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ScienceDirect

Energy Procedia 126 (201709) 115–122

Energy Procedia

www.elsevier.com/locate/procedia

72nd Conference of the Italian Thermal Machines Engineering Association, ATI2017, 6-8 September 2017, Lecce, Italy

Prediction Of Indoor Conditions And Thermal Comfort Using CFD Simulations: A Case Study Based On Experimental Data

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Abstract

In the present paper CFD tool was used for thermal comfort evaluation in natural convection and in transient conditions in a room by setting only the external weather conditions as input parameters. A survey in a classroom at the Department of Engineering, University of Perugia, was carried out and data required for the thermal comfort evaluation and CFD simulation model set up was acquired. The simulation model was validated with experimental data and it was used for the thermal and velocity profiles simulation and for the thermal comfort indexes calculation, according to UNI 7730.

Peer-review under responsibility of the scientific committee of the 72nd Conference of the Italian Thermal Machines Engineering Association

Keywords: computational fluid dynamics (CFD); thermal comfort; building simulation; model validation; experimental data;

1. Introduction

In the modern society an increasing number of people spends most of their time in confined environments, with artificial climatic conditions, in which thermal comfort is a basic factor: glazing systems, both for dimensions and material characteristics, are very important because they influence the parameters involved in thermal comfort evaluation. Many studies were carried out in the recent years about thermal comfort in moderate environments by applying different kind of methods such as the classic approach introduced by Fanger [1] and the adaptive approach [2, 3]; the classic approach was introduced by Fanger [1], by means of the indexes Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD), also adopted in EN ISO 7730 [4], which provides a method to calculate

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1876-6102
Peer-review under responsibility of the scientific committee of the 72nd Conference of the Italian Thermal Machines Engineering Association
10.1016/j.egypro.2017.08.130

and to interpret global and local thermal comfort. However, the acquisition of the data necessary for the calculations requires specific instruments, not always available, and much time. Many studies are focused on the implementation of alternative tools for thermal comfort prediction; one interesting method could be the simulation implemented with CFD codes, which allow to simulate the thermal and the velocity profiles within environments [5, 6].

A wide bibliographic research was carried out in order to evaluate the state of the art of CFD applications in building thermal comfort predictions; several studies [5-15] were conducted in order to determinate the thermal comfort with CFD simulation in various indoor environments such us stadium [7], theatre [10], museum [12] or in a test room [13]. Stamou et al. [7] evaluated thermal comfort in a Galatsi Arena stadium with CFD simulations, considering heating, ventilating and air conditioning systems and assuming two possible inlet air temperatures: 14°C and 16°C. The calculated values of PMV and PPD showed that the thermal conditions were satisfactory when the inlet air temperature was equal to 16°C. Cheong et al. [10] evaluated the thermal conditions of an air-conditioned lecture theatre, both with experimental campaign and CFD simulations. It was shown that the values of temperature, air velocity and relative humidity were within the limits of thermal comfort standards. Papakonstantinou et al. [12] studied the velocity and temperature field in three dimensional simple geometry and in a museum, by setting external meteorology conditions, but without validating the model by means of experimental data. Catalina et al. [13] used a CFD model to evaluate the average velocity and temperature and the values of PMV in a test room with chilled ceiling panels; the results were first validated with experimental data and then the velocity fields were investigated.

In the present paper the application of a 3D CFD model simulation was used to support the experimental investigations, the temperature fields and the global and local thermal comfort sensation in a non-residential environment by setting only the external weather conditions, considering natural convection and the solar radiation influence [14-17].

2. Methodology

2.1. Experimental Campaign

An experimental campaign in a classroom at the Department of Engineering (University of Perugia) was carried out in the month of April when the HVAC system was turned off. All the parameters necessary for determining thermal comfort according to UNI 7730 [4] and for setting and validating the CFD model were measured. Specifically, the indoor and outdoor air temperatures, the relative humidity of air, the indoor air speed, the globethermometer temperature, the air pressure, the internal and external solar radiation on a vertical plane, the surface temperatures of opaque and transparent walls were acquired. The heat flux through the opaque wall was also monitored in order to calculate the equivalent thermal conductivity of the opaque wall and it was set as input data on the CFD model. The technical features of the measurement equipment are already described in [18] with uncertainty of measurement of about ±2÷7%.

