Thermal comfort in office buildings with underfloor air supply—quantitative and qualitative analysis

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ABSTRACT
Thermal comfort in office buildings is usually unsatisfactory when ceiling air distribution is employed, because it is hard to make adjustments to reach specific occupancy needs. On the other hand, underfloor air distribution allows some flexibility for adjustments. In order to evaluate thermal comfort conditions in office environments with underfloor air supply system, a laboratory facility was built at the Universidade de Sao Paulo, Brazil. In this work, quantitative and qualitative results obtained in such facility are discussed. At the first stage, evaluations were made with simulators instead of users' participation, when thermal comfort variables measurements were performed. At the second stage, the qualitative analysis was made by a sample of people exposed to thermal conditions previously established in accordance with ISO 7730 recommendations. The results highlighted that the underfloor air supply system is adequate to promote thermal comfort conditions for office buildings users.

INDEX TERMS
Thermal comfort; Office buildings; Underfloor air supply

INTRODUCTION
Currently, in Brazil, the air conditioning system applied to office buildings is the ceiling air distribution. A centralized control strategy is used to control the temperature and/or the airflow supplied to the environment to maintain a uniform temperature distribution. However, thermal comfort, which is one of the most important office attributes, is not being well promoted by this kind of system, causing users' complaints (Leite, 1997; Ornstein *et al.*, 1999).

In the contemporary buildings, where the concept of landscape office has been adopted, the lay out changes constantly, causing problems with thermal comfort due to lack of flexibility for changes in the air distribution system. It means that the office buildings have special needs for environment conditioning. To solve this problem, the air conditioning system with underfloor air distribution was considered. This is a system where the airflow for comfort is supplied from the bottom to the top direction by means of floor diffusers. This kind of system also allows the supply of air directly to the workstations, where the users are allowed to control the airflow and flow direction so as to obtain their favourite thermal condition for comfort.

Despite the fact that this technology is still unusual, this kind of system is starting to be used also in Brazil. However, evaluation results of an underfloor air supply system, installed in a building located in Rio de Janeiro (Brazil), showed thermal discomfort conditions due to project and operational problems (Leite *et al.*, 2000).

Aiming to help to solve the lack of information, studies are being done in a laboratory facility with controlled conditions built at the Universidade de Sao Paulo, Brazil (Leite and Tribess, 2001, 2002a,b).

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In this paper, quantitative and qualitative experiments carried out in this laboratory are presented. A discussion of the results in order to evaluate the thermal characteristics of the environment and the users' acceptance of the conditions generated by the underfloor air supply system is provided.

CHARACTERISTICS OF THE LABORATORY

The laboratory was designed and built with similar characteristics to those of actual Brazilian office building environments. The laboratory represents, in actual scale, a significant environment area of offices (34.8 m^2) and the experimental procedures were applied here. This area means a fraction of an office building typical floor, whose characteristics: lay out, type of people and equipment occupation, localization and envelope are very close to the actual conditions of environments of this kind of building.

The laboratory is consists of the following basic components:

- tests chamber (climatic chamber), with underfloor air distribution (pressurized plenum);
- air conditioning unit (indirect expansion);
- automation and control systems; and
- environment data acquisition system.

In one of the test chamber walls (Figure 1), there is a lamp panel (with blinds) which was built to simulate the solar radiation through a glass surface (Figure 2). The equipment on the desks consists of personal computers and printers. In the four workstations, heated black cylinders (simulators), whose heat load is equivalent to a person engaging in light activities (120 W per person), were placed in the tests without users (Figure 3).

The air conditioning system with underfloor air distribution operates with air supply temperature higher than that of the ceiling air distribution system. Thus, the cooled air is mixed with a percentage of the hot return air in a mixture box having two ducts, one for hot air and another for cold air.

The control system is made in accordance with a strategy based on four loops: (a) the refrigeration unit (chiller), where the control is made on the inlet water temperature; (b) control of the chilled water flow in the coil by a three-way valve; (c) the control of the fan frequency, based on pressure differential values from the plenum to the environment; (d) control of return airflow dampers before the mixture box, based on the air supply temperature.

