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EVALUATION OF ENVIRONMENTS WITH UNDERFLOOR AIR SUPPLY USING CFD

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***Abstract**. Environments in which people develop their daily activities should provide appropriate thermal comfort conditions. Although each person can feel comfort differently, the temperature, the velocity and the humidity of the air should be adequate to people activities. In the solution search to promote better thermal comfort conditions, technological innovations using different air distribution systems are developed, as for example, the underfloor air distribution (UFAD) system. As it is a relatively new technology, studies need to give support to its better use. In the present paper numerical evaluations of environments that reproduce, in real scale, offices environments with cold underfloor air supply are accomplished. Different turbulence models available in Fluent code were tested. Numerical results presented values relatively close to the experimental ones, showing good matching for some analyzed points. It was verified that simulations involving low air flow velocities still presents great difficulties in the calculation procedure. The use of k-ε models, largely used in the literature, in more complex cases don't present appropriate results. In the context of more complex flows it should be considered the use of the Reynols Stress Model (RSM) to produce more satisfactory results.*

***Keywords**. Air conditioning, underfloor air supply, simulation, CFD*

1. Introduction

The man's activities have been developed more and more in acclimatized environments. The coexistence and the execution of productive activities in these environments have been demanding the development of more effective technologies in the search of well-being and salubrity conditions. The attainment of these conditions, however, has not been reached satisfactorily.

One of the great problems to be solved is the establishment of conditions of air distribution that propitiate conditions of thermal comfort. One of the technologies that have been developed to try to solve this problem is the use of cold underfloor air distribution (UFAD system) for comfort.

This technology was introduced initially in offices buildings in Germany as a solution for the adjustment of cables as well for the removal of located thermal loads due to office equipment (David, 1984; Sodec and Craig, 1990). Owing to the growing use of arise floors in office environments, also in Brazil the technology of underfloor cold air distribution began to be applied for comfort in new buildings and in retrofits (Leite, Tribess and Ornstein, 2000).

Other factors that have been contributing to this change in the air conditioning systems are the results of researches, which have been demonstrating that the traditional air supply system by the ceiling is not fulfilling the users' thermal comfort needs (Schiller et. al, 1988; Ornstein et al., 1999). Even so, the expressiveness in the use of the technology of underfloor air distribution is still low due to the lack of information that reinforces the concept and its use in wide scale.

For a better understanding of the concept, of the project conditions, of the thermal comfort and of the potential of conservation of energy, there are the need of experimental tests and the accomplishment of numerical simulations. For such a laboratory was built in the Department of Mechanical Engineering of the Polytechnic School of the University of São Paulo, with the support of the Research Foundation of the State of São Paulo (FAPESP) that reproduces, in scale, office environments and allows the evaluation of air conditioning systems with cold air supply by the floor and by the ceiling (Leite and Tribess, 2001a, 2001b; Leite and Tribess, 2002; Leite, 2003; Leite et al., 2003; Leite and Tribess, 2004; Okuyama et al., 2005; Leite and Tribess, 2006).

Owing to economical and time aspects it is not reasonable to build prototypes for each new project. In this sense it has been made a big effort in developing computational tools that try to reproduce fluid dynamic models close to the reality.

In the present work results of numerical simulation of environments with cold underfloor air supply using Fluent CFD code are presented The numerical simulations were accomplished considering the geometry and boundary conditions of the laboratory that reproduces, in scale, real office environments. Results of the simulations are compared with measurements accomplished at this laboratory (Leite, 2003). Results obtained with the turbulence models k-ε and of the Reynolds Stress Model (RSM) are compared and a discussion regarding the model that best describes the airflow in these kind of environments is addressed.

2. Numerical simulation

Several authors have been used computational fluid dynamics (CFD) techniques to study and evaluate air distribution conditions in ventilated environments (Chen and Jiang, 1992; Gan, 1995; Versteeg and Malalasekera, 1995; Chow and Fung, 1996, Weizhen, Howarth and Jeary, 1997; Chung and Rankin, 1998; Kim and Boysan, 1999; Huo et al., 2000; Kitada et al., 2000; Hong; Chou; Bong, 2000; Wang and Ward, 2000; Chow, 2001; Lam and Jam, 2001; Murakami; Kato; Kim, 2001; Koskela et al. , 2001; Rosa, 2001; Xing, Hatton and Awbi, 2001; Cheong et al., 2003a; Cheong et al., 2003b; Wang and Zhu, 2003; Desta et al. ,2004; Xu and Niu, 2005; etc)

The use of CFD codes to predict internal and external airflows grew enormously in the last decades. The use of workstations for engineering, added to the development of efficient algorithms for the solution of the equations, made possible the use of commercial CFD codes by researchers and planners. In spite of the codes be extremely powerful, it is still necessary to have operators with appropriate technical qualification to obtain correct results in complex situations.