In addition to the thermal characteristics of the external walls, only the outdoor air temperature and the solar radiation were set as input parameters, while the temperatures of opaque and transparent surfaces and the indoor air temperature monitored within the classroom were chosen for validating the simulation model as showed in previous papers [5-15]. The solar radiation was set up by using the solar model available in the CFD code. In Fig. 1 the geometrical characteristics of the external wall and the plant of the classroom are reported: the position of the measurement points is highlighted and a view of the classroom during the experimental campaign is shown.

2.2. CFD model and preliminary settings

A CFD solver package, ANSYS Fluent, was used to perform all the CFD computations; it allows to evaluate the thermal and flow fields based on continuity, momentum, and heat transfer equations already described in [7]; in particular, in agreement with a previous work [5], the energy model and the k-ε model were used. In addition, two additional equations were implemented: the Boussinesq approximation, which allows to simulate the natural convection, and the solar model for the solar gain [19, 20]. The transient condition was simulated by setting a specific simulation time size in the CFD code; this value also depends on the implemented equations. Considering the geometric characteristics of the investigated environment, a time size equal to 2 seconds was calculated [19, 20] and set on CFD model; with this time size an User Define Function (UDF) was also written in order to impose the monitored external temperature on the external walls. A sensitivity analysis was carried out preliminary in order to check the best mesh size to be used in the CFD model; the mesh size was varied in 0.01-0.5 m and the surface temperature and the heat flux through the opaque wall were checked. According to these preliminary simulations by setting 0.01 m mesh size for the opaque wall and 0.1 for the air volume, a good convergence of the solution and a very small error were found. These mesh sizes are lower than the ones used in previous works [5-15], because of the implemented equation models as the natural convection, which requires a lower mesh size in order to obtain the convergence of solution.

According to preliminary simulations, the 3D simulations model was implemented by adopting the following simplification: the external opaque wall was modeled as a homogeneous equivalent wall. This assumption involves a very small error in the time lag calculation and in the surface temperature of the opaque wall. Fig. 2 shows the 3D simulation model implemented (2a) and the mesh used in the CFD simulations (2b). According to the adopted simplifications, two materials were also defined: the first one for the opaque wall and the second one for the glass surface. The thermal characteristics of these two materials are shown in table 1. The day April 10th was simulated and the simulations were carried out for 24 hours. The defined UDF was set as boundary conditions on both glass and opaque walls by using convective thermal transfer conditions. On the other surrounding opaque walls, two different conditions were chosen and tested: adiabatic and constant temperature conditions (equal to the mean monitored value 294 K). The geographical coordinates of Perugia and the North direction with respect to the building were also set and the absorption and transmission coefficients of the materials were chosen and defined according to previous work [21]. In agreement with the position of the experimental equipment shown in Fig. 1, three control points were also defined in the CFD model, where the CFD results were saved every time step.

