Comfort in the Science Garden

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ABSTRACT: This paper presents methods developed to predict comfort in an indoor-outdoor courtyard and describes the comfort conditions, adaptive comfort strategies and architectural opportunities identified for use in renovating an historic building. As part of a new school in Los Angeles by Morphosis Architects, the parade ground of the adjacent armory building was opened to the sky and renovated as a hands-on science garden including a bamboo grove, water features, heavy mass walls and overhead trusses. Since the courtyard is neither an outdoor space nor an indoor space, exterior climatic conditions can be both mediated and exaggerated. The predictive methods developed addressed the impact of the geometry of the courtyard, the orientation and size of the roof opening, the introduction of a bamboo grove and water features, and the presence of heavy mass walls, both shaded and receiving solar radiation.

Keywords: comfort, climatic design, modelling, simulation, courtyard

1. INTRODUCTION

As part of the new Science Center School in Los Angeles by Morphosis Architects, the parade ground of the adjacent 1912 State Armory building was redesigned to house an open-to-sky atrium. Now called the Big Lab, this courtyard houses hands-on science learning activities for school children, teachers' workshops and pubic events.

Figure 1: Aerial view of school and the open to sky courtyard in the attached armoury building to the south.

Courtyards and open atria pose a thermal comfort challenge in temperate climates because the horizontal opening to the sky admits the most sun during overheated summer days and allows unwanted heat loss to the night sky during cool, clear winter weather. The authors were asked to predict annual comfort conditions in the courtyard to inform the exhibit design and to assist with scheduling the use of the garden. If the courtyard remains within the "modified comfort zone" [1], then personal and architectural means could mediate periods of discomfort and the courtyard could remain unconditioned and connected to the outside.

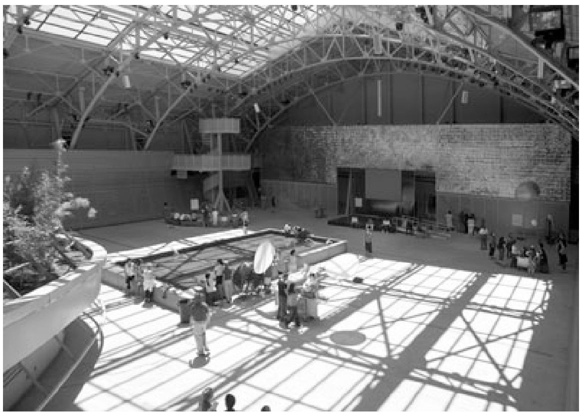

Figure 2: The courtyard interior looking southeast from the bamboo grove.

The accepted standard for thermal comfort in the United States is Standard 55 published by the American Society of Heating, Refrigeration, and Air Conditioning Engineers (ASHARAE). [2] Standard 55 defines the conditions in which a specified percentage of the occupants of a space will find their immediate environment thermally acceptable and is used to design and evaluate thermal comfort in mechanically conditioned closed building spaces. The indoor-outdoor conditions of the courtyard will not be controlled to a narrow range of comfort by mechanical systems, but at the same time the occupants are likely to tolerate a wider range of thermal conditions.

Our task was to develop a methodology that could quantitatively predict the thermal conditions in the courtyard, describe the patterns and extremes, identify the potential for non-mechanical strategies for mediation and indicate possible adaptive mechanisms to help keep the occupants comfortable throughout the year.

To predict comfort conditions in the science garden, we first modelled the complex sun and shade patterns within the courtyard. Thermal simulations predicted the temperature and humidity conditions in the courtyard. These results were evaluated with a bioclimatic chart to identify general periods of comfort and discomfort and identify the potential means of mitigating discomfort.

To describe localized comfort conditions within the courtyard, solar radiation and mean radiant temperature (MRT) calculations were developed for four areas in the courtyard. Coupled with relative humidity and temperature, the solar radiation and MRT factors enabled us to develop a descriptive narrative of the seasonal and diurnal comfort conditions for each area. For each of these, strategies for personal and architectural adaptive comfort in each of the areas were identified and described.