It must be also emphasized that the simulation doesn't substitute the experiment, because in many cases the experiment supplies boundary conditions or empiric constants to adjust the adopted modeling appropriately. Besides, the lack of generality of the turbulence models implicates in the reduction of the reliability of the obtained results being necessary the comparison with experimental results of the problem in study (when available) or of airflows with great similarity.

The commercial Fluent code (Fluent, 2003) is a powerful simulation tool that allows choosing turbulence models (one equation, k- ε, Reynolds Stress Model (RSM) or Large Eddy Simulation (LES) model, etc.), to adjust in these models parameters and other constants, besides the possibility to choose the type of numerical simulation to be used. Chen and Jiang (1992) present an interesting discussion as for the turbulence models and to the most significant subjects in the prediction of airflow in rooms.

The models of one equation not always supply accurate results and the LES model, although is becoming more and more interesting, has not been finding great application in the simulations involving ventilation problems. The LES model has not been presenting better results than the models k-ε, in spite of its largest complexity added to the need of computers of larger capacity (Davidson & Nielsen, 1996; Teodosiu et al., 2000).

Encouragement results have been reached by the use of the k-ε models for a great number of problems in ventilated rooms (Chen, 1996). These models have been used in the study of air velocity and temperature distribution, turbulent intensity, relative humidity, concentration of pollutants and quality of the air inside the room.

On the other hand, according to Hawkins et al. (1995), the construction differences among diffusers in ventilated rooms modifies completely the jet behavior, affecting significantly the airflow dynamics and the thermal characteristics in the room. Problems concerning jets simulation are also discussed by Costa et al. (2000), that present results of a 2-D turbulent airflow parametric study for different room geometries, sections of the inlet jet, temperature of the walls, return airflow velocity, among others.

3. Mathematical equations

The following equations (Eq. (1) to Eq.(4)) were used to solve the airflow in ventilated environments. Equation (1) is the continuity equation.

$$\frac{\partial \rho}{\partial t} + div(\rho \vec{u}) = 0 \tag{1}$$

Equation (2) is the momentum equation in cartesian coordinates.

$$\frac{\partial}{\partial t}(\rho u) + div(\rho \vec{u}\vec{u}) = -grad\ p + div(\tau_{eff}) + \rho \vec{g} + \vec{F} \tag{2}$$

Equation (3) represents the effective tensor stress.

$$\tau_{eff} = (\mu + \mu_t)\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) - \frac{2}{3}\rho k \delta_{ij} \tag{3}$$

Equation (4) represents the energy equation, where k_{eff} is the effective conductivity and Φ is the viscous work

$$\frac{\partial \rho e}{\partial t} + div(\rho e \vec{u}) = -p\, div(\vec{u}) + div(k_{eff}\, grad\, T) + \Phi + S_e \tag{4}$$

To solve the turbulence in the flow four turbulence model were tested: k-ε standard, k-ε RNG, k-ε realizable and Reynolds Stress Model (RSM). Equations can be found in Fluent (2003).

4. The laboratory with cold underfloor air distribution (UFAD system)

The laboratory, schematically presented in the Figure 1, has an area of 34.8 m² (5.5 x 6.3) m², with height of 2.7m, containing three complete workstations, with compatible dimensions with the Brazilian occupation pattern, being two workstations with 4 m² and one with 8 m², delimited by removable partitions of heights h=1,20 m e/ou h=1,60 m; chairs and tables with equipments (computers, printers, etc.). Heat sources substitute the people, represented by the simulators (S1, S2, S3 and S4).