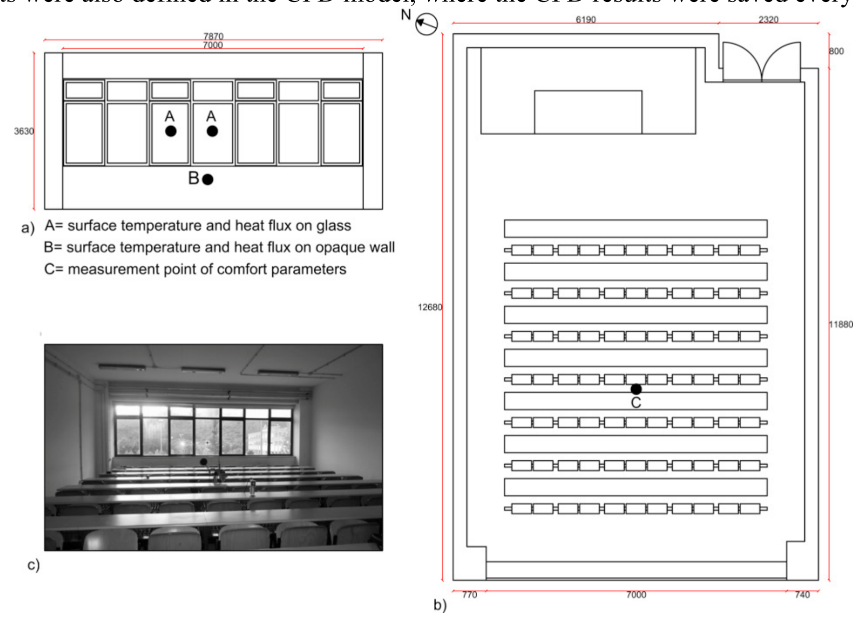

Fig. 1. The investigated environment: a) external wall of the examined classroom – measurement points; b) classroom plan - measurement point; c) a view of classroom during the experimental campaign

3. Results and discussion

3.1. Model validation

The CFD model validation was carried out by using experimental data as in [5, 7, 11, 13], and it was performed considering the real occupancy period of the classroom (8 a.m.- 6 p.m.).

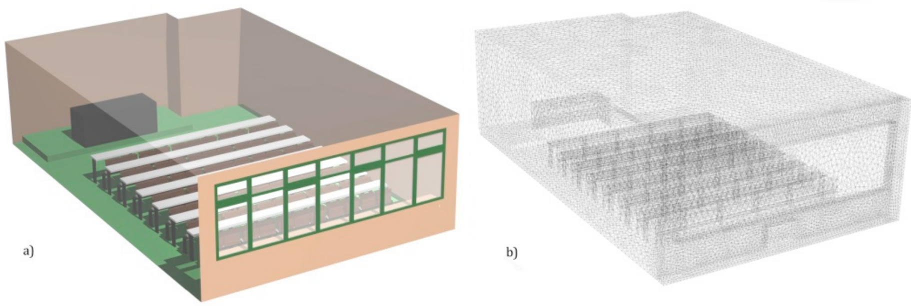

Fig. 2. Room model: a) simulation model; b) mesh implemented

Table 1: Characteristics of the homogeneous equivalent materials.

Thermal characteristics	Thickness (m)	Density (kg/m3)	Specific heat (J/kgK)	Thermal conductivity (W/mK)
glass (4-12-6)	0.022	1000.66	929.42	0.12
opaque wall	0.342	482.49	919.47	0.178

The CFD simulation was performed starting from the 12:00 am instead of 8:00 am, in order to consider the effect of the variation of the external conditions on the temperature and velocity profiles within the room in the earlier hours of occupancy. The indoor air temperature, the surface temperature on the opaque wall, and the one monitored on the transparent surface were compared to the simulated ones; as an example, Fig. 3 shows the comparison between the monitored transparent surface temperature trend (black line) and the ones simulated with the CFD code according to the boundary conditions set on the surrounding walls: adiabatic (red line) and temperature condition (blu line). Until the 11 a.m. the solar radiation gains did not affect the external wall because of the South-West orientation of the classroom and the simulated data is very close to the real ones (the mean difference between 8 a.m. and 11 a.m. is about +0.6 and +0.45 for the two conditions respectively). Between 11 a.m. and 3 p.m. the CFD code correctly simulates the contribution of the solar radiation on the external surfaces; in this period a mean difference of about -0.26 K and -0.14 K for the two conditions was found. Between 3 p.m. and 6 p.m. the simulated temperatures are higher than experimental data: with the adiabatic condition a difference of about 2.5 K was found, while with constant temperature condition the difference is about 1.5 K.