The laboratory counts on two independent systems for environment data acquisition: thermal couples, for the superficial temperature measurements, and transducers for air temperature, mean radiant temperature (globe temperature), plain radiant temperature asymmetry, relative humidity and mean air velocity measurement. To accomplish the measurements, the transducers were placed in six heights above the floor (0.10, 0.60, 1.10, 1.70, 2.00 and 2.35 m) (Figure 3).

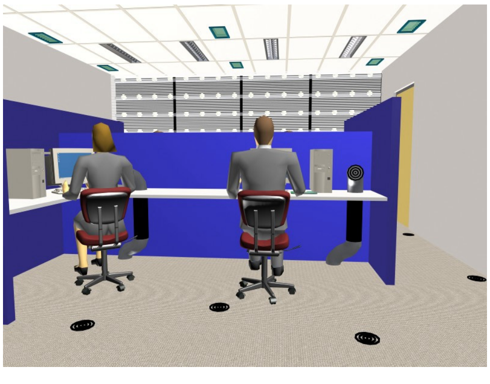

Figure 1 Test chamber.

Figure 2 Panel lamp.

Figure 3 Simulators and data acquisition system.

EXPERIMENTAL EVALUATION

The evaluation of the environmental thermal comfort conditions is based on local measurements of the comfort variables and on the survey of the users' satisfaction level. The experimental method consists of techniques used by Fanger (1972), in procedures indicated by the standards: ISO 7730 (ISO, 1994), ISO 7726 (ISO, 1985), Standard ASHRAE 55a (ASHRAE, 1995) and techniques and procedures of post-occupancy evaluation (Leite, 1997), contain a specific method for this application (Leite, 2003). The evaluation of the thermal comfort conditions was carried out in two stages:

First stage: Measurements of the environment thermal comfort variables (air temperature; air relative humidity; mean air velocity; globe temperature; plain radiant temperature asymmetry and superficial floor temperature), at the points P1–P20 (Figure 4), under six thermal conditions: C1 (26°C), C2 (25°C), C3 (24°C), C4 (23°C), C5 (22°C) and C6 (21°C). The air temperatures of the six thermal conditions were measured in the medium point of the room (width, depth and height). At this stage, four simulators, named S1, S2, S3 and S4 (Figure 4), were used.

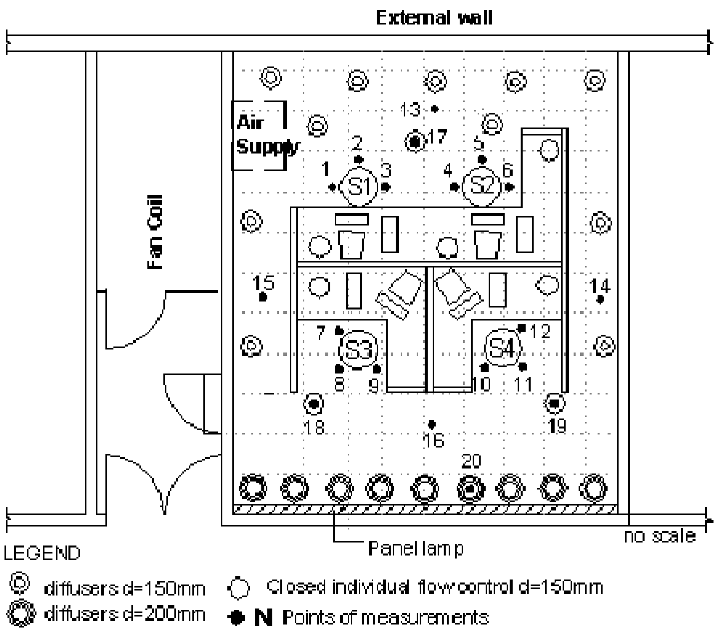

Figure 4 Measurement points.

Second stage: A subjective evaluation of the thermal comfort conditions was performed with the substitution of the simulators by people in the environment (users), subjected to the same thermal conditions of the first stage. The users wore clothes with compatible indices of insulation with the temperatures established in the tests (0.6–1.1 clo†, respectively, in the decreasing order of the temperature conditions C1–C6). For this evaluation, the users gave opinions on thermal sensations, expressed by means of answers to a questionnaire.

