VISUALIZING PEDESTRIAN COMFORT USING ENVI-MET

Akram Rosheidat[1], Dan Hoffman[2], Harvey Bryan[3]
1. Ph.D. Student, Environmental Design + Planