EXPERIMENTAL INVESTIGATION ON ROOM AIR FLOW PATTERN & THERMAL COMFORT QUANTIFICATION

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ABSTRACT

It is well known that indoor environment is an important factor not only for occupants' comfort as a whole, but also for their health and productivity. Air distribution achieves the acceptable levels of temperature, humidity, cleanliness and air motion in the occupied zone of conditioned area. All this is done in such a manner that the occupant does not experience any draft. Airflow and transport phenomena play an important role in air quality, thermal comfort and energy consumption in buildings. Air movement is one of the six main variables determining human thermal comfort.

The present work focuses on the room air flow pattern in terms of temperature and velocity along with thermal comfort quantification by varying clothing index. Room air flow pattern in the two test rooms, University conference hall and RAC (Refrigeration and Air Conditioning) Lab are studied under four conditions; natural, only fan, only AC, fan with AC. Effect of air conditioner position on the room air flow pattern is also studied. Thermal comfort is quantified using standard ASHRAE sensational equation based on the feelings of the four B. Tech students at various clothing index and exposure period. The contour of the flow patterns are plotted using ORIGIN 6.1 software.It is advisable to operate the ceiling fan at moderate speed with air conditioner to get the uniform flow pattern with respect to temperature and velocity which leads to saving in energy. Air flow pattern depends on the location of the air conditioner. Thermal comfort depends on the clothing resistance and activity level.

KEYWORDS: *Flow pattern, Thermal comfort, Room air flow, Air quality.*

I. INTRODUCTION

One of the main aims in designing storage enclosures, hospitals, offices or application in sensitive areas is to ensure a uniform targeted temperature and humidity in the relevant enclosures. A methodology for obtaining reduced order models for temperature distribution in air conditioned rooms was developed and analysed by Sempey et al. [2]. The focus of the work was to test the feasibility of the approach. Yongson et al. [3] had done the simple numerical study of the turbulent flow over an enclosed air conditioning system. The different locations of blower placement were analyzed for better comfort of occupant in the room. Sevilgen Gokhan et al. [4] had done a three-dimensional steady - state numerical analysis in a room heated by two - panel radiators. The results showed that energy consumption can be significantly reduced while increasing the thermal comfort by using better insulated outer wall materials and windows.

An airflow pattern sensor was developed to measure the trajectory of a non-isothermal air jet in a building with a single or multiple air inlet(s) by Ozcan and Vranken [5]. Ho Son H. et al. [6] presented air velocity and temperature distribution in a refrigerated warehouse. It was found that a better cooling effectiveness and uniformity of temperature in the refrigerated space could be achieved by using higher blowing air velocity and/or locating the cooling units lower and closer toward the arrays of product packages.

Experiments were conducted in a mock - up of an office room to study the air velocities in the occupied spaces by Kosonen Risto et al. [7]. The maximum air velocity measured was still below 0.25 m/s with the extremely high heat gain of 164 W/m^2. Myhren Jonn Are et al. studied [8] thermal comfort aspects, different heating systems and their position effect on the indoor climate in an exhaust-ventilated office under Swedish winter conditions. Computational fluid dynamics (CFD) simulations were used to investigate possible cold draught problems, differences in vertical temperature gradients, air speed levels and energy consumption. Nielsen [9] had done the work on velocity distribution to achieve the thermal comfort of the occupant. Velocity distribution was simulated and concluded the airflow from an air terminal device influences the occupant's thermal comfort. Ho Son H.et al. [10] performed a thermal comfort analysis for a person standing in a room with an inlet and an outlet for air conditioning and a ceiling fan. It was found that as the normal air speed from the fan increases, thermal comfort significantly shifts toward the cooler scale to allow higher supply air temperature or higher heat load in the room while maintaining the same comfort level.

Karyono Tri Harso [11] had done a field study on thermal comfort in the capital city of Jakarta, Indonesia. There were 596 office workers working in seven multi-storey office buildings participated in this study. Human feeling temperature is focusing on and human thermal load was proposed as an index by Yasuhiro Shimazaki et al. [12] With using this human thermal load index, countermeasure techniques for severe thermal environment were evaluated from the perspective of human feeling.

The investigation on a personal chair arm rest - embedded air system had proposed by Zhang et al. [13]. The system delivers conditioned, outside air directly to the breathing zone of a passenger from the air terminal devices embedded within both chair armrests. This study found that by combining the under-aisle air supply with the personal air supply at the chair armrests, the system is robust to prevent the contaminants released at any height to the passenger's breathing region. The characteristics of thermal comfort and indoor air quality (IAQ) measurements by Sekhar S.C. et al. [14] were carried out during sleeping period in 12 Naturally/Mechanically Ventilated (NMV) and 12 AC bedrooms over a period of 2 months in hot and humid climate. It was found that NMV bedroom was a better sleeping environment.

Budaiwi Ismail M. [15] presented a systematic multi-phase and solution–oriented approach through which thermal-comfort problems can be assessed, identified and treated in a systematic way without utilizing unnecessary resources and time has been introduced. The approach can be helpful to building operators and facility managers when dealing with thermal-comfort problems. Human feeling temperature is focusing on and human thermal load was proposed as an index by Yasuhiro Shimazaki et al. [16] With using this human thermal load index, countermeasure techniques for severe thermal environment were evaluated from the perspective of human feeling. The numerical analysis was carried out for predicting human thermal load as a criterion of human thermal comfort from weather conditions. In the results, some effects on human thermal comfort were obtained. The use of highly reflective material leads to a reduction in environmental heat load, There is a great deal of variation of human thermal load when the subject was naked. On the other hand, human thermal load of the dressed subject has relatively small change.