2. SUN AND SHADE PREDICTIONS

Understanding the sun and shade patterns of the two-story semi-indoor, semi-outdoor space was crucial for local comfort calculations. Additionally, the exhibit designers needed to know the patterns of direct beam radiation to locate activities such as a media wall, a giant sundial and an eco-pond. A three dimensional CAD model was developed and imported to a rendering program which used accurate latitude, longitude and orientation data to simulate the sun and shade patterns. Shadows were simulated at three minute intervals for the full daylight hours of the equinox, winter and summer solstice dates. These results were presented as hourly still images for the three days and as animations to understand how the sun and shade patterns move throughout the courtyard space. The shade patterns (in stills and in animation) were developed as perspective views looking toward the northeast to see the bamboo grove (Fig 3) and looking toward the southeast to see the sun and shade conditions on the large wall at the south side of the courtyard (Fig. 4).

Figure 3: Sun and shade simulation. Perspective view looking northeast at 2:00 pm on the equinox.

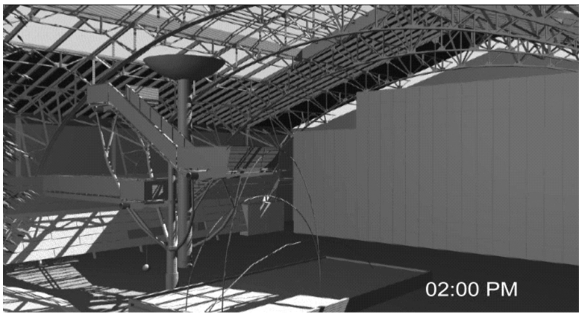

Figure 4: Sun and shade simulation. Perspective view looking southeast at 2:00 pm on the equinox.

The shade patterns were also developed in plan (Fig. 5). This view is rendered as a perspective plan viewed from above as though the roof has been removed in order to see the sun and shade conditions on the east and west mass walls and the big wall on the south. As can be seen in the rendering, the shadows are accurately cast including the partial roof the trusses.

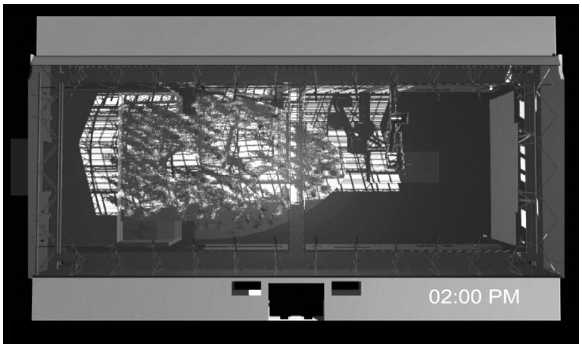

Figure 5: Sun and shade simulation. Plan view at 2:00 pm on the equinox. (North is to the left.)

3. THERMAL SIMULATIONS

Thermal simulations predicted hour-by-hour temperature and relative humidity conditions within the courtyard based on Typical Meteorological Year (TMY) data. The closest available TMY data for the Los Angeles International Airport was compared with data from a National Oceanographic and Aeronautic Administration (NOAA) weather station located close by at the University of Southern California. The comparison indicated that the TMY data was within 2-5 degrees of the armory site and was a close match in terms of daily temperature swings, percent relative humidity patterns, precipitation and sky condition. This means that our predicted conditions would be a bit cooler than the real space.

Hour by hour DOE2.1e simulations were run for the same four days that the sun patterns had been modelled: December 21, March 21, June 21 and September 21. The initial runs included the architectural geometry and materials of the courtyard. Additional factors in the thermal performance were researched to understand their potential impact on the microclimate conditions. These included the effects of water evaporating from the ponds, transpiration from the large grove of bamboo and the air movement within the courtyard compared to the exterior wind speed and direction in the TMY climate data.

The effect of the open pools of water was modelled using US Department of Energy software developed for predicting water loss and resulting temperature and humidity levels from outdoor and indoor swimming pools. [3] Open water will evaporate in a predictable manner that is affected by the local climatic conditions. We found that the pools will lower the temperature and increase the relative humidity of the overall courtyard, but by a very small amount due to their relatively small size within the large garden.