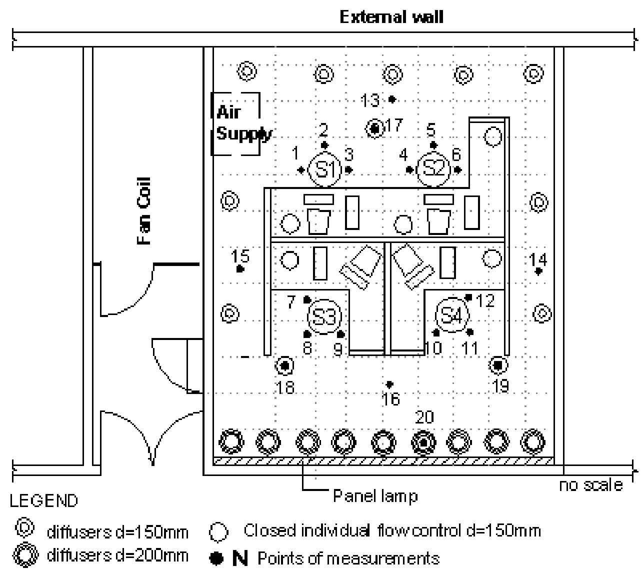

Figure 1 – The laboratory with the identification of the measurement points, simulators and diffusers (Leite, 2003).

For air diffusion the following configuration was determined: 9 Ø 200 mm floor-mounted diffusers by the light panel and 14 Ø 150 mm floor-mounted diffusers for the internal zone. The chosen diffusers are of the swirl type with horizontal discharge direction, with the following maximum airflow rates: for Ø 150 mm, up to 20 1/s, and for Ø 200 mm, up to 40 1/s, according to information provided by the manufacturer.

All of the walls and flagstones that delimit the total space of the laboratory have thermal isolation, so much so that don't occur thermal changes between the internal and the external environment and like this test steady state conditions are verified. To simulate the solar insulation, in one of the walls a panel of lamps was totally set up covered by adjustable blinds. The internal heat sources in the laboratory are simulators, illumination, panel of lamps and microcomputers. The respective thermal sources are represented in Table 1.

Table 1- Thermal sources (Leite, 2003).

Thermal sources	Load generated
Four microcomputers	390, 4 W
Four simulators (people in light activities)	399,6 W
16 fluorescent lamps (illumination)	696 W
80 incandescent lamps (panel of lamps)	2723,1 W
Total	4209,1 W
Thermal load	**121,00 W/m^2**

5. The numerical simulation of the laboratory environment

Initially, a study of mesh independence was accomplished with the choice of the hexahedral mesh with 489475 elements, presented in Figure 2.

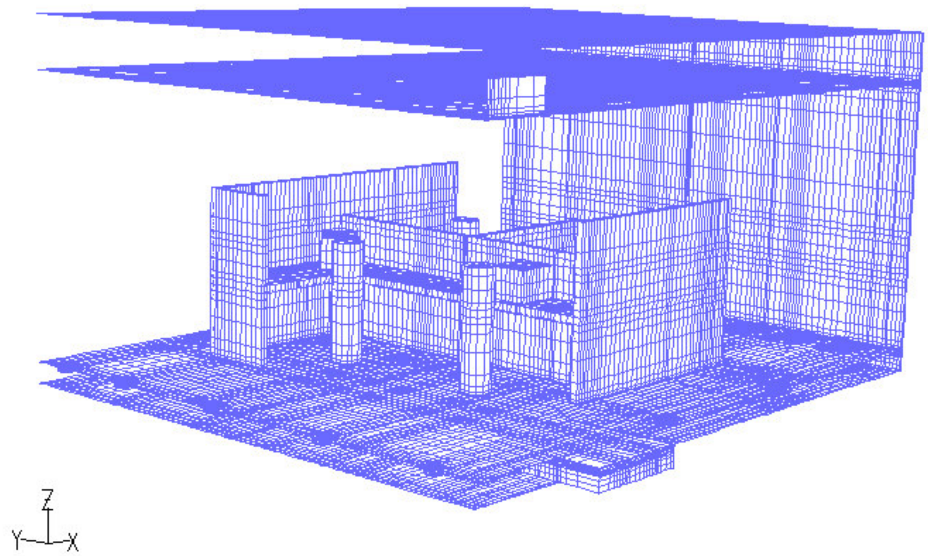

Figure 2 – Simulation hexahedral mesh.