It can be summarized that for achieving a uniform flow distribution in terms of temperature and velocity mostly higher blowing velocity and location of the cooling units at different places were suggested depends on the situation. In comparison to Fanger's PMV model, much less work has focused on the validity of Fanger's Draught Model. Hence, the objective of the present work is to characterisation of the room air flow with respect to temperature and velocity, experimentally and the quantification of the thermal comfort based on the occupants vote.

The present work is focused on the characteristics of room air flow pattern in terms of temperature and velocity with thermal comfort quantification by varying the clothing index.

The whole paper is divided into five sections. Section 1 introduces the topic by characteristic and performance of room air flow pattern with thermal comfort standards and aspects from ASHRAE journal as well as work carried out by various researchers on the room air flow pattern and thermal comfort is presented. Experimental test facility described section 2 and section 3 deals the details of the experimental work carried out in the University conference hall and RAC Lab room. Results and discussion are described in section 4. It includes the details and comparisons of the contours obtained from ORIGIN 6.1 software and thermal comfort results. The conclusions derived from the work carried out in the tests room as selected with all the conditions mentioned and thermal comfort in context of clothing index summarized in section 5.

II. EXPERIMENTAL TEST FACILITY

An in house test facility was created to measure the room air velocity and temperature. Experiments were conducted in two different test rooms of different shape and size under different conditions [Fig. 1 & 2]. A hot wire anemometer is employed to measure the room air velocity. First test room with a 1 TR window air-conditioner in Refrigeration and Air Conditioned (RAC) Laboratory is selected as shown in Fig.1 where AC1 indicates the position of the AC at the entrance wall of the room and AC2 indicates the position of the same AC in the window.

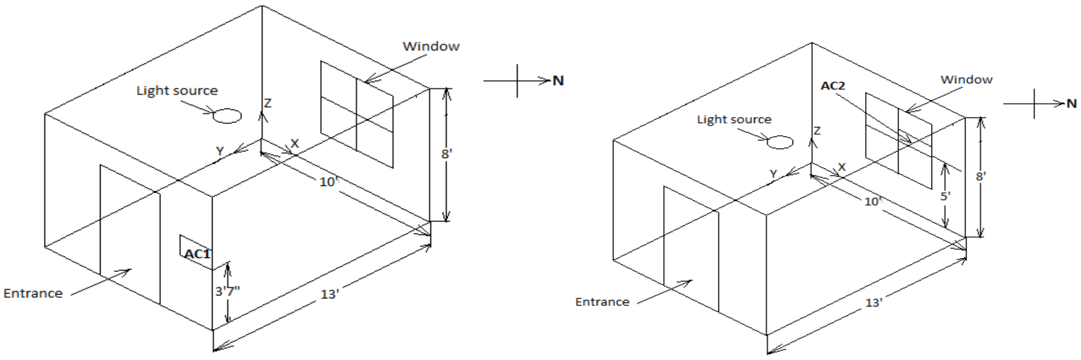

Figure 1. Schematic of the test room with AC positions AC1 and AC2

The test room is the size of L × H × W = 13 feet × 8 feet × 10 feet with a nearly cubical shape. The room facilitates 1 TR Air Conditioner (AC) and a window on opposite of the entrance wall owing to low height of the room, no ceiling fan is installed.
CTV100 hot wire anemometer used for the measurement of velocity and temperature in the experiment of specifications mentioned in Table 1:

Table 1. Specifications of CTV100 anemometer

	Velocity	**Temperature**
Measuring range	0 to 30m/s	0 to +50°C
Accuracy	±3% of reading ±0.3 m/s	±0,5% of reading ±0,4°C
Response time	1/e (63%) 2 sec	1/e (63%) 5 sec
Resolution	0.1 m/s	0.1°C
Type of fluid	air and neutral gases	air and neutral gases
Type of sensor	Pt100 class A as per DIN IEC751	Pt100 class A as per DIN IEC751

The detailed view of the anemometer and a temperature measuring facility has shown in Fig. 3. A rigid plastic pipe of the 3 meter is selected with the facility to attach the anemometer probe at the required position (at equal interval) on the pipe. The pipe was rested on the iron stand with the heavy base to keep the pipe at vertical position. Care was taken to keep the probe position at all the locations on the entire height of the pole at same orientation to maintain the uniformity.