Empirical data shows that the transpiration effects of even significant vegetation in courtyards is negligible. [4] The main impact of the plants in increasing humidity is the act of watering and, most importantly, the actual method of watering. Watering through drip irrigation is likely to have no effect in increasing overall relative humidity in the courtyard. If watering is accomplished with a sprinkling or misting system, there will be an immediate effect during the watering of raising the humidity level and lowering the air temperature in the surrounding space.

Most courtyards exhibit a lack of air motion even when there is wind on site due to the protective wind shadow effect of the surrounding walls. This is further exacerbated by the pooling of cool air at the bottom of the courtyard (stratification). On-site observations during construction confirmed these conditions in the courtyard.

The interior temperatures and relative humidity conditions calculated with DOE2.1e track the exterior climate data closely, generally falling within a single degree of temperature and a single percent of humidity. The courtyard remains slightly warmer than exterior conditions during the night and slightly cooler during the middle of the day.

4. BIOCLIMATIC COMFORT EVALUATION

The courtyard temperature and humidity conditions are only a first step toward understanding the comfort of courtyard occupants. The hourly conditions were graphed for each of the four seasons on bioclimatic charts [1] to characterize the thermal comfort in the garden. The bioclimatic chart was also used to identify potential factors that could mediate the comfort conditions toward the comfort zone -- specifically air movement, shade, additional radiation, additional water vapor and MRT (surrounding surfaces warmer or cooler than air temperature).

4.1 Typical courtyard comfort conditions

Typical March conditions in the courtyard cluster between 55^{o}F to 60^{o}F (12. 8^{o}C to 15.6 ^{o}C) and 70% to 90% relative humidity (RH). This means that 100 to 200 Btu/h (150 to 300 cal/h-m^2) of radiation would bring the conditions into the comfort zone, but that simply increasing the MRT would be unlikely to achieve the same degree of comfort.

June conditions in the courtyard are warmer, with the daily range between 65^{o}F and 78^{o}F (18.3^{o}C and 25.5 ^{o}C), the RH between 63% and 88%. Daytime hours in June require shade for comfort in the courtyard, while night hours would require a minimal 50 Btu/h additional radiation or a MRT of 73^{o}F (22.2^{o}C) to feel comfortable. September temperature and %RH conditions in the courtyard are identical to June.

In December, courtyard temperatures range from 50^{o}F to 68^{o}F (10^{o}C to 20^{o}C) and the %RH swings broadly from 25% to 98%. During the afternoon hours, an increased MRT up to 75^{o}F (23.9^{o}C) or some additional radiation of 50-100 Btu/h (75 to 150 cal/h-m^2) would provide comfort. During morning and evening hours, additional radiation of up to 250 Btu/h (375 cal/h-m^2) would accomplish the same.

4.2 Extreme climatic conditions

When the typical conditions for each season are graphed, comfort can be provided in the courtyard by slightly moderating the surrounding surface temperatures and the existence of shade. However, the Los Angeles climate cannot be entirely characterized by the typical conditions, even those found in the TMY tapes. Recorded extremes for both the LAX and the USC NOAA sites demonstrate that in December the high temperature can reach over 90^{o}F (32.2 ^{o}C) and can sink to below freezing. June has a record high temperature of over 100^{o}F (37.8^{o}C) and a recorded low temperature of 48^{o}F (8.9^{o}C).

Summer high temperatures can reach over 110^{o}F (43.3^{o}C) in June through September and even during the winter, the high temperatures are recorded over 90^{o}F (32.2^{o}C). These high temperatures are usually a result of the Santa Ana phenomenon, a 3-5 day event in which winds normally arriving off the Pacific Ocean are reversed and blow from the California desert areas such as Death Valley and the Mojave. These heat storms are accompanied by conditions of extremely low relative humidity, generally between 5% -10%.

These extremes, both winter and summer, are as important as the typical conditions in terms of courtyard comfort. According to the bioclimatic chart, the winter extremes will require a means of supplying radiation during night hours (when the sun is not available), in addition to whatever increased MRT is possible. The summer highs require shade, air movement and additional water vapor or evaporative cooling in order for the courtyard occupants to remain comfortable.

5. LOCALIZED COMFORT IN THE GARDEN

Beyond temperature and relative humidity, comfort in a specific location can be affected by MRT, solar radiation and air movement. [5] These two comfort factors were calculated hour by hour for four individual locations within the courtyard because they vary significantly depending on the exposure to sun and shade patterns.