5.1 Boundary conditions

Turbulent airflow in steady state conditions was considered. The gravity was taken into account with value of 9.8 m/s^2. To simulate natural convection was used the Boussinesq ideal gas model and coefficient of thermal expansion equal to 10^{-5} K^{-1}. The other values and boundary conditions were:

a) Air inlet in the plenum (0.3 m height) with average velocity of 2.65 m/s (1800 m^3/h), turbulent intensity 4.9%, hydraulic diameter of 0.333m and air temperature of 17.9 ^oC.

b) Walls, roof and floor: Adiabatic condition

c) Roof outlet condition: pressure of 0 Pa.

d) Equipment were considered with constant heat flows and uniform distribution

e) Panel of lamps heat flow was considered as convective and conduction heat transfer. This hypothesis approaches the real case, once the heat generated by the lamps is absorbed by the sheets of the blinds and only later change heat with the environment.

f) Return grills were modeled as porous system with load loss only in the vertical and perpendicular direction

g) Diffusers were modeled as fans and porous system also with load loss only in the vertical and perpendicular direction. The fans boundary condition was used to introduce a tangential velocity to reproduce a whirl in the diffuser exit. This velocity was fixed in 0.3 m/s (for the negative z axis).

5.2 Simulation procedure

The convergence criterion was the maximum number of 4000 iterations. In the first 2000 iterations, just the hydrodynamic airflow calculations are done and soon afterwards the equation of the energy participates in the simulation. Besides, the vertical lines passing through measurement points are used to check velocity values.

Initial conditions of null velocities in the coordinates (x, y, z) and temperature of 300 K were imposed. The numerical schemes used to solve the conservation equations and other auxiliary equations were of second order.

6. Results

Results of numerical simulation are presented in Figure 3 and Figure 4. The legends of each turbulence model used in the simulations, as well as of the experimental points, are presented in Table 2. Only the results obtained using k-ε and RSM models are presented, because they are the most appropriate models for simulation of ventilated environments and presented the best results when compared with measured values in the present work. More detailed results, including results for k-ϖ models, can be found in Pustelnik (2005).

Table 2– Legend for the graphs of temperature profiles (Fig.3) and velocity profiles (Fig. 4).

Symbol	Meaning
●	Experimental data
□	k-ε standard
△	k-ε RNG
×	k-ε realizable
+	RSM