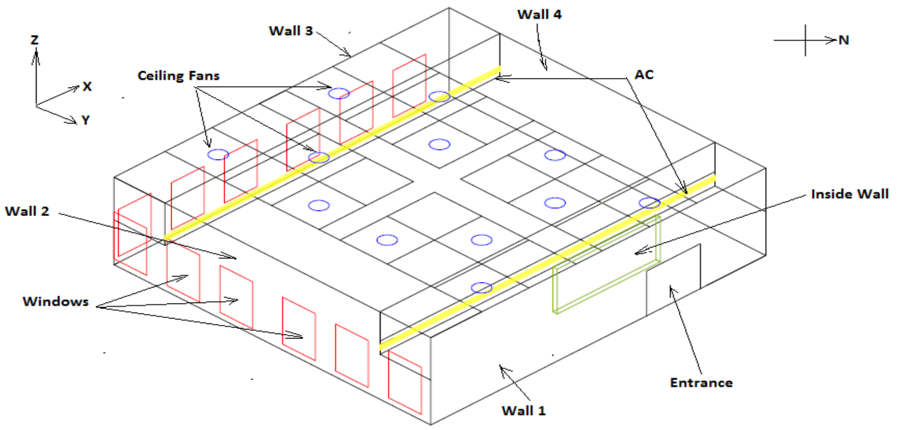

Figure 2. Schematic of the University conference hall

Figure 3. Photograph of hot wire anemometer Temperature measuring facility

III. EXPERIMENTATION

3.1. Room air flow

Experiments were conducted in two test room located at different location at different conditions. In test room 1, tests were carried out at two conditions, position 1 (AC1) where air-conditioner is placed at the entrance wall of the room at 3 feet 7 inch height from floor and position 2 (AC2) where air-conditioner is placed in the opposite window at 5 feet height from floor as shown in Fig. 4 and 5. The floor was divided into 7 × 5 = 35 points of 2 feet × 2 feet square [Fig. 4]. The grid points were designated as x_{ij} such as 11, 12, 13, 14, 15, 25, 24...., as per the grid position on the array shown in Fig. 4. At each grid point the velocity and temperature were recorded along the Z axis at the distances 2 feet, 4 feet, 6 feet and 8 feet from the floor.

The experiments were carried out in test room 1 for following conditions:

Condition No.1: A/C and Fan both were OFF (Natural)

Condition No.2: A/C ON when AC placed near the Entrance (AC1)

Condition No.3: A/C ON when AC placed in the window (AC2)

The test room 2 of the size L × H × W = 46.1 feet × 11.9 feet × 43.6 feet with 12 ceiling Fan, 2 AC each at the entrance wall and opposite to the entrance wall was divided into 10 × 9 = 90 points of 5 feet × 5 feet distance as shown in Fig. 5. The measurements of temperature and velocity were taken along the Z axis at 2.5 feet, 5 feet, 7.5 feet and 10 feet from the floor in the sequence of 11, 12, 13, 14, 15, 16, 17, 18, 19, 1-10, 2-10, 29, 28, 27, 26...9-10 as shown in Fig. 5.

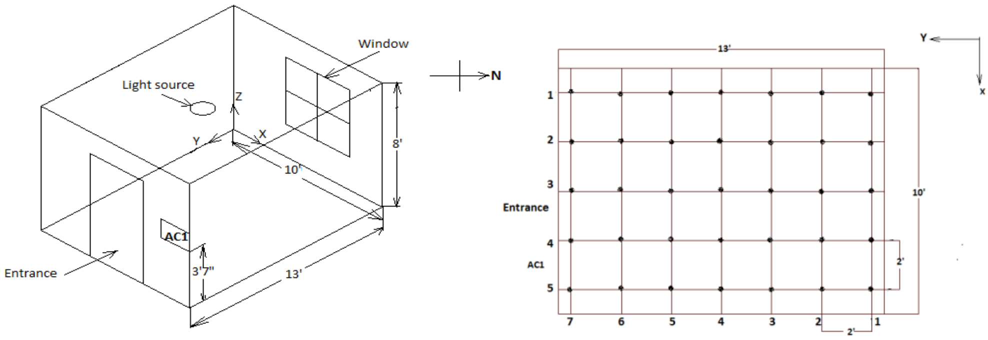

Figure 4. Test room 1 with grid points at base

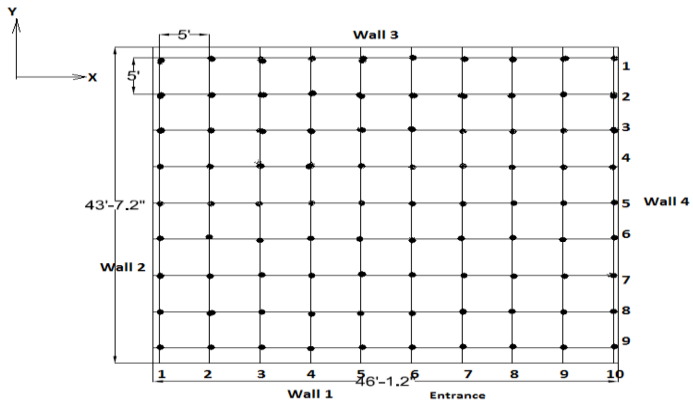

Figure 5. University conference hall grid points

The experiments were carried out in test room no 2, for following conditions:
Condition No.1: A/C and Fan both were OFF (Natural)
Condition No.2: A/C ON and Fan OFF (Only AC)
Condition No.3: A/C and Fan both were ON (AC + Fan)
Condition No.4: A/C OFF and Fan ON (Only Fan)
Atmospheric temperature and humidity measured at the start and end of the measurement by using slinge psychrometer. To check the effect of the ambient conditions experiments were conducted at different calendar days. A 1000W fog machine of model Q1, A0010 was used in the test room 1, University RAC Lab room to capture the actual flow pattern using 12MP digital camera.

3.2. Thermal comfort

Thermal comfort was measured based on the feeling recorded of the four B.Tech students of the age group 20 - 24 yrs with different clothing index at the positions A, B, C, D corresponding to grid points 25, 45, 43, 23, respectively as shown in the Fig. 3.10. It was assumed that the metabolic rate is 1 met (58.1 W/m^2). Further, exposure time period were also varied, 15 min, 30 min, and 60 min. The responses were recorded by each student at each clothing index with three exposure timings as per the ASHRAE thermal sensation scale as shown Table 2 with voting which can be called as Y value.

