MC2 021/22
Proceedings of 11th Master Conference: People and Buildings
University of Westminster, 16th September 2022
Network for Comfort & Energy Use in Buildings: https://www.nceub.org.uk

Comparative Analysis of Thermal Comfort Surveys with computational fluid dynamics (CFD) Simulations

Hassan Safdar Malik[1], Waqas Khalid[1], Absaar ul Jabbar[2], Adeel Waqas[3], Adnan Munir[1], Jawad Aslam[1], Hafiz Ali Haider Sehole[2]

[1] School of Mechanical and Manufacturing Engineering, National University of Sciences and Technology(NUST) H-12, Islamabad, Pakistan. Email: waqaskhalid@smme.nust.edu.pk

[2] School of Interdisciplinary Engineering & Sciences, NUST H-12, Islamabad, Pakistan.

[3] U.S. Pakistan Center for Advanced Studies in Energy, NUST H-12, Islamabad, Pakistan.

Abstract: This paper presents thermal comfort studies using three-dimensional CFD simulations and their comparison with the field assessments, for the two cases (sun-exposed ceiling and sun-exposed wall) of air-conditioned room environments having wall-mounted units. For CFD simulations, the P1 radiation model is used to calculate the solar gains, by incorporating the measured solar irradiance values of the survey day along with the actual geo-coordinates and time in both cases. Moreover, air flow rates and temperatures of air-conditioning units for simulations are taken from original equipment manufacturer (OEM) data. The solution is solved for predicted mean vote (PMV) contours in post-processing and local PMV values are compared with the actual measurements from instruments. Results show that simulations yield closer results to the field data in the case of solar gains from the sun-exposed ceiling as compared to the case where solar gains are from the windows.

Keywords: Thermal Comfort, Workplaces, CFD Indoor Simulations, Thermal Sensation Vote, Offices, Workplaces

1. Introduction

Air-conditioning consumption accounts for 15% of global electricity consumption (Ali *et al.*, 2022). To check the validity of effectiveness of any air-conditioning environment, the ASHRAE Standard 55-2017, ISO 7730:2005 and EN 16798-1-2009 standards point towards thermal comfort surveys. However, these surveys can only be conducted when the building has already been built, air-conditioning (AC) systems installed and occupied by its residents translating into accrual of capital as well as operating costs.

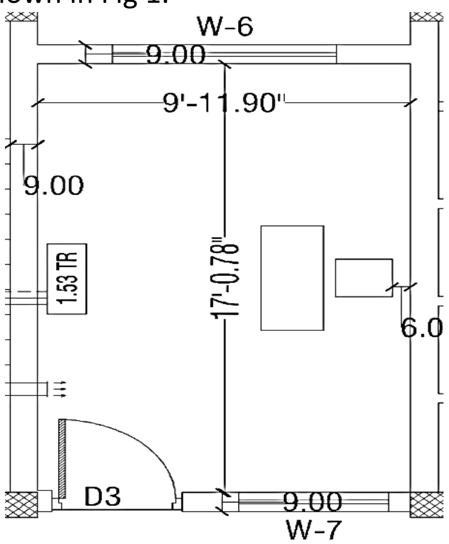
Building simulations featuring CFD can be used at the design stage, however, the accuracy of such software packages is largely dependent on careful problem setup and correct boundary conditions initializations, as multiple methods and equations need to be solved in the correct order to obtain an agreeable solution. The need for a robust yet economical CFD methodology warrants a comparative study of field collected real-time results. Nevertheless, the rigorous literature review done for the past four decades of indoor CFD simulations rarely addressed this concern.

