Impact of Radiant Asymmetry of Thermal Comfort

Comparison of real data with simulated data

VAMSHI GOOJE

Thornton Tomasetti, Portland, Maine, USA

ABSTRACT: Daylighting is a desirable space quality that enhances occupants' comfort and productivity. To facilitate this enhanced spatial experience, the perimeter zones are made narrower and fenestration area is optimized for daylighting and energy use. This brings the occupants closer to the windows and may result in thermal discomfort due to radiant asymmetry, if appropriate strategies are not adopted. Most energy analysis and thermal comfort tools typically overlook radiant asymmetry in a space. In commercial applications, due to time constraints, thermal comfort calculations are based on average space air temperature rather than operative temperature. This results in calculations, in which each surface is assumed to be of uniform temperature, and each thermal zone is assumed to be of uniform temperature. Under real world conditions, many surfaces may have non-uniform temperatures and occupants may experience some degree of radiant asymmetry. This research is focused on thermal comfort as a result of radiant asymmetry in a space. An actual data set from an Adobe house at Carefree, Arizona is used in validating the simulation output. The validated outputs from the simulation program have been used to create thermal comfort model. Fanger's PMV-PPD model is used to study the impact of radiant asymmetry on human comfort. This research emphasizes the need in the green building industry to focus on the effects of radiant asymmetry on thermal comfort in lieu of average space temperature. A holistic approach in designing spaces with thermal comfort needs of most occupants is key to achieving a successful high performance building.

Keywords: Radiant asymmetry, Thermal comfort, Energy Simulation.

INTRODUCTION

Building performance could be analysed either by installing thermal sensors or by simulating the appropriate conditions. The former process would consume precious time and money for the instrumentation and data acquisition. Whereas Simulation tools, for its precision and relatively short period of predicting results, are increasingly playing crucial role in the field of building design; be it at preliminary design stage or for retrofitting purposes. Depleting natural resources and uncertainty in the economy makes simulation inevitable in the energy analysis. Certain decision-making should be incurred at the formulating stage and the utility stage of simulation to avoid unpredictable uncertainties that may arise later.
The future probabilities are mostly non-linear functions; hence a definite model cannot be prepared for future predictions. There are many energy analysis tools floating in market each of them having their own merits and demerits in modelling and output.

COMFORT VARIABLES

Conduction, Convection and Radiation are the three modes of heat transfer. Radiation, in this typical case, is a major factor altering the human comfort in the building. Operative temperature, the comfort variable in the model under study, is average of Mean Radiant Temperature and the temperature of air.

$$T_o = (T_{mrt} + T_a)/2 \quad [1]$$

To= Operative temperature
Tmrt= Mean Radiant Temperature
Ta = Air Temperature

From equation [1], two inferences could be drawn. Firstly, Convection plays an important role where the building uses conventional forced air HVAC system to control the temperature. The air is distributed inside the enclosure at a predetermined ACH (Air changes per hour) according to the thermostat setting. This circulating air takes the heat from the surroundings to get down to the desired comfort temperature. Secondly, Radiation plays a crucial role in passively cooled/heated heavy mass residences or the residences using radiantly cooled/heated system. Studies conducted by the American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE) indicate that with radiant heating systems people can be comfortable at temperatures 6°F to 8°F lower than with convective systems.
Radiation is transfer of energy from one body to another in the form of electro-magnetic waves. Stefan-

Boltzmann law governs Radiative heat transfer between bodies:

$$P=e\sigma A(T^4-Tc^4)$$

P= Radiated power
e = Emissivity
σ = Stefan-Boltzmann constant = 5.67 x 10 –8 W/m2K4
A = Radiating area
T = Temperature of radiator
Tc = Temperature of the receiving body

Temperature distribution on surfaces

MRT is a function of surface temperatures and the view factor. Hence surface temperatures become a significant comfort-controlling factor. Comfort could be achieved by controlling the surface temperatures inside a building. As mentioned earlier, most of the simulation tools assume the surface temperatures on a wall to be uniform. A three dimensional conduction of heat makes a stratified temperatures over a surface. The other factors are surface area seeing the sun through the day, Ground reflectivity, Position of windows and Distance of the reference point from the ground. MRT has been simplified by taking view factors just across one plane instead of a solid angle for our understanding. It could be observed from Figure 1 that stratified conditions, either vertically or horizontally across the wall, might potentially alter the MRT. Even a difference of 2-3 **Δ**F in the overall computation of operative temperature would have a significant impact on the cost of running active system.