5.1 Solar Radiation

Intensity of solar and sky radiation is an important comfort factor and is not described in the sun and shade patterns modelled with the 3D program. Using the TMY data and the DOE2.1e simulations, we calculated the incident solar radiation within the courtyard. These calculations included local climatic effects, such as cloud cover and turbidity, and the building geometry. The radiation intensities, coupled with the sun/shade patterns, were used to evaluate the effect of solar radiation (increasing or decreasing comfort) for a set of seasonal comfort narratives developed for each location.

5.2 Mean Radiant Temperature (MRT)

The thermal model then was used to calculate how much of the radiation was absorbed by the surrounding building mass and floor. This was used to calculate the final surface temperatures and MRT for each of the four locations. Mean Radiant Temperature is an area-weighted average of all the surface temperatures in a space, and is affected by the relative position the body in relation to the various surfaces. "The mean radiant temperature in relation to a person in a given body posture and clothing placed at a given point in a room, is defined as that uniform temperature of black surroundings which will give the same radiant heat loss from the person as the actual case under study." [5] MRT is important for comfort as it takes into effect one of the most significant thermal exchange mechanisms for the body. To calculate MRT we developed new software to calculate the individual view angle of all exposed surfaces according to a protocol established by ASHRAE.

5.3 Combined effects in four locations

The combined effect of temperature, surface temperatures and solar radiation were best expressed by charting those factors over the 24 hour day for each location in the courtyard and for each season. For example, in Fig. 6, the conditions for a June day are graphed.

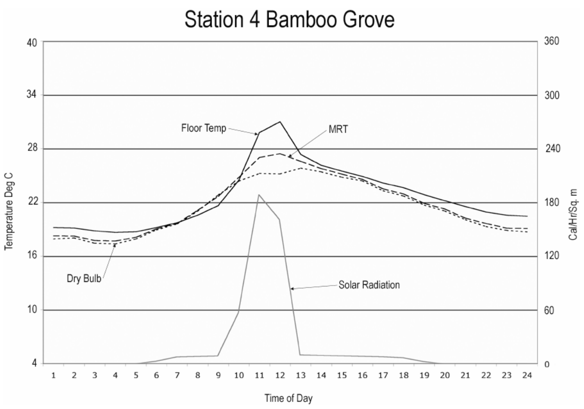

Figure 6: Typical conditions of temperature, surface temperature, MRT and solar radiation for a June day in the bamboo grove.

6. COMFORT NARRATIVES

Climate and comfort are characterized by a large amount of variation and detail, which is reflected in the graphic data generated for this project. However, for the results to be useful for the exhibit designers and the building owners, detailed narratives for each season and for the four locations within the courtyard were developed.

For each season, a description of the typical diurnal comfort conditions, based on the courtyard data graphed on the bioclimatic chart, is followed by a description of potential extreme conditions and an analysis of the four specific locations within the courtyard. Suggested strategies for achieving comfort, both in terms of personal adaptations and architecture are included. A final section for each season identifies extreme weather conditions and strategies for achieving comfort under those conditions.

6.1 Typical Seasonal Conditions

The narrative for “A Typical Spring Day (March)” includes the following descriptions: “Late winter and early spring days and evenings are typically cool and moderately humid, with temperatures ranging from the mid 50's to the mid-60's in March (12 ^{o}C to 18 ^{o}C). Conditions are similar in February and climbing into the low 70's (22 ^{o}C) during April and May. The temperature swing from day to night is moderate, usually less than 10 degrees both inside and outside of the Garden. All hours from 8 am to midnight will require some additional radiation to move into the comfort zone. As a result, during daytime hours, being in the sun will tend to be more desirable than being in the shade and the sun penetration into the courtyard becomes a thermal asset for the occupants. After sunset, around 6 pm, other means of providing heating will be required.