Table 2. ASHRAE Thermal Sensation Scale

-3	-2	-1	0	1	2	3
Cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot

The measurements were taken at three different clothing indexes:
Condition No. 1 0.36clo = short shirt + short sleeve
Condition No. 2 0.57clo = trousers + short sleeve

Condition No. 3 0.61clo = trousers + long sleeve shirt

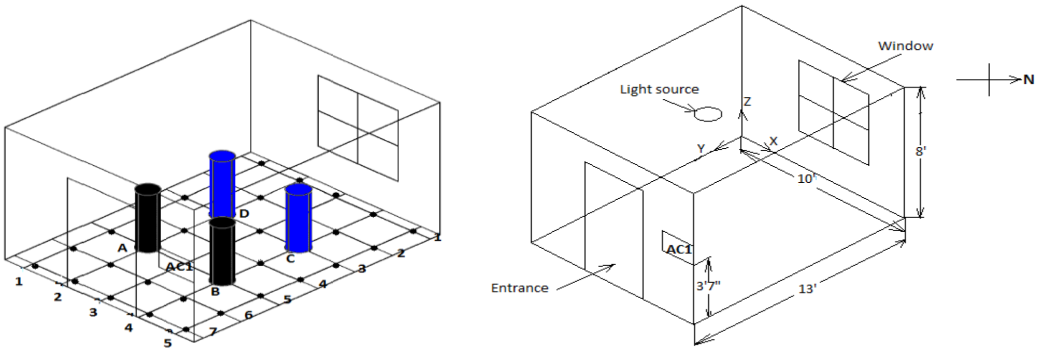

Figure 6. Schematic of thermal comfort measurement

IV. RESULTS AND DISCUSSION

Flow patterns are generated using ORIGIN 6.1 software. Further, thermal comfort was quantified using standard correlations, based on the feelings of the occupants at different clothing index and exposure time.

4.1. Flow pattern in test room 1, University RAC Lab

a. Temperature contours

As the darkness of the color decreases from red to blue color in the contours; the temperature also goes on decreasing. Thus the red color shows the higher temperature and blue color shows the lower temperature. The maximum temperature difference of 1.9^{0}C had been seen in between opposite wall of the room. The temperature pattern was not distributed uniformly in natural condition [Fig. 7] because of very low air velocity in the enclosed test room with higher temperature from 31.8 to 32.9^{0}C where the occupant feels discomfort and not much variation observed in the temperature up to height 6 feet which subsequently sudden increased.

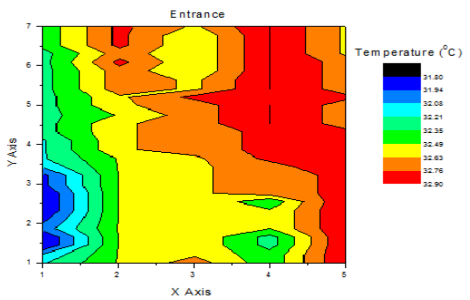

Figure 7. Temperature variation in test room 1 for condition 1

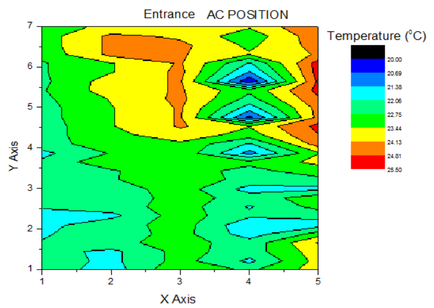

Figure 8. Temperature variation in test room 1for condition 2

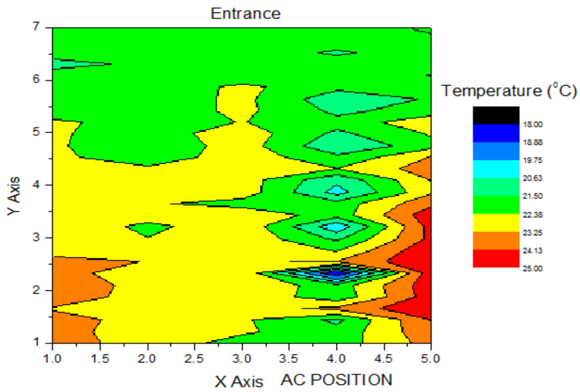

Figure 9. Temperature variation of test room 1 for condition 3

However, the temperature flow pattern seen to be more uniform at condition 2, depicted in Fig. 8.Though the maximum temperature difference had seen to be 5.5^0C which was more than natural condition. The lowest temperature had been recorded as 18^0C exactly in front of the AC at 6 feet from the ground when AC shifted in window (AC2) with condition 3 as shown in Fig. 9 and temperature variation similar to condition 2. However, air pockets were formed in of corner of the window. Though the maximum temperature difference 7^0C, but it was due to the only one grid point showing very lowest temperature exactly in front of AC2.

b. Velocity contours

Fig. 10 depicts velocity variation in the test room 1, at Condition 1 with less velocity values i.e. from 0.058 to 0.12 m/sec, the air pattern showed non uniformity in 3D surface graph with lowest velocities at the floor and ceiling. In 2D contour the mixing color clearly indicates the non uniformity in the pattern because of the lower velocities.