2. Literature Review

The pioneering study which evaluated thermal comfort through numerical simulations featured 18 cases for 2 buildings and simulated the enclosed space in 3d using K-Epsilon (k-ε) Turbulence Model . Converged solutions for air velocity, temperature, PMV and predicted percentage of dissatisfaction (PPD) were found using Under Relaxation Technique(Yuan *et al.*, 1992). A three-dimensional CFD code called Vortex was used and the results obtained from CFD code were compared with each other as mechanically ventilated and naturally ventilated, however, the field assessments and measurements were not part of scope of this study (*Awbi and Gan, 1994*) .Another research (*Gan, 1995*) used experimentally validated 3d CFD simulation codes to investigate the effect on PMV and PPD by different mechanical ventilation strategies utilizing Simple algorithm which simultaneously solved Navier Stokes Equations (Continuity Equation, momentum equation, and Energy Equation) with k- epsilon (k-ε) turbulence model. Similarly, commercial solver Fluent 5.3 was used to simulate the air temperatures and velocity for the lecture hall with furniture and all energy sources using k-epsilon (k-ε) turbulence model. Thermal sensation was subjectively assessed using questionnaires and objectively measured and calculated PMV and PPD, however, the aforementioned thermal indices were not simulated in CFD simulations (*Cheong et al., 2003*). Research (*Ravikumar and Prakash, 2009*) studied the effect of aspect ratio of windows sizes of naturally ventilated office buildings on thermal comfort using CFD codes and Network Model and found optimum window opening area ensuring maximum thermal comfort without compromising the strength of buildings**.** Another study also conducted simultaneous experimental and simulation studies for the assessment of thermal comfort for a sub-tropic region office utilizing the cooling ceiling for mechanical ventilation. CFD simulation were subsequently reused to address temperature stratification and thermostat strategy was revised to achieve thermal comfort and energy savings up to 8%. Humidity levels were assumed in this study(*Chiang, Wang and Huang, 2012*)**.** A latest study (*Ismail et al., 2021*) compared 3 operative temperatures of 21ºC, 23ºC and 25ºC by calculating PMV and PPD values through CFD simulations using Ansys Fluent Software Package for a workspace

3. Study Setup

In the current study, two cases were simulated for finding PMV contours to access thermal comfort through CFD Simulations and subsequent comparison with field assessments. Case A was based on an Office located on the 1st floor, whereas, Case B was based on an office on the 3rd Floor of G+3 academic building of Islamabad. The HVAC layouts for both rooms are shown in Fig 1.



AC Layout for Room of Case A

AC Layout for Room of Case B

Fig 01: Air Conditioning (AC) Layouts for Case A and Case B.

Room A had two windows named W-6, W-7 and a door D3. W-6 was exposed to sun, whereas W-7 and D-3 were opened in an air-conditioned environment. Room A was provided with 1.5 TR wall mounted unit with a diffuser for fresh air providing 50 CFMs. Room B had a door and a window both opening in the corridors. Being on the 3rd floor, the ceiling of room was exposed to sun. Room B was provided with 1 TR wall mounted unit with a diffuser for fresh air providing 52 CFMs.

4. Assumptions

Following assumptions were made for CFD simulations.

1. Heat from electrical items such as lights, PCs, laptops, scanners, and printers was ignored, and furniture in the room was not modelled. (*Horikiri, Yao and Yao, 2015*)
2. For surfaces exposed outside to air-conditioned environment air temperature of 26°C was taken as a thermal boundary condition and for the surfaces exposed to the sun outside, the ambient air temperature was taken as a thermal boundary condition. (*Bonefacic, Wolf and Frankovic, 2015*)
3. Air conditioner's operational data like volumetric flow rate and rated capacity was taken from the catalogues provided by OEM (*DC Inverter Multi Vrf Service Manual T1/R410a/50hz, N.D.*).

4. Governing equations and mathematical modelling

Continuity equation, momentum equation, energy equation and radiative heat transfer equations were used for mathematical modelling of problem. Realizable k-ε model using standard wall functions for near wall treatments was used for turbulence modelling, whereas P1 Model using solar calculator with actual geo-coordinates and solar irradiance values was used for simulating solar gain.