ENVIRONMENTAL THERMAL COMFORT CONDITIONS

The following results of environment thermal comfort conditions are presented. The details of these results can be found in Leite (2003).

†1.0 clo = 0.155 m^2°C/W.

Quantitative Evaluation

According to the results of the measurements carried out at the first stage (Leite, 2003; Leite and Tribess, 2002a), the environment presents conditions for thermal acceptance, satisfying Fanger's comfort requirements (Fanger, 1972) adopted by ISO 7730 (ISO, 1994). The values of the predicted mean vote (PMV), calculated by means of the Fanger's comfort equation (Fanger, 1972) varied from –0.35 to +0.47, with predicted percentage of dissatisfaction (PPD) lower than 10%.

The measurement data also showed that the analysed environment did not present situations of localized thermal discomfort due to vertical difference of air temperature, once the determined maximum values had not exceeded 1.5°C between levels 0.10 and 1.10 m (levels for seated person). Similarly, the measurement data did not point out discomfort due to draught, with mean velocities not higher than 0.1 m/s; discomfort due to radiant temperature asymmetry and superficial floor temperature did not occur either.

Qualitative Evaluation

Qualitative evaluation was based on the opinion of a sample of 33 people, exposed to the six different thermal conditions, who chose the values of the 'ASHRAE thermal sensation scale' (ASHRAE, 1995), in which –3, –2, –1, 0, 1, 2 and 3 mean, respectively, cold, cool, slightly cool, neutral, slightly warm, warm and hot. The results of the votes are represented by the graph in Figure 5, for each test condition (C1–C6).

According to the results presented in Figure 5, it is possible to observe that most of the conditions created in the environment are thermally acceptable (ISO 7730, 1994), without significant thermal discomfort for the body as a whole, with values in the interval considered comfortable ($-0.5 \leq PMV \leq +0.5$).

However, in test condition C6 (21°C), people demonstrated dissatisfaction, and most of the votes were for value –2 of the thermal sensation scale, which means that this temperature may be below the comfort limit for the users of this kind of environment (cold). On the other hand, the thermal condition preferred by the people is the C1 condition (about 26°C), which got the biggest number of votes for the 'zero' value of the scale.

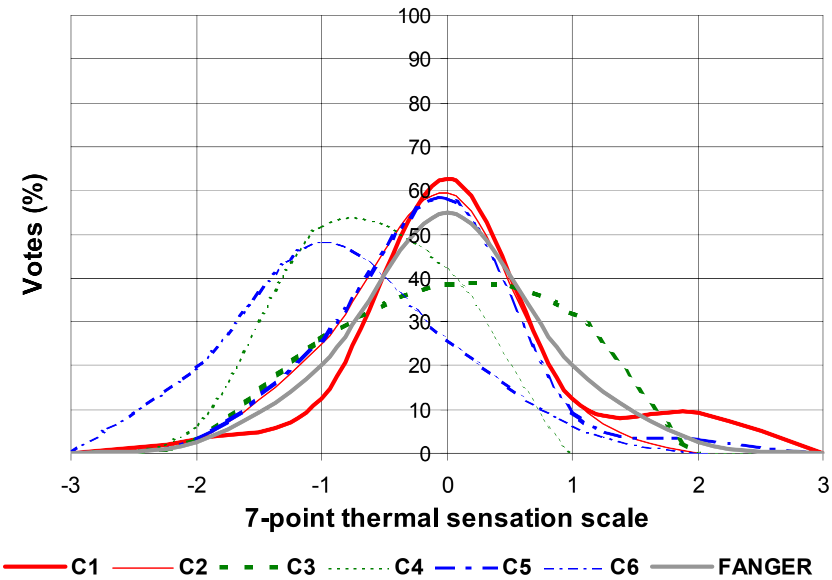

Figure 5 Curves representing users' votes in the seven-point thermal sensation scale.