Velocity variation at Condition 2 in Fig. 11 shows more uniformity in the contour graph than natural condition (condition no.1); while the increased velocity observed only in front of the AC positions. Velocity values vary from 0 – 0.9 m/sec. 3D surface pattern showed that the flow from AC at 4 feet height from ground goes upwards slightly striking the opposite wall and then goes to downwards; hence uniformity of lower velocities seen in blue color more than other region in 2D contour.

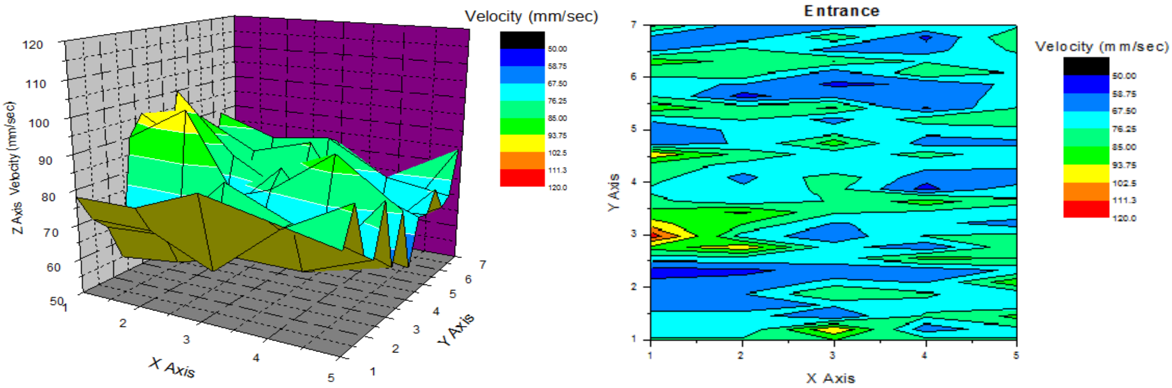

Figure 10. Velocity variation in test room 1 for condition 1

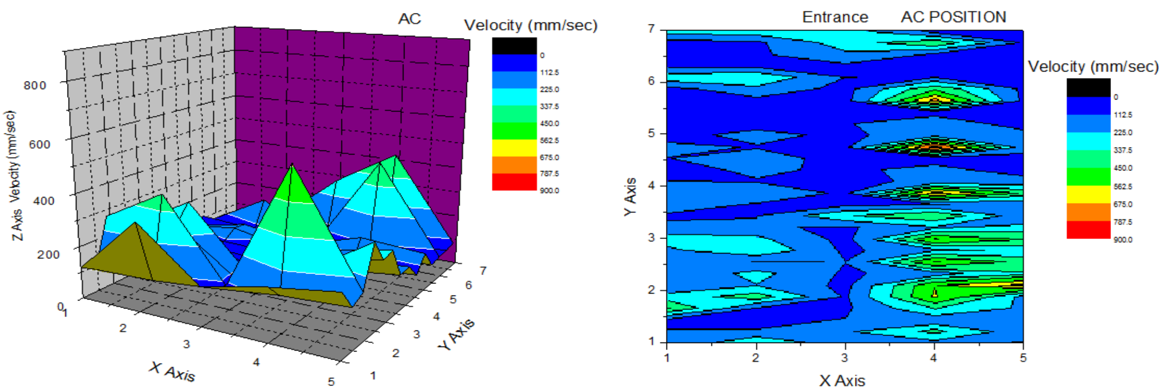

Figure 11. Velocity variation in test room 1 for condition

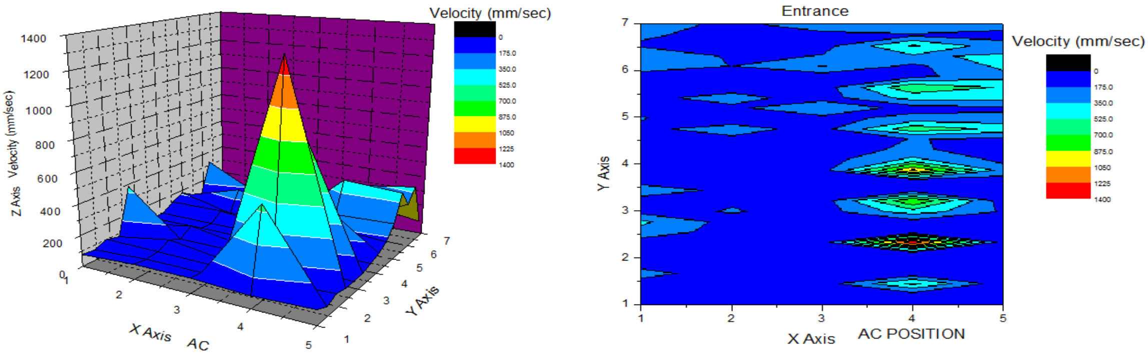

Figure 12. Velocity variation in test room 1 for condition 3

However the more uniform velocity pattern observed when AC position shifted from entrance wall (AC1) to window (AC2) i.e. condition no.3 in Fig. 12. The maximum velocity of 1.4 m/sec recorded exactly in front of the AC2 at 6 feet height from floor. Thus the flow moved from AC2 to the opposite wall (entrance wall) and then to downwards and mixes in the whole room uniformly. The same flow behavior had been matched by capturing the fog from a 1000W fog machine with model Q1A0010 at the same condition shown in Fig. 13.