Solar Gain Parameters	**Case A**	**Case B**
Direct normal irradiance	324.63 W/m^2	403.79 W/m^2
Direct horizontal irradiance	0.85 W/m^2	231.1943 W/m^2
Outside air temperature	35.38°C	23.83°C

5. Results and Discussions

5.1. Field Assessments

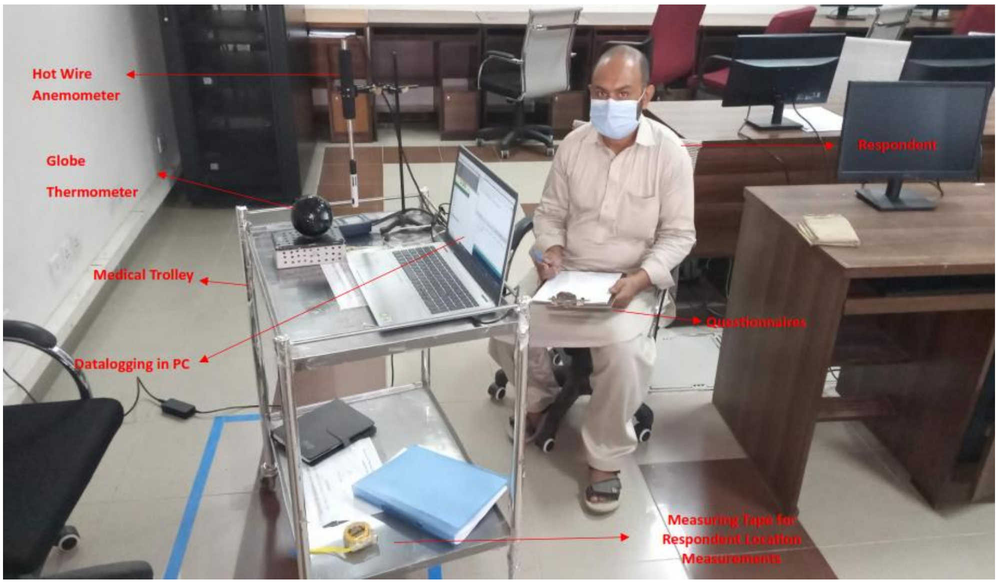


Fig 02. Field Assessment Typical Setup with Instrumentation and Respondent

Calibrated instruments were setup on a trolley for field surveys and data was logged into PC with one minute interval for ten minutes as shown in Fig 02. During this time subjective assessments were also conducted with the help of questionnaires. Air temperature, air velocity, globe temperature, and humidity were measured through instruments whereas clothing and activity level data was collected from respondents. Mean radiant temperature was further calculated from globe temperatures and all 10 minutes data was averaged and plugged in PMV Equation (1) to obtain local PMV values and corresponding local PPD values were calculated from Equation (2).(Fanger, 1970)

$$PMV_{Local} = [0.303e^{-0.036.M} + 0.028].L .....(1)$$

$$PPD_{Local} = 100 - 95e^{(-0.03353(PMV)^4 - 0.2179(PMV)^2)} .....(2)$$

5.2. CFD Results

During field surveys, the dimensions for position of equipment was noted and later in CFD simulation same position PMV and PPD was compared with PMV and PPD calculated from field surveys as shown in Table 01 and Fig 03 (Case A) and Fig 04 (Case B).

Thermal Indices	**Case A**		**Case B**	
	Simulations	**Field surveys**	**Simulations**	**Field surveys**
PMV (Maximum)	2.20	-	0.45	-
PMV (Minimum)	-3.0	-	-1.28	-
Coordinates for local PMV	0.77,1.01,0.57	-	2.89,1.04,-1.43	-
PMV_{Local}	-0.12	0.13	0.72	0.85
PPD (Maximum)	95.0	-	39.3	-
PPD (Minimum)	5.0	-	5.0	-
PPD_{Local}	5.3	5.4	5.1	20.4

Table 01: Comparison of PMV and PPD found from simulations and field surveys of Case A