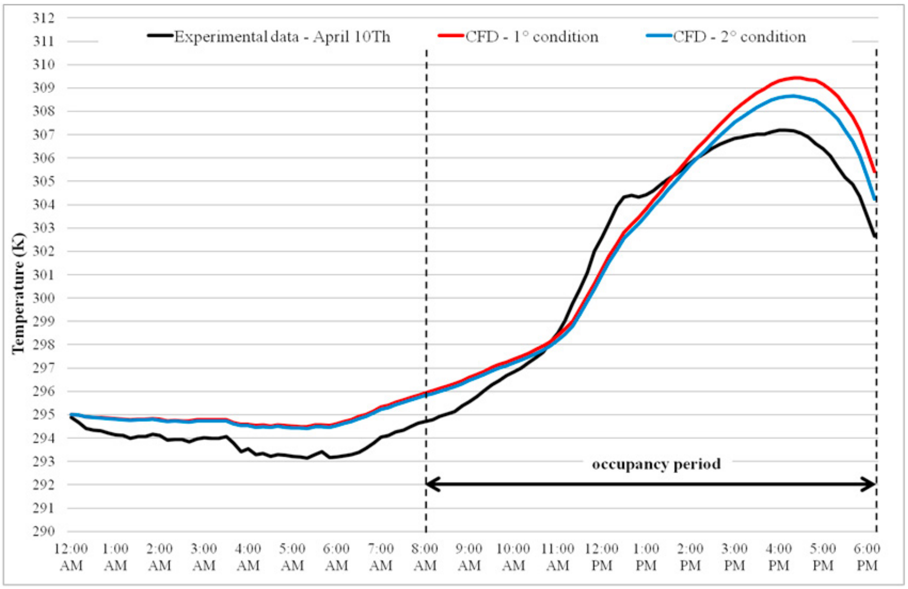

Fig. 3. Comparison between experimental data and CFD results: transparent surface temperature.

In table 2, the comparison between the mean values and the standard deviations of experimental data and CFD results for each control parameter (air temperature, surface temperature on the opaque and transparent surfaces) is shown where 1° and 2° represent the adiabatic and the constant temperature conditions respectively. Concerning the adiabatic condition the difference with experimental data is about +0.1 K, 0.61 K, and -0.91 for the indoor air temperature and for the opaque and transparent surfaces. With the second condition, instead, these differences are about 0.48 K (opaque surface temperature), -0.03 (indoor air temperature), and -0.47 K (transparent surface temperature). Besides, the standard deviation obtained by adopting the 2° condition for each control parameter is closer to experimental data than the one simulated by using the adiabatic one. According to the results, the second condition was chosen to be set on the surrounding walls, allowing a better correlation with experimental data especially for indoor air temperature.

Once validated, the CFD simulation model was used for evaluating the thermal field (Fig. 4) and the velocity profile (Fig. 5) within the environment and to point out the effects and the influence of solar radiation in the classroom and in all the occupancy period.

Table 2. Temperature mean value and mean difference for the chosen control parameters.

control parameter	**experimental data (8 a.m.-8 p.m.)**		**CFD - 1° condition**		**CFD - 2° condition**		**Mean error**	
	mean value	**Dev. St.**	**mean value**	**Dev. St.**	**mean value**	**Dev. St.**	**1° condition**	**2° condition**
opaque surface	299.8	2.0	299.2	3.3	299.3	2.5	0.61	0.48
air temperature	299.2	1.5	299.1	3.7	299.3	1.8	0.10	-0.03
transparent surface	302.1	4.7	303.0	5.1	302.5	4.9	-0.91	-0.47