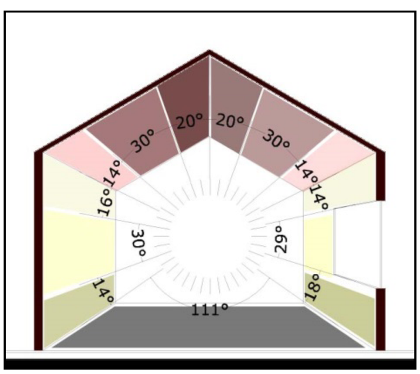

Figure.1: View factors for calculation of MRT

CASE STUDY

This ASHRAE funded project in Carefree, Arizona, is a high-mass adobe residence with insulation on the exterior and radiant panels in both the ceiling and the floor supplied by a hydronic source. The house is a single story slab on grade of approximately 2500 sq. ft. (250 m2), with 14"(0.30 m) adobe exterior walls and sloping roofs without attic space.

The control strategy has been designed to use the mass in walls and floor for thermal storage so as to keep the spaces within the comfort envelope while using the minimum amount of on-peak energy. The residence is divided into 3 zones, east, centre and west. The highlighted zone (west zone) in Figure2 has been simulated for the study.

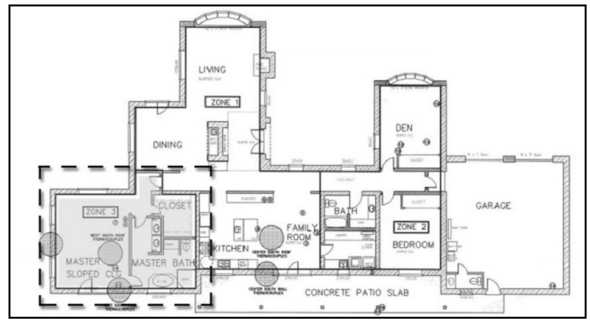

Figure2: Plan showing simulated zone (highlighted)

DATA ACQUISITION

Apart from the existing instrumentation, new set of thermocouples was installed as shown in the Figure3 to get surface temperatures at different points on the wall. A total of 42 data points have been fixed. Out of these, 24 were on walls, 4 on windows, 8 on ceiling and 6 on the floor. Data from one thermocouple on the west wall has been abandoned, as there was erratic data due to short circuit in the module. A program designed in Labview™ by Bruce Steele of Arizona State University (ASU) was used to collect data incessantly for ten days. The data was collected during passive performance of the house when the average of outside maximum and minimum keeps the operative temperature inside the house within comfort zone.

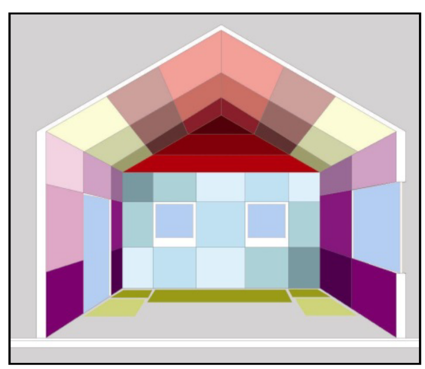

Figure3: Thermocouples are located on each of the shaded panels

In other words, the radiant cooling system was not running. Data through May 19th – May 28th has been collected. Only the data from May 22nd and 23rd have been scrutinized since the transient solution in the simulation would take 2-3 days to reach the real condition in taking mass effects into consideration.

SIMULATION

Radtherm™, a thermal modelling program that predicts the full temperature distribution, is used to compare and validate the data acquired from the case study house. It could accurately simulate the surface temperatures of building components using the three modes of heat transfer for both steady state and transient conditions. It is capable of seamless integration with Computational Fluid Dynamics (CFD) results from major CFD applications, such as Fluent, Star-CD, and Vectis. This program has been extensively used for the thermodynamics in mechanical engineering purposes. There has been constant updating of the program to cater to multi-disciplinary fields.

Weather file

A customized weather file is created from the climatic data available from Carefree. The weather file requires input such as solar radiation, wind speed and direction, air temperature, humidity and cloud clearness factor. Some of the data that was not available from Carefree, AZ, was interpolated from the Phoenix weather file, which is approximately 5º F warmer than Carefree. The sky temperatures are put to modelled condition, as there was insufficient data on the same.