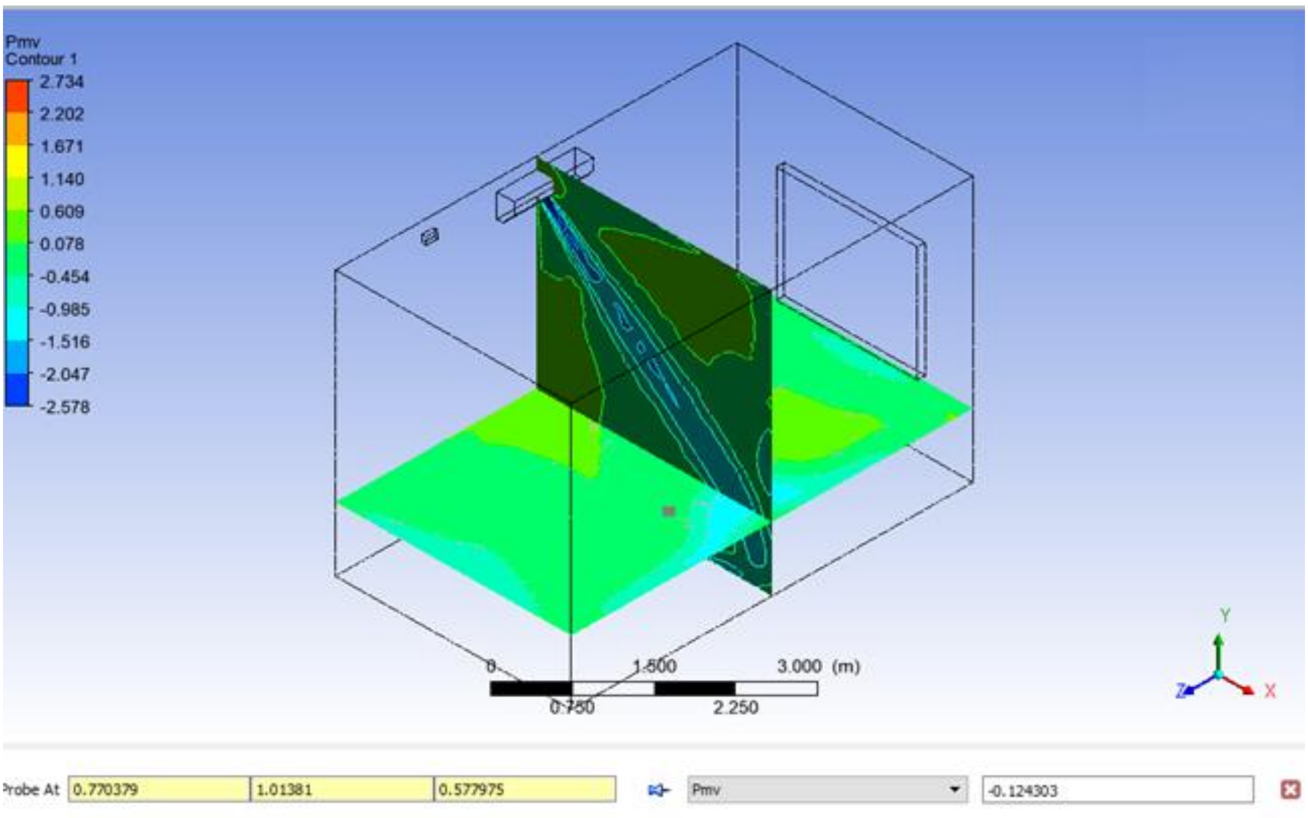


Fig 03. Local PMV at x= 0.77, y=1.01 and z=0.57 from simulation results for Case A