Figure 13. Actual flow patterns recorded in AC2 position by Fog machine

4.2. Flow pattern in test room 2, University conference hall

a. Temperature contour

Maximum temperature difference of 0.6^{0}C had been seen from natural condition as shown in Fig. 14. The non uniform but symmetric nature of the 2D contour graph had observed due to the higher temperature range of 32.9 to 33.5^{0}C and lower velocities of the air. The minimum 24.8^{0}C and maximum 31^{0}C temperature were recorded for condition 2 [Fig. 15].

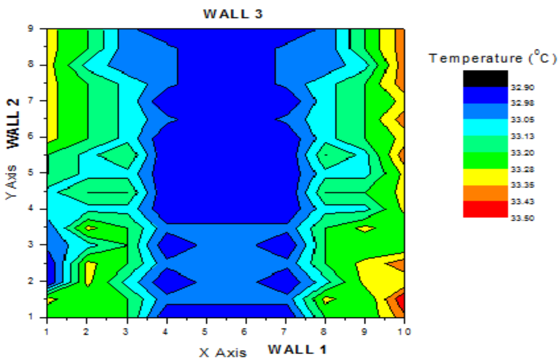

Figure 14. Temperature variation in test room 2 for condition 1

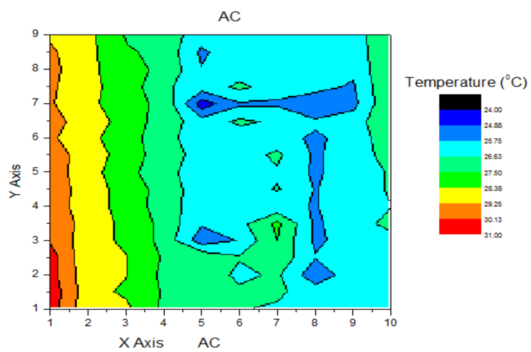

Figure 15. Temperature variation in test room 2 for condition 2

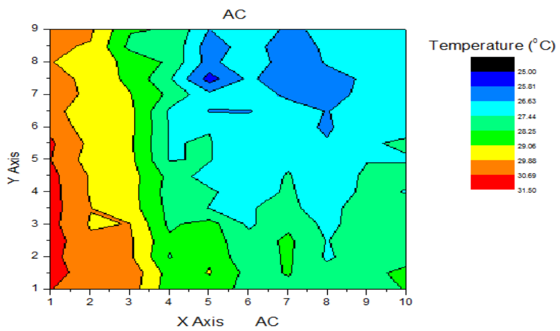

Figure 16. Temperature variation in test room 2 for condition 3

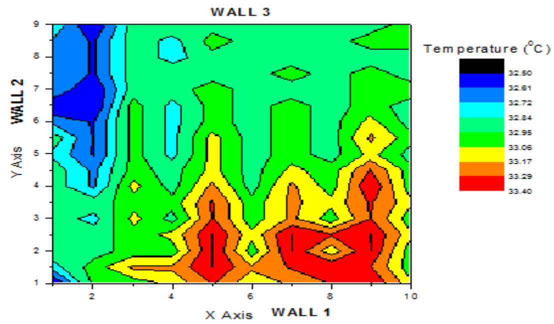

Figure 17. Temperature variation in test room 2 for condition 4

Temperature pattern showed more uniformity in-between both AC walls than natural and only fan condition with higher temperature zone at wall 2 and 4. Also the pattern shows more uniformity than condition 1(Natural) and condition 4 (only fan). Maximum 6^{0}C temperature had been seen in condition 3 and showing nearly same uniform pattern as in case of condition 2 with some more uniformity [Fig. 16].

Only condition 4 had showed higher temperature region at ceiling and relatively lower temperature region at floor [Fig. 17]. However the temperature pattern had been seen to be more uniform than condition no.1 (Natural). The temperature ranges from 32.5 to 33.4^{0}C. The red zone near the wall 1 showing higher temperature region than other due the inside wall at that position which prevents the air circulation in that region.

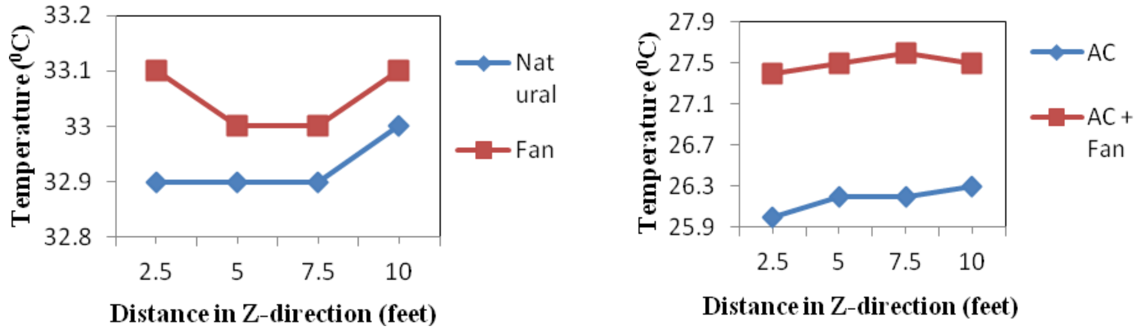

Figure 18. Variation of temperature at all the conditions in test room 2

Variation of temperature at all the conditions in test room 2 with height along Z axis had been shown in Fig. 18. Temperature rise with height seen in condition 1, 2 and 4. However the temperature decrease at ceiling observed only at condition 3.