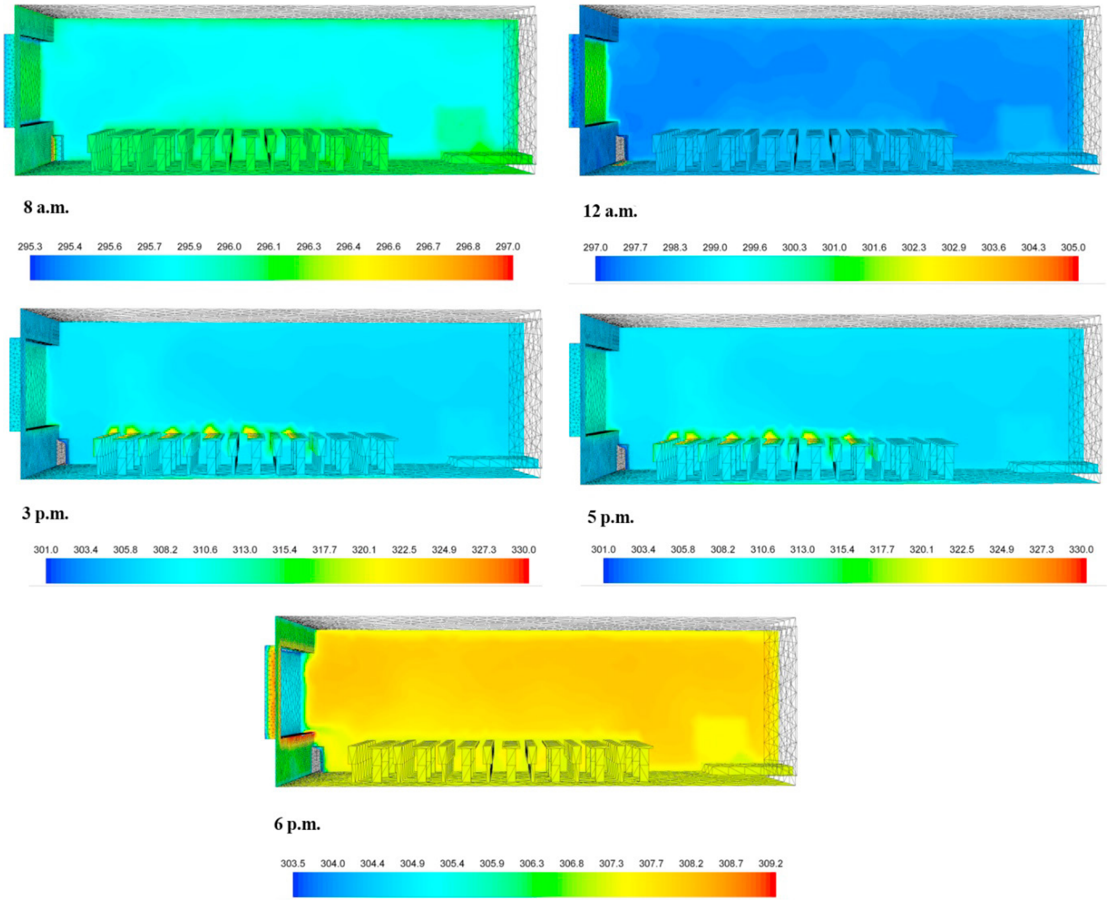

Fig. 4. Thermal field on cross sections and on plane sections within room: 8 a.m., 12 p.m., 3 p.m., 5 p.m. and 6 p.m.

In Fig. 4 five views of the simulated thermal filed are shown, in particular the thermal field on the cross vertical section are reported in five different time periods related to the real occupancy period: 8 a.m., 12 p.m., 3 p.m., 5 p.m., and 6 p.m. Until the 12 p.m. the effect of solar radiation within the environment is negligible and the thermal field is almost uniform, while since the 3 p.m. the influence of solar radiation becomes not negligible and the thermal filed is no longer uniform. In this case, the effect of solar radiation are more important next to the work benches and in the surrounding areas. At 5 p.m. the influence of the solar radiation is more significant, however, except for the zone next to the transparent surface, the thermal field did not vary significantly within the environment even if higher temperature values were simulated within the room.

The velocity profile on the cross vertical and on the plane sections at 3 p.m. and 5 p.m are shown in Fig. 5; it shows that velocity profile is very uniform within the environment in all the occupancy period and the small simulated velocity magnitude is in agreement with the experimental data and with the natural convection conditions.