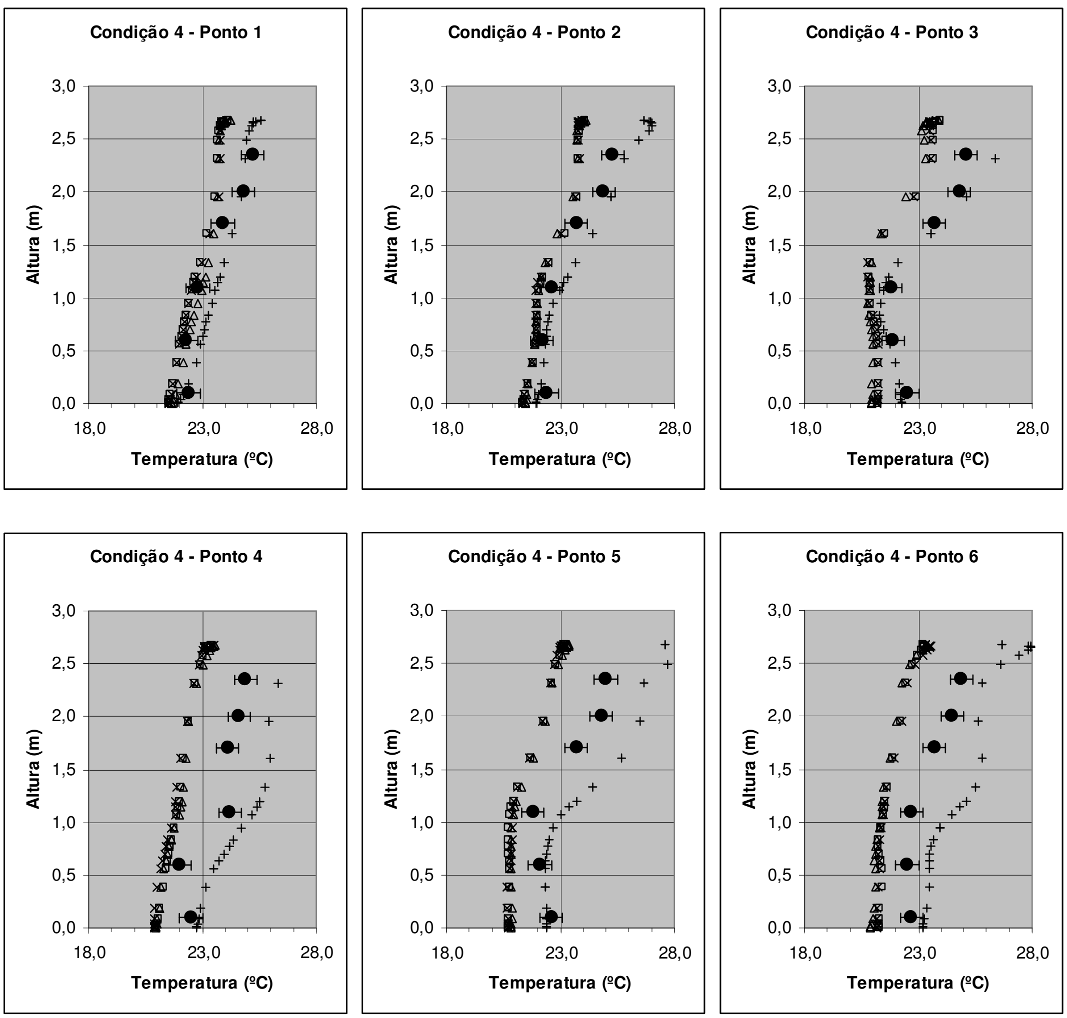

Figure 3. Temperature profiles for the measurement points and simulation results around of the simulators

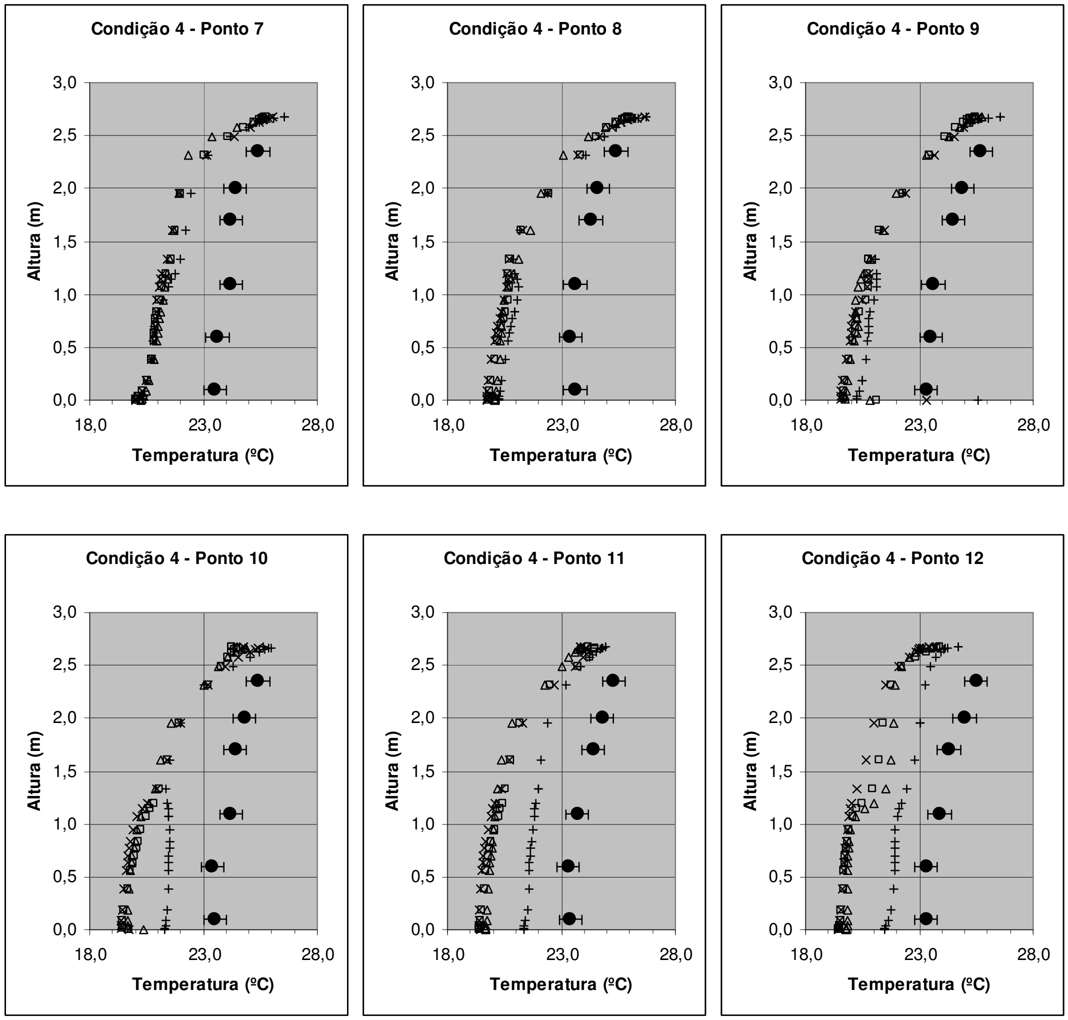

Figure 3. Temperature profiles for the measurement points and simulation results around of the simulators (cont.)