b. Velocity contour

Fig. 19 shows velocity variation in test room 2 for natural condition where not more velocity variation found at natural condition and flow pattern was almost steady and slow which can be seen through the 3D surface graph. The maximum velocity of 0.7 m/sec would be observed at 53 and 57 points at 10' height from ground i.e. exactly at middle and in front of AC positions from Fig. 20. Thus the cool air flow from both AC came downward after striking to each other and then mixes uniformly at 2.5 feet from floor as the more bluish region has seen in 2D graph.
Fig. 21 showed the most uniform pattern of the velocity at fan and AC condition. Due to the 12 fan running in the conference hall the cool flow from AC moved downwards and mixes uniformly; thus the more air circulation had been observed than the only AC condition. 0.7 to 1 m/sec velocities were observed at 12 to 13 points at only fan condition as shown in Fig. 22. It is shown that more air circulation at 2.5 feet to 5 feet from floor and giving the uniform pattern than the other conditions.
Thus to achieve the uniform flow pattern in terms of temperature and velocity condition with air conditioner, fan with moderate speed creates the uniform distribution of the air which create the proper air diffusion and provide better comfort for the occupants. Consequently, keeping the AC at higher set temperature load on the AC can be reduced and energy is saved.

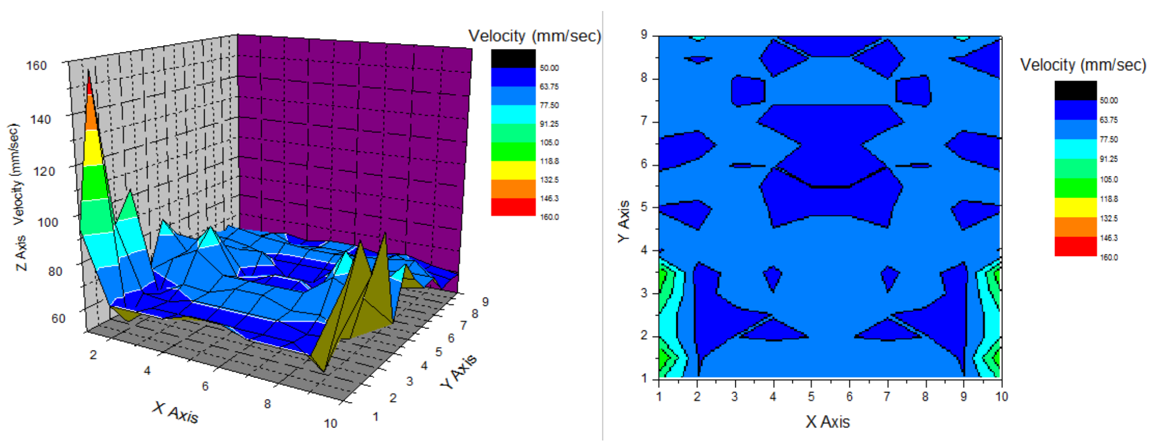

Figure 19. Velocity variation in test room 2 for condition 1

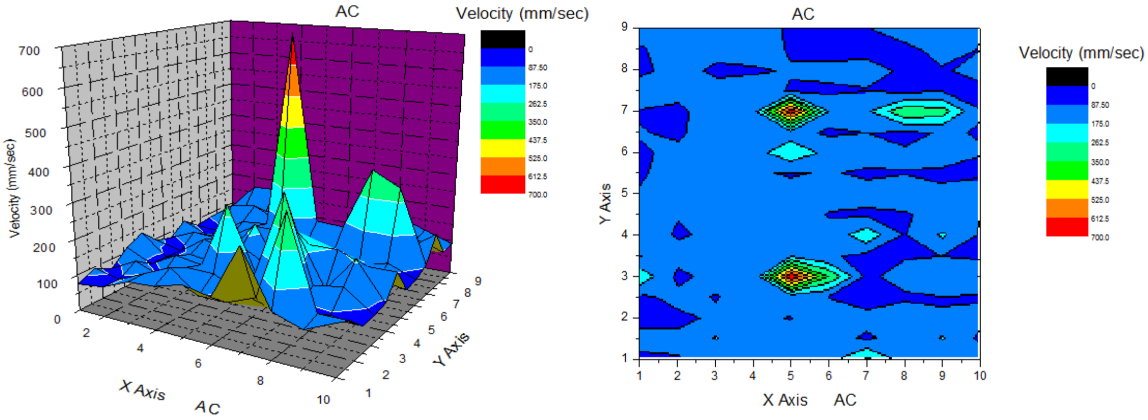

Figure 20. Velocity variation in test room 2 for condition 2

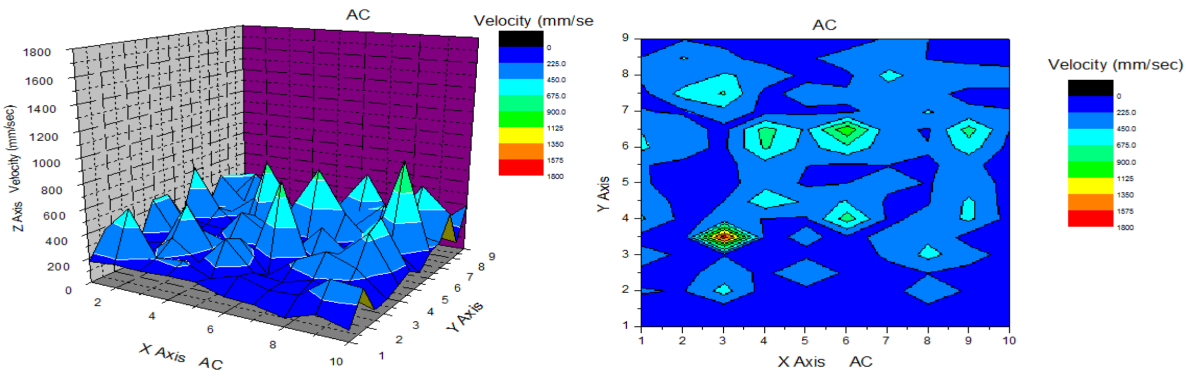

Figure 21. Velocity variation in test room 2 for condition 3

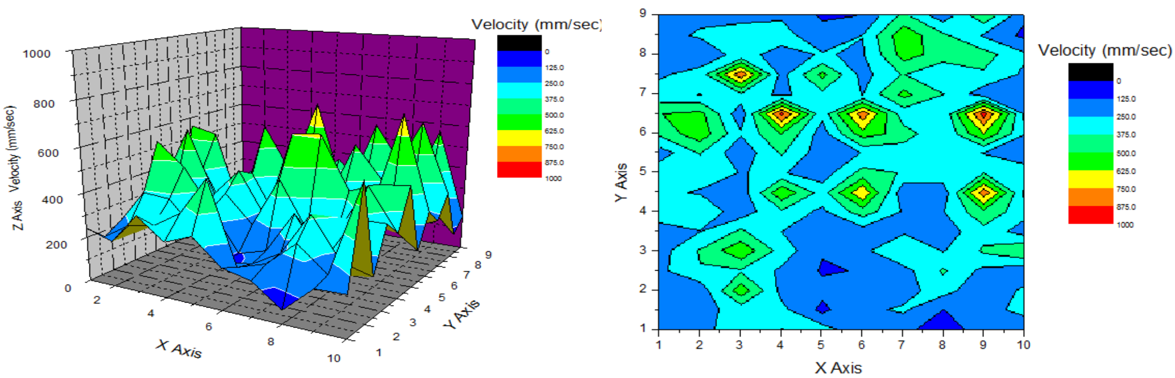

Figure 22. Velocity variation in test room 2 for condition 4

4.3. Thermal comfort quantification

At every observations the metabolic activity had been kept constant i.e. 1 met (58.7 W/m^2). Also the responses from individual were recorded as per ASHRAE thermal sensation scale [1] and it is indicated by 'Y'. For calculating the responses we choose the correlation of 1 hour exposure period for men as per ASHRAE, given as;