CONCLUSION

On the basis of our results, the following observations can be made:

- The thermal conditions promoted by the underfloor air conditioning system (general conditioning) satisfies the thermal comfort requirements adopted by ISO 7730 (ISO, 1994) and can be well accepted by people. Although this type of air supply induces temperatures stratification, it was evidenced that this condition does not pose any risk for comfort because the temperature differences between the occupation levels (0.10–1.10 m, for seated people, and 0.10–1.70 m, for standing people) are small (inferior to 3°C) and the air velocity is low (<0.1 m/s), with characteristics of natural convection, not promoting perceivable or undesirable air currents. Moreover, the possible discomfort with 'cold feet', aspect that is generally questioned, does not occur with the underfloor air supply system because this system operates with higher air temperatures in comparison with the ceiling air distribution system. In addition, it is necessary that the diffusers distribution arrangement contemplates adequate distances to the users (minimum 0.80 m).
- The experimental data indicated that the temperature band, proper for this kind of environment and for Sao Paulo (Brazil) offices users, is close to Fanger's (1972) proposal, adopted by ISO 7730 (ISO, 1994) and that of ASHRAE 55a (ASHRAE, 1995). However, the limits of air temperature[‡] so that discomfort occurs obtained in this research (22–26°C) are superior to those defined in the interval between 21 and 26°C.
- According to the observations made above, it is possible to estimate the parameters, which will promote thermal comfort for people to develop light activities (1.2 met[§]) in office environments with underfloor air supply. They are related in Table 1.

Table 1 Thermal comfort parameters for office buildings with underfloor air supply

Variable	Winter	Summer
Clothing, I_{cl} (clo)	$0.7 \leq I_{cl} \leq 1.1$ clo	$0.5 \leq I_{cl} \leq 0.7$ clo
Operative temperature, t_0 (°C)	22–24	23–26
Air velocity , V_a (m/s) (at 1.10 m level)	$V_a \leq 0.1$	$V_a \leq 0.1$
Relative humidity (RH) (%)	40–60	40–60

REFERENCES

ASHRAE (1995). *ANSI/ASHRAE Standard 55-1995*. Thermal Environmental Conditions for Human Occupancy. Atlanta, GA: American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.

Fanger, P.O. (1972). *Thermal Comfort: Analysis and Applications in Environmental Engineering.* New York: McGraw-Hill Book Company.

ISO (1985). *ISO 7726*, *Thermal Environments—Instruments and Methods for Measuring Physical Quantities*. Geneva: International Standards Organization.

[‡]The air temperature was considered equal to the operative temperature based on measurement results.

[§]Metabolic rate for light activities (office work).

ISO (1994). *ISO 7730, Moderate Thermal Environments—Determination of the PMV and PPD Indices and Specification of the Conditions for Thermal Comfort*. Geneva: International Standards Organization.

Leite, B.C.C. (1997). Automated office buildings performance analysis through post occupancy evaluation. Masters Thesis, FAU-USP, Sao Paulo (in Portuguese).

Leite, B.C.C. (2003). Air conditioning with underfloor air supply applied to office environments: thermal comfort evaluation and operational conditions. PhD Thesis, Polytechnic School of Universidade de Sao Paulo, Sao Paulo (in Portuguese).

Leite, B.C.C. and Tribess, A. (2001). Thermal comfort in office environments with underfloor air distribution. *Proceedings of the 7th Brazilian Congress of Refrigeration, Ventilation, and Air Conditioning—CONBRAVA*, Sao Paulo. pp. 119–127. (in Portuguese).

Leite, B.C.C. and Tribess, A. (2002a). Analysis of the underfloor air distribution system: thermal comfort and energy consumption. *Proceedings of the 8th International Conference on Air Distribution in Rooms—ROOMVENT 2002*, pp. 245–248. Copenhagen: The Technical University of Denmark and Danvak.

Leite, B.C.C. and Tribess, A. (2002b). Thermal comfort parameters and operational conditions for air conditioning system with underfloor air supply. *Proceedings of the II National Congress of Mechanical Engineering—CONEM/2002.* João Pessoa (CD ROM) (in Portuguese).

Leite, B.C.C., Tribess, A. and Ornstein, S.W. (2000). Work environment thermal evaluation with underfloor air supply applied to a commercial building in Rio de Janeiro, Brazil, *Proceedings of the 7th International Conference on Air Distribution in Rooms—ROOMVENT 2000*, Vol. II, pp. 989–994. Oxford: Elsevier Science Ltd.