Model

Radtherm™ imports 3d faces, which have to be meshed into quads. The surfaces are not shown thickness. At most, three layers of different materials could be assigned to a surface. The adjacent surfaces need to have common vertices in order for conduction to take place between them.

The simulated zone has been thermally disjointed from the other zones to simplify the parameters. The partition that is isolating west zone and the others is modelled as an adiabatic wall. The terrain of the model is extended approximately 25 ft (8 m) beyond the perimeter of the interior floor so as to facilitate multi bounce radiation from the ground. On the same lines, the east wall has been extended to north as seen in fig 4.

Terrain around the building has been attributed with typical desert soil conditions. Adobe walls are modelled as 3-layer section with polyurethane foam sandwiched between masonry. The roof section containing 9 different materials in section has been mimicked as 3-layer section. The floor is given properties of 4” (0.10 m) concrete slab with granite surface. The insulation around the perimeter of the floor, which protects perimeter heat loss/gain, is overlooked due to limitations in the modelling program.

Some of the limitations could be enumerated as follows:

a. Infiltration of air inside the building is ignored.

b. Schedule for occupancy, lighting and opening which plays crucial role in imitating real interactive conditions cannot be assigned.

c. Any kind of active systems cannot be simulated, which limits this study to thermal behaviour of the building.

d. The output data is in a raw format, which has to be manipulated to get the desired variables such as mean radiant temperature or operative temperature in this example.

ANALYSIS

A temperature differential (henceforth would be addressed as ΔT) of 3-4º F is observed over a surface from the actual data. The ΔT on one surface was found to be approaching zero in the morning and was increasing as the day passed away. The same phenomenon was not observed on north wall, which had same ΔT among different points on the wall surface throughout irrespective of time of the day. The direct radiation is uniformly distributing the temperature on the surface as the sun is moving along its path, and the energy stored in the walls as heat is dissipated later to the cooler surroundings and the contiguous walls. The 3-dimensional conduction, governed by ‘Fourier’s law’, between the wall receiving direct radiation and the others is giving a stratified condition in the process of achieving thermal equilibrium. There is more stratification in the vertical direction compared to horizontal stratification. The 4 ft (1.2 m) overhang on all the external walls has reduced ΔT between the top two vertical elements. Despite the shading provided, the top nodes along horizontal are warmer than the lower ones. The heat transfer from roof to walls and walls to floor is causing this thermal behaviour.

On the floor, a 5º F ΔT is observed. The surface closer to the south French window and which is seeing more sun than the others is warmer. The temperatures start rising at around 7:15 AM and starts dropping at 9:00 PM.

There is a substantial temperature difference between ‘sim 2’ and the ‘actual 2’ (Figure5) in the mornings. This double pane low-e coated glass could not be given appropriate material properties due to limitations in the program. The owner of the house, to let in fresh air, opens the windows every morning at 5:30 AM for about an hour or so. This causes a rise in the temperature at that time of the day (refer Figure5), which is not observed on the profile from the simulation output because of the incapability to assign schedules to the openings.

The vertical stratification from simulation has not shown similar results as that of actual data in magnitude. When roof temperatures and the south wall temperatures were compared, it showed that the heat flux from roof to wall (simulation output) is less, compared to the actual data. Discounting the differences observed in actual data to simulation, Operative temperature has been calculated manually in a spreadsheet both for stratified and unstratified conditions.

Figure 6 shows the plot of operative temperature, where the actual data represents the simplified and uniform temperature conditions while the simulation represents the operative temperature derived from non-uniform conditions. The deviation of the operative temperature in stratified condition establishes that the more surfaces included in the calculation of Mean radiant temperature would increase fluctuation. In simulation output, Operative temperature that rises above the comfort band after 12:00 AM and drops below the band at 3:00 AM could be appropriately moderated by intervention of proper passive strategies.

CONCLUSIONS

There is a significant concurrence in the trend lines showing stratification along vertical plane and horizontal plane, discounting the deviation in the roof temperatures from the simulation. Specifications for the roof has to be revised to mimic the actual roof properties, which would substantially, bring closer the trend lines from simulation to actual data. It could be inferred from Figure 6 that the comfort zone could be expanded to a degree or two without causing any discomfort. EnergyPlus™, a high-end energy analysis program will be used to explore this case study. Comparatively, this program offers more flexibility in manipulation of parameters. Furthermore the calculation of MRT or Operative temperature would be replaced by simulating a reference point as fluid particle and analysed for its proximity to the calculated temperature.