“March, like February, April and May, has clear skies for just under half the days of the month, with the remaining days evenly divided between partly cloudy and cloudy days. The sun shines about 75% of daylight hours, with low clouds and possibly fog usual for nights and mornings. On cloudy days, solar radiation will be felt minimally. March is typically the last month of the rainy season, and receives about 3 inches of rain over the month, much like January and February. The maximum precipitation recorded for March is over 8 inches (20.3 cm). There are usually about 6 days in the month on which rainfall is measured.”[6]

6.2 Extreme Seasonal Conditions

For each seasonal day, a narrative was also developed for extreme seasonal conditions for the courtyard overall based on NOAA data from the TMY tape and the USC weather station. Here follows the narrative for March:

“Although the data historically indicate March is a cool month, recorded high temperatures are much hotter than and recorded lows are definitely cooler than typical March weather conditions. At the USC Weather Station, the highest recorded temperature in March is 98 degrees F (36.7 ^{o}C), nearly 40 degrees F (22 ^{o}C) hotter than typical March highs predicted for the courtyard. The mean of the recorded maximum temperatures, which is likely to be a better indicator of the extreme to be faced in any given year, is still a hot 84 degrees F (28.9 ^{o}C). Even with the moderating conditions of the courtyard, these temperatures will remain in the 80's and 90's Fahrenheit (26 – 36 °C) during mid-day hours. These extreme conditions are similar in February and even hotter in April and May.

"The courtyard should be prepared to provide places of cooling for short duration high temperatures, such as experienced in an unseasonable heat storm that might last two or three days. This would mean using those adaptive opportunities, which are most easily deployed on short notice. It is important to remember that unseasonable high temperatures will be experienced as even hotter and more uncomfortable than normal and the more visible the relief that is provided, the more comfortable the occupants will feel.

"The low temperatures do not present quite as serious a challenge as the highs because they are not far out of range the modified comfort zone which simply requires additional radiation. An evening event on a record cold day, however, would face the challenge of keeping people warm below 40 degrees Fahrenheit (4.4 °C). In this case, warm radiant surfaces and radiation barriers to the night sky for clear skies would be the most strategic approaches."

6.3 Local comfort narratives

For a local condition, the narratives were developed from the graphs of temperature, MRT, surface temperatures and solar radiation, coupled with the bioclimatic graphs described above. The graph in Fig. 6 describes the conditions in the bamboo grove on typical June day. The Narrative is as follows: "The location in the grove receives solar radiation for almost three hours from 10 am – 1 pm (11 am – 2 pm daylight savings time). Coupled with increased local humidity within the grove and the proximity of filtered shade, this additional radiation is likely to be considered "normal" for the location and not perceived as uncomfortable unless physical activity is greatly increased."

7. ADAPTIVE COMFORT IN THE GARDEN

In the descriptive narrative that interprets the data for the designers and the users, we try to indicate occupant expectations as well as conditions. Brager notes [7] that "comfort is almost impossible to measure directly. As a result, scientists have resorted to measuring only the physical variables that influence a body's heat exchange with the environment, asking questions about thermal sensation (and sometimes preference), and then making *assumptions* about which of those sensations might be associated with satisfaction or dissatisfaction."

7.1 Adaptive comfort

The Adaptive Comfort Model developed for ASHRAE Standard 55 is based on extensive field studies, recognizes that occupant comfort is also affected by conditions which are harder to quantify than the six factors identified above. Some of these factors identified in the research are applicable to characterizing the courtyard conditions.

Occupant expectations related to conditioning capabilities can contribute to the determination of a comfort temperature. [8] People develop different expectations of comfort relative to whether the building is controlled by a mechanical system or "free-running" much like the courtyard conditions, with no mechanical conditioning and dependent on exterior weather.

There is also evidence that occupants learn to expect particular temperatures as appropriate to particular sorts of places (offices, theaters, churches, malls, homes, indoors vs. outdoors, etc.). [9] Those expectations are, of course, learned and not innate, and persons appear to be quite willing to tolerate quite different environmental conditions in different settings—as long as conditions are considered appropriate to those settings.

An additional aspect of occupant comfort depends on the "courtyard" factor. Unlike a sequence of interior spaces, a courtyard such as the science garden is unique in the building and immediately identifiable as a "separate realm". Courtyards, especially those with animated shadows, vegetation and water, create visual and sensory delight, which earns them much affection and wide comfort tolerances on the part of people who visit. "The courtyard can represent many things: an oasis in the desert of city streets, a fragment of nature … a center of interest for the building; a concentration of light, sounds and water." [3]

7.2 Personal adaptive comfort opportunities

The occupants of the courtyard hold powerful adaptive means of finding comfort when the space is too cool or too warm. The architecture, the vegetation, the exhibit and the operation of the building need to support these personal adaptations to the greatest extent possible, for in doing so the range of thermal conditions that will be considered comfortable can be broadened significantly.