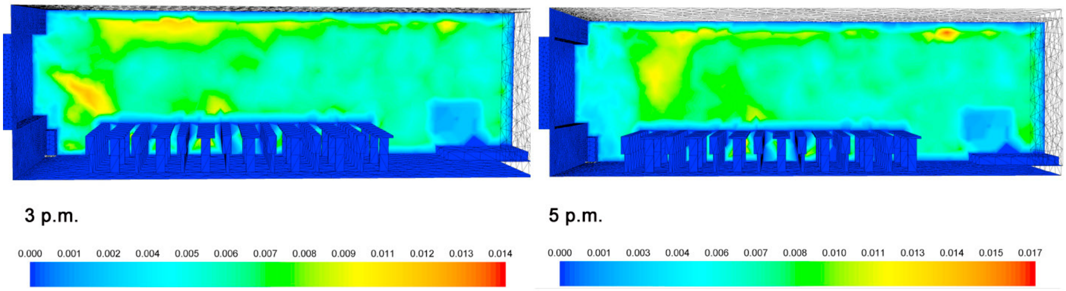

Fig. 5. Velocity profile on cross sections and on plane sections within room: 3 p.m. and 5 p.m.

3.2. PMV and PPD index calculation

PMV and PPD indexes were calculated according to ISO 7730 [4] starting from experimental and simulation results. Several assumptions were done: the metabolic energy (M) equal to 1.20 met, the clothing insulation (Icl) equal to 0.98 clo for men and 0.88 clo for women (spring). Table 3 shows the comparison between the thermal indexes calculated with CFD and experimental data in three specific periods: 8 a.m. - 1 p.m., 1 p.m. - 6 p.m., and 8 a.m. - 6 p. m.. Concerning all the occupancy period (8 a.m. - 6 p. m.) the simulated PMV is very close to experimental one for both the configurations (mean error less than 0.1 and about 2% for PMV and PPD respectively); however, concerning the morning period, a higher discrepancy between experimental data and CFD is found (0.18-0.-0.21). In the afternoon, instead, the PMV and PPD values simulated with CFD code increase due to a higher indoor air temperature simulated, with a mean error of about -0.08 for both the configurations. Concerning the thermal comfort scale (7-value thermal comfort scale), these differences can be considered acceptable because they do not involve a significant variation of the perceived thermal sensation.

The 3D simulation model was also used for the local thermal comfort evaluation; in particular the effects of solar radiation through the semitransparent surface on thermal sensation at different time of day was pointed out. Thermal sensation maps were traced by CFD simulations results, in order to evaluate the variation of thermal sensation during the day. In Fig. 6 three comfort maps are reported respectively at 12 p.m., 3 p.m. and 6 p.m. calculated for the man configuration. In the absence of the solar radiation (12 p.m.), the thermal sensation is very uniform in all the environment, with a very small variation. In this case the thermal comfort sensation calculated with experimental data can be considered a good representative value for all the environment. Since 3 p.m. the thermal comfort sensation is still uniform, but the zone near the transparent surface presents higher values of PMV: a difference of +0.6 PMV was calculated with respect to the value calculated by using experimental data; therefore the value measured cannot be considered representative of thermal sensation in the whole classroom. In this case other measurement points should be necessary in order to estimate the real thermal sensation in different points. At 6 p.m. the thermal sensation maps pointed out an important increase of PMV values in all the environment; in particular, a warm sensation was found due to direct solar radiation influence. Also in this case the thermal sensation is not uniform, with a variation of PMV inside the room of about 0.4.

Table 3. PMV and PPD indexes calculated starting from experimental data and CFD simulations.

	Men		Woman		Men		Woman	
	PMV	PPD	PMV	PPD	error - PMV	error - PPD	error - PMV	error - PPD
Experimental - 8 a.m. - 6 p.m.	1.03	27.37	0.94	25.40	0.05	2.02	0.01	-0.16
CFD - 8 a.m. - 6 p.m.	0.98	25.35	0.92	25.56				
Experimental - 8 a.m. - 12 a.m.	0.79	18.28	0.79	14.44	0.18	5.40	0.21	4.01
CFD - 8 a.m. - 12 a.m.	0.61	12.88	0.59	10.43				
Experimental - 1 p.m. - 6 p.m.	1.31	40.89	1.30	41.37	-0.06	-3.20	-0.11	-6.37
CFD - 1 p.m. - 6 p.m.	1.37	44.10	1.41	47.74				