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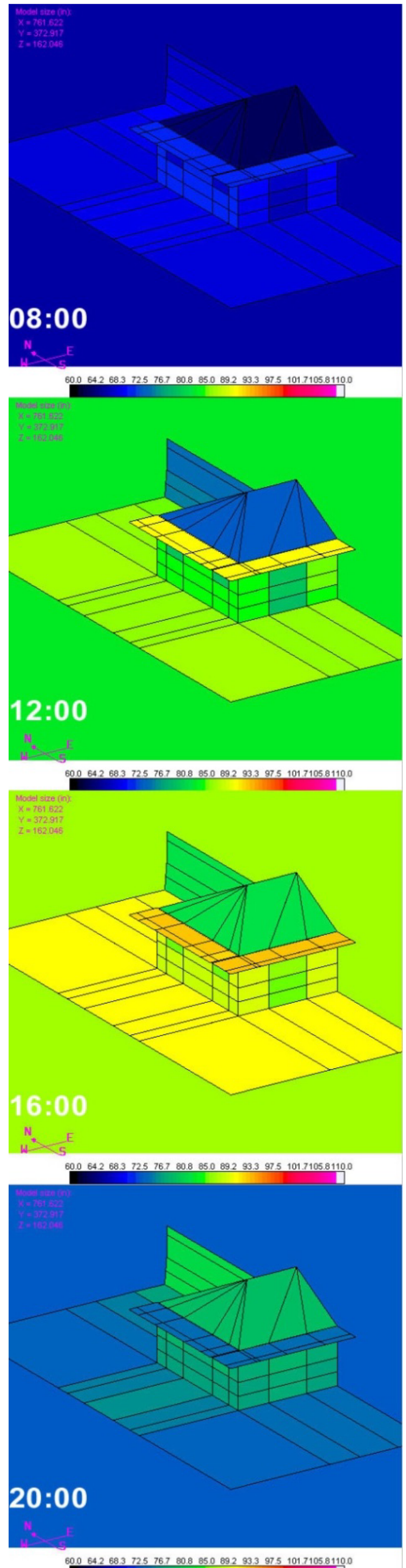

Figure 4: Snapshots from Radtherm™ for May 23, 2003 showing the temperatures on different surfaces.

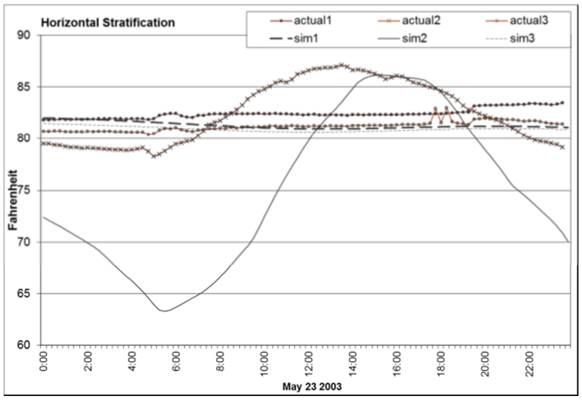

Figure 5: Horizontal stratification of temperatures on south wall– Actual data vs. Simulation data

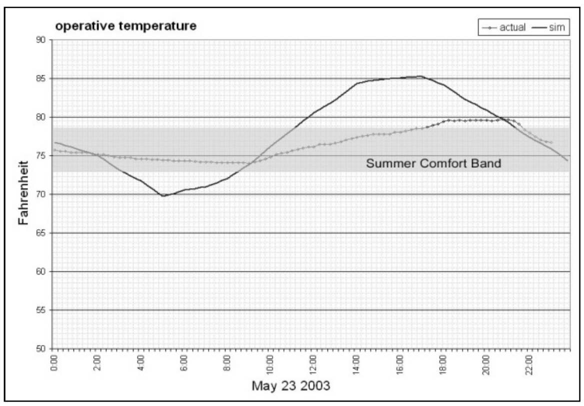

Figure 6: Operative temperature: Actual (uniform condition) vs. Simulation (non-uniform condition)

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