.10m, for seated people, and from 0.10 to 1.70m, for standing people) are small (less than 3°C) and the mean air velocity is low (< 0.1 m/s), with characteristics of natural convection condition, promoting no draught risk. Moreover, the possible discomfort with "cold feet" that generally is questioned does not occur with the system operating with higher temperatures for the supplied air than the one adopted in the ceiling air supply systems. So that these conditions really are taken care, it is important that the system operates with parameters defined for the intervals determined in the tests, which are related in Tab. 3, concomitantly with an adequate design of the diffusers distribution.
- The experimental data had indicated that the interval of temperatures, proper for this type of environment and users of offices in São Paulo - Brazil, is close to that proposed by Fanger (1972). However, the limits of the operative temperature so that discomfort occurs, defined in this research (22°C 26°) are superior to those, defined as from 21°C to 26 °C.

In accordance with the above considerations, it can be considered that the more indicative thermal comfort parameters for people in light activity (1.2 met), in office environments with underfloor air supply, are the ones described in Tab. (4).

Table 4. Parameters of thermal comfort

Variable	**For environments with winter thermal characteristics**	**For environments with summer thermal characteristics**
Clothing (clo)	$0.7 \leq I_{cl} \leq 1.1$	$0.5 \leq I_{cl} \leq 0.7$
Operative temperature (°C)	23 ± 1.0	24.5 ± 1.5
Air velocity (m/s) (at 1.10 m level)	$V_a \leq 0.1$	$V_a \leq 0.1$
Relative humidity (%)	50 ± 10	50 ± 10

Note: The winter and summer thermal characteristics are indoor thermal conditions stablished in accordance to the seasons.

To get the comfort conditions inside the interval shown in Table 4, the parameters best adjusted for the system operation are shown in Tab. (5).

Table 5. Parameters for the system operation

Variable	**Intervals for environments with winter thermal characteristics**	**Intervals for environments with summer thermal characteristics**
Air temperature (^{o}C)*	22.0 a 24.0	24.0 a 26.0
Relative humidity (%)*	40 a 60	40 a 60
Fan coil discharge air temperature (^{o}C)	13.0 a 15.0	13.0 a 14.0
Plenum air supply temperature (^{o}C)	16.0 a 19.0	19.0 a 20.0
Plenum air supply relative humidity (%)	60 a 80	60 a 70
Static pressure - differential (Pa)	11.0 a 18.0	9.0 a 11.0

(*) These values refer to the medium point of the room (width, depth and height).

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