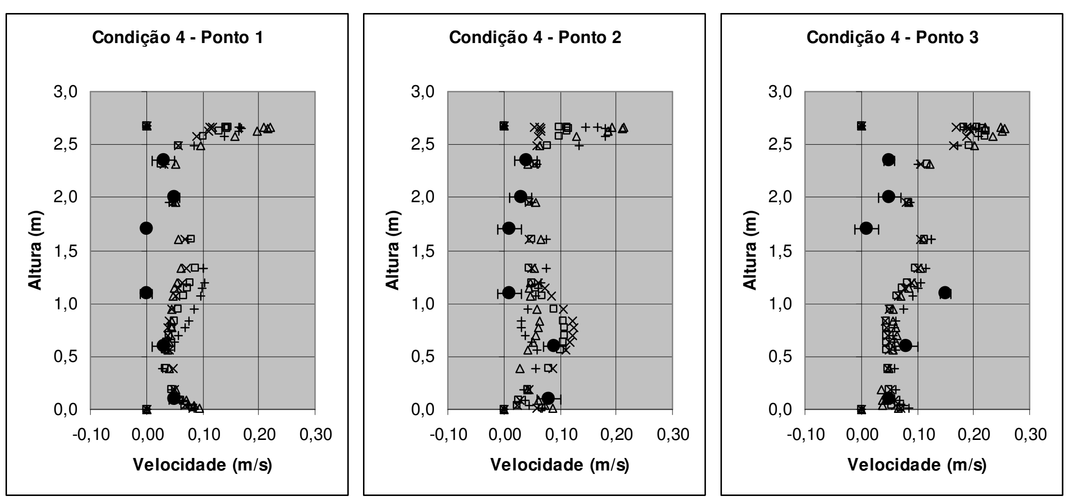

Figure 4. Velocity profiles for the measurement points and simulation results around of the simulators.