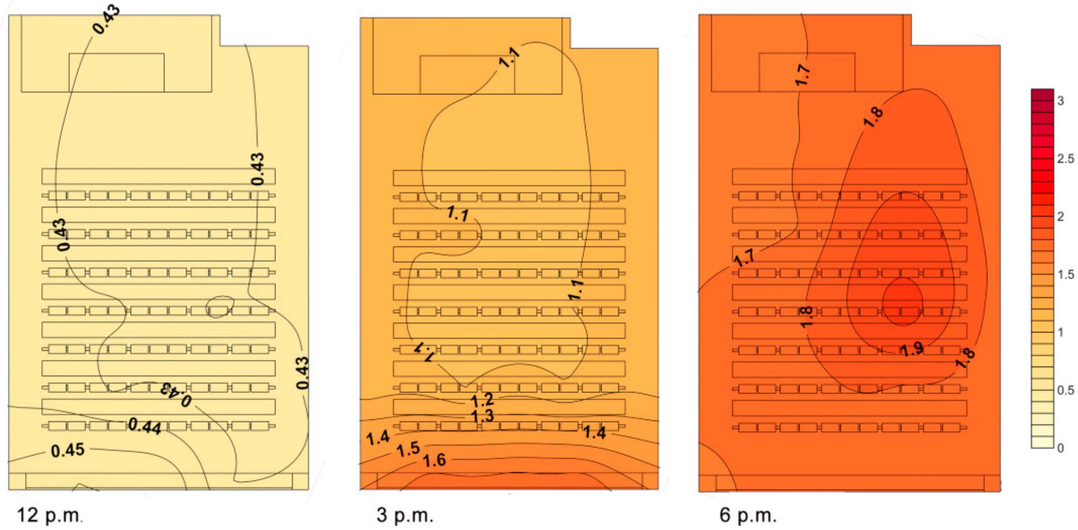

Fig. 6. Comfort sensation maps calculated by CFD simulations at 12 p.m., 3 p.m. and 6 p.m. for men configuration.

4. CONCLUSION

In the present paper the thermal comfort sensation was evaluated by both experimental data and CFD code. A 3D simulation model was implemented, the thermal and the velocity profiles within the environment were simulated.

A classroom of University of Perugia was chosen as case study and an experimental campaign was carried out in order to measure the parameters necessary to determine thermal comfort, to set input data in the CFD code, and to validate the simulation model. Only the following external climatic conditions were used as input data in the CFD code: external air temperature and solar radiation on vertical surface. In order to simulate the natural convection, a Boussinesq approximation was adopted, while to consider the influence of solar radiation the solar model of the CFD code was used. All the simulations were carried out in natural convection and in transient conditions with a time size equal to 2 seconds.

The model validation was carried out by checking three different control parameters (air temperature, surface temperature of opaque and transparent surfaces) and considering the real occupancy period of the room. The CFD model was validated with experimental data and it was used for the global and local thermal comfort prediction within the room. Considering all the occupancy period, the PMV values simulated with CFD code are very close to experimental ones for both men and women configurations; in fact a slightly warm sensation was obtained with both approaches. The simulation model was also used for the local thermal comfort evaluation within the room and the thermal sensation maps were traced. Results show that the thermal sensation is uniform in the absence of the direct component of solar radiation, while in the afternoon the influence of direct solar radiation is significant. At 3 p.m., the thermal sensation of the zone next to the transparent surface is tending to warm, due to direct solar radiation, while at 6 p.m. a warm thermal sensation was found.

Results highlighted the importance of CFD simulations to support experimental campaign thanks to their ability to evaluate the local thermal comfort. According to CFD results, in order to evaluate a representative PMV value in a large environment, it should be necessary to measure many data in several points, with very high time and money demanding, therefore the CFD code could be a very useful tool to support the experimental campaign and to evaluate the thermal local sensation.

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Nomenclature

CFD	Computational Fluid Dynamics
PMV	Predicted Mean Vote
PPD	Predicted Percentage of Dissatisfied
UDF	User Define Function
Icl	thermal resistance of clothing [clo]
M	metabolic rate [met]
T0	operative temperature [K]