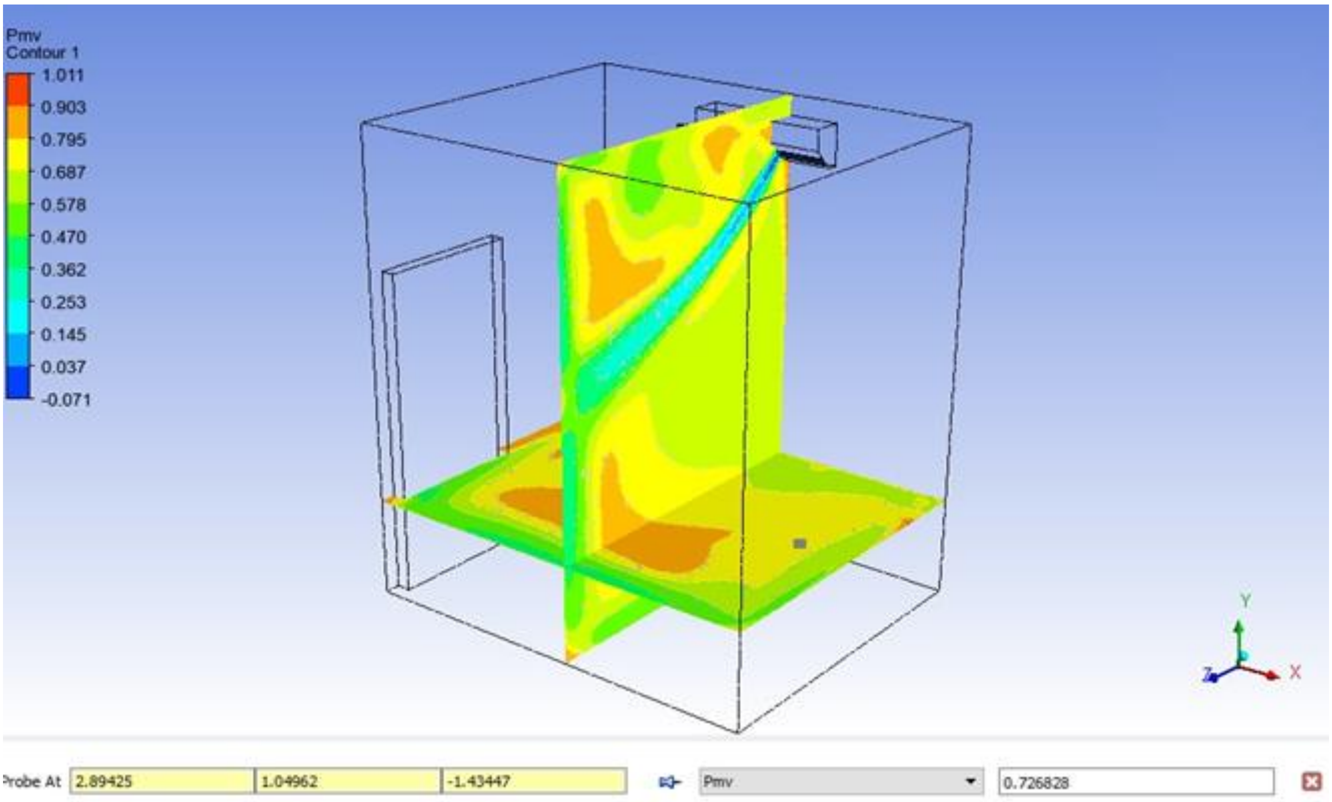


Fig 04. Local PMV at x= 2.89, y=1.04 and z=-1.43 from simulation results of Case B.

The PMV contour is dispersed for Case A varying between a range of 2.2 to –3.0, however, the variation is less in PMV contours for Case B as 0.45 to -1.28. The local PMV for both cases show an inclination towards cooler side of thermal sensation scale whereas in actual field measurements the calculated PMV for both cases were higher. The local PMV for Case B is closer to actual data as compared to Case A.

Room A was situated on first floor of eastern wing whereas room B was situated on the 3rd floor of central wing which is the topmost floor of the building. The sun-facing component for Case A is Wall with a window, whereas the sun-facing component for Case B is the roof. The installed capacity in room A is 1.5 TR for 170 Sq-ft whereas the installed capacity in room B is 1 TR for 75 Sq-ft making the load factors as 113 Sq-Ft/TR and 75 Sq-ft/TR respectively. Both rooms had individual thermostat controls for occupants.

The lower values of PMV values calculated in contrast to field survey calculated PMV values can be attributed to the mechanical wear of air-conditioners blower fans over the years hence providing flow rate lower than that of rated values as noted in OEM Manuals.

6. Conclusion and Recommendations

Thermal comfort is evaluated from CFD simulations with real-time field survey data, and it is found that simulations yield better results for the cases where ceiling is exposed to sunlight as compared to the cases where only walls are exposed to sun. It was also found that within a single room, Predictive Mean Vote experiences variations in PMV values. Better results can be drawn for future studies if:

- ✓ Actual mass flow rate for the air-conditioners vents is considered.
- ✓ Actual mass flow rate for the diffuser vents is considered.