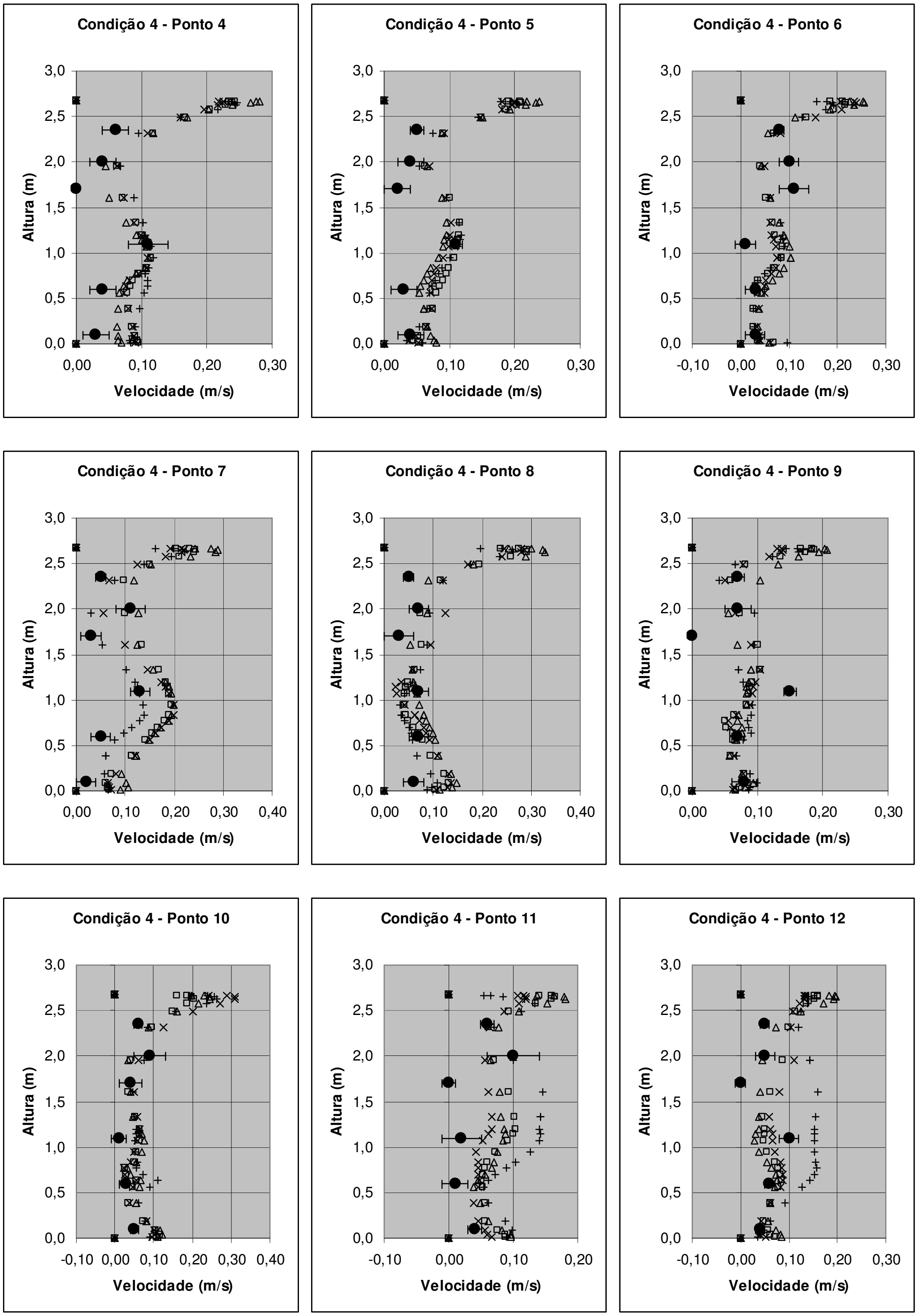

Figure 4. Velocity profiles for the measurement points and simulation results around of the simulators (cont.)

6.1 Analysis of temperature profiles

Analyzing the graphs of temperature profiles presented in Figure 3 and considering that in the evaluation of thermal comfort conditions the results for heights up to 1,1m starting from the floor (seating person, working) are of greater interest (ASHRAE 55:2004), the turbulence model that best represents the experimental data was the Reynolds Stress Model (RSM). Good agreement of results was also verified in the use of the k-ε models.

Although the Reynolds Stress Model presents the best agreement of results, the computational effort with this model is significantly larger. The RSM model time processing was practically 2.5 times greater than the k-ε models, which presented quite the same time of processing amongst themselves.

6.2 Analysis of velocity profiles

The analysis of the velocity profiles presented in Figure 4 is more difficult, once the values of the velocities are very low and the measurement accuracy was of ± (0.03 + 3% V) m/s. Even so it can be verified that occurs a reasonable agreement of results in most of the situations. However, it is difficult to conclude which turbulence model presents the best results.

7. Conclusions

Environments in which people develop their daily activities should provide appropriate thermal comfort conditions. Although each person can feel comfort differently, the temperature, the velocity and the humidity of the air should be adequate to people activities. In the solution search to promote better thermal comfort conditions, technological innovations using different air distribution systems have been developed, as for example, the underfloor air distribution (UFAD) system. As it is a relatively new technology, studies need to give support to its better use. In this context, the use of computational tools is especially important, because it propitiates the accomplishment of simulations with low cost and economy of time.

The simulation results of temperature profiles show good agreement with the experimental results and the Reynolds Stress Model presented the best agreement. Regarding the velocity profiles it was not possible to identify the best turbulence model, but the agreement among simulation and experimental results was also good in most of the situations.

The results of numerical evaluation of the laboratory environment with UFAD system show that the use of computational codes for simulation of flow of fluids is not still a simple task. There is the need of a deep knowledge of fluid dynamics, of the potentialities and deficiencies of the simulation programs and of the appropriate use of these programs.

Finally, it can be concluded that simulations involving low velocities still present great difficulties in the calculations and they cannot be neglected. The use of simpler models as the k-ε models, largely used in the literature, in more complex cases don't present appropriate answers. In the context of more complex airflows the use of the Reynolds Stress Model should be strongly considered to produce more satisfactory results, as verified in the present work.

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