Many occupants are likely to find their own level of comfort by adjusting their levels of clothing (putting on, buttoning up, taking off sweaters and jackets). As perceptions of comfort vary individually, the ability to select a location in the garden becomes key. Equally, increasing and decreasing level of physical activity (and related metabolic rates) can successfully respond to conditions outside the comfort zone.

7.3 Architectural adaptive comfort opportunities

Since people will tend to search out conditions that are comfortable, especially in an environment as thermally varied as the courtyard, we identified a set of design opportunities that would expand the potential for comfort throughout the year.

"Places of warmth" describes a strategy of making localized areas warmer than the ambient air temperature. These can include radiant surfaces such as the floor or walls. Traditional gardens have long used surfaces warmed up by the sun to counteract cool air. [10] Beyond the warm surfaces that result from the natural patterns of solar radiation, "warm benches" and "warm walls" could be installed for locations that are continually too cool during the winter and heated with solar hot water or electric resistance. Additional "*thermal aedicula*" can include small glass pavilions positioned to catch and trap incoming solar radiation and tents or pavilions made of radiant barriers to block heat loss through radiation to the night sky. The edge spaces under the overhang, an umbrella and an awning can all serve in this way thermally.

"Cool places" offer occupants a refuge from sources of heat or a means of reducing and exhausting their own heat. In the courtyard, shading would be the first and most necessary way of making a cool place. The bamboo provides shade in the grove and the side overhangs provide morning and afternoon shade, so benches can be placed to take advantage. A movable fabric awning that pulls across the courtyard, called a *toldo* and widely used in Spain, Mexico and South America, can provide large areas of seasonal shade, while smaller scale trellises, trees and umbrellas can all be used.

Air movement can be created locally using ceiling fans under the overhangs. Some parts of the garden, like the shaded mass walls, will be cooler than the air temperature during the day and provide radiant cooling. Other surfaces, much like the warm floor, benches and walls, can be cooled with chilled water to provide surface cool to the touch that lower the MRT.

Evaporative cooling, while partially provided by the bamboo grove and the water features, can be more emphatically and locally provided during the heat storm periods of low humidity. Fountains that create spray add delight and animation in addition to cooling, as do misters. Washing down surfaces such as the walls and floor can also effectively cool down the air temperature and provide added humidity for comfort.

8. CONCLUSION

Predicting comfort conditions and occupant response in an indoor-outdoor courtyard space involves a wide range of factors relative to the band of comfort conditions required in a mechanically conditioned space. The methodology used to predict the comfort factors was developed in response to the questions that we were asked to answer: 1. What are the patterns of solar radiation and shade within the courtyard and how do they change over time and throughout the space? 2. What are the conditions and experience of thermal comfort or discomfort within the courtyard over the course of the seasons and through the occupied hours of the day and evening?, and 3. What are strategies for achieving or improving the thermal comfort experience of the occupants?

Working with a wide variety of software, we coupled data from sun and shade animations, weather data and DOE2.1e thermal simulations with time and space maps of solar radiation and Mean Radiant Temperature calculations. Interpreting the results in narrative form allowed the designers and owner to understand the typical and extreme conditions that were likely to occur in the garden. By using Olgyay's bioclimatic chart to understand comfort conditions in the non-conditioned space, we were also able to identify non-mechanical responses to bring conditions closer to the ideal comfort zone. Finally, the climatic responses for comfort were described in architectural terms to allow the designers and owner to include climate modifications as required by the thermal conditions and occupants in the courtyard.

The courtyard was occupied in 2004 and the Big Lab is heavily used throughout the year for teaching and special events, including banquets and presentation ceremonies scheduled during the evening. We expect that as infrequent extreme conditions occur over the first decade of operation, small climatic and comfort modifications will find their place next to the hands-on exhibits, which would be an appropriate application of learned science.

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