$$Y = 0.220t + 0.233p - 5.673 \qquad (1)$$

Where,

t = dry-bulb temperature (^{0}C), p = vapor pressure (kPa)

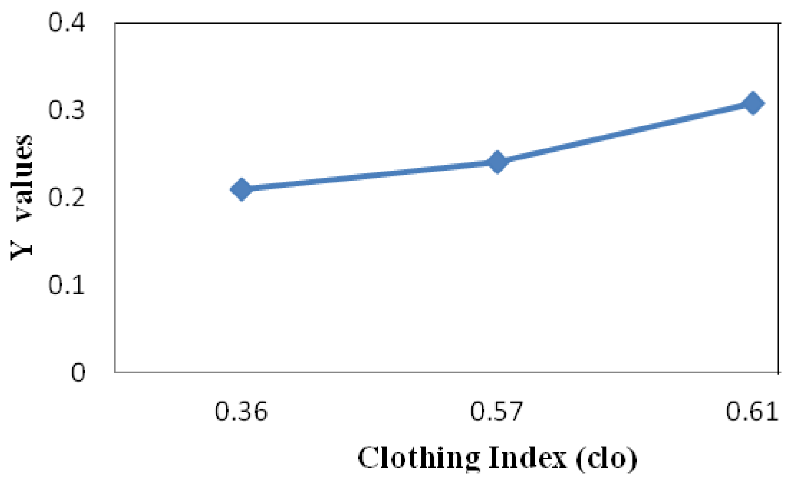

Figure 23. Variation of clothing index with ASHRAE thermal scale (Y values)

Variation of Y (ASHRAE thermal sensation scale) with clothing index (clo) is shown in Fig. 23 which depicts that by increasing the clothing resistance from 0.36 clo to 0.61 clo there is increase in Y from 0.1 to 0.4. It can be said that for the choosing clothing resistance there is not much variation was observed in the thermal comfort. In most of the feelings were comfortable.

V. CONCLUSIONS

It was observed that the most uniform pattern of temperature as well as velocity observed when both fan and AC kept ON condition. It was recommended that lower fan speed provides better air flow pattern which mainly depends on the location of the air conditioner. Room air flow pattern of the test room 1 was well matched with the flow pattern, generated through the smoke pattern. Thermal comfort depends on the clothing resistance and activity level. It can be concluded that room air flow pattern cannot be standardized, it is quite subjective and situation dependent.

ACKNOWLEDGEMENTS

I am extremely grateful and deeply indebted to my beloved Guide, Dr. Neeraj Agrawal, for his excellent guidance and whole hearted involvement during my M. Tech work without whose invaluable suggestions, versatility and untiring guidance. I sincerely and gratefully acknowledge Dr. P. K. Brahmankar, head of the mechanical engineering department, and all other teaching and nonteaching staff of university for their kind co-operation and permission to utilize the facilities available in the institute for my research work.

I wish to thank my all friends for their encouragement and time to time help for my project work. Last, but not the least, I express my heartfelt thanks to my parents for their love, patience, sacrifices and providing a favourable environment for the completion of the project work.

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