- ✓ Actual temperature for the AC outlet vent is taken.
- ✓ Actual temperature for AC diffuser vent is taken.
- ✓ Actual values for thermal resistance, absorptivity, transmissivity, and emissivity are calculated for materials like glass and wall and incorporated in CFD simulations.
- ✓ Wall temperatures are measured and incorporated in the studies.
- ✓ Heat sources from office appliances are considered.
- ✓ Boussinesq approximation model is used to consider the buoyancy effects.

7. Nomenclature

ASHARE	American Society Of Heating, Refrigerating And Air-Conditioning Engineers	**OEM**	Original Equipment Manufacturer
CFD	Computational Fluid Dynamics	**PMV**	Predicted Mean Vote
CFM	Cubic feet per minute	**PPD**	Predicted Percentage Of Dissatisfied
EN	European Norm	**SIMPLE**	Semi-Implicit Method For Pressure Linked Equations
G+3	3 floors excluding ground floor	**Sq-Ft**	Feet Squared
HVAC	Heat Ventilation and Air Conditioning	**TR**	Ton Of Refrigeration
L	L is a function of Activity Level, Air Temperature , Mean Radiant Temperature, Air Velocity, Relative Humidity and Clothing Insulation Level.	**TWh**	Terawatt-Hour
M	Metabolic Rate in W/m^2	e	Euler's Number 2.718281828459045
ISO	International Organization for Standardization		

8. References

Ali, W. *et al.* (2022) 'Energy conservation and climate change mitigation potential of improving efficiency of room air conditioners in Pakistan', *Energy Reports*, 8, pp. 6101–6109.

Awbi, H.B. and Gan, G. (1994) 'Predicting air flow and thermal comfort in offices Latent heat storage systems for building cooling applications View project Indoor air quality in low energy dwellings View project', *ASHRAE Journal*

Bonefacic, I., Wolf, I. and Frankovic, B. (2015) 'Numerical modelling of thermal comfort conditions in an indoor space with solar radiation sources', *Strojniski Vestnik/Journal of Mechanical Engineering*, 61(11), pp. 641–650.

Cheong, K.W.D. *et al.* (2003) 'Thermal comfort study of an air-conditioned lecture theatre in the tropics', *Building and Environment*, 38(1), pp. 63–73. Available at: https://doi.org/10.1016/S0360-1323(02)00020-3.

Chiang, W.H., Wang, C.Y. and Huang, J.S. (2012) 'Evaluation of cooling ceiling and mechanical ventilation systems on thermal comfort using CFD study in an office for subtropical region', *Building and Environment*, 48(1)

DC Inverter Multi VRF Service Manual T1/R410A/50Hz ELECTRIC APPLIANCES INC. OF ZHUHAI . Available at: www.Manualslib.com.

Fanger, P.O. (1970) 'Thermal comfort. Analysis and applications in environmental engineering.', *Thermal comfort. Analysis and applications in environmental engineering.*

Gan, G. (1995) 'Evaluation of room air distribution systems using computational fluid dynamics', *Energy and Buildings*, 23(2), pp. 83–93. Available at: https://doi.org/10.1016/0378-7788(95)00931-0.

Horikiri, K., Yao, Y. and Yao, J. (2015) 'Numerical optimisation of thermal comfort improvement for indoor environment with occupants and furniture', *Energy and Buildings*, 88, pp. 303–315. Available at: https://doi.org/https://doi.org/10.1016/j.enbuild.2014.12.015.

Ismail, A.R. *et al.* (2021) 'Experimental investigations and computational thermal simulation on human thermal comfort during performing office tasks', *Journal of Physics: Conference Series*, 1793(1), p. 012076. Available at: https://doi.org/10.1088/1742-6596/1793/1/012076.

Ravikumar, P. and Prakash, D. (2009) 'Analysis of thermal comfort in an office room by varying the dimensions of the windows on adjacent walls using CFD: A case study based on numerical simulation', *Building Simulation*, 2(3)

Yuan, X. *et al.* (1992) 'Numerical Simulation of Air Flows in Gymnasia', *Indoor Environment*, 1(4), pp. 224–233. Available at: https://doi.org/10.1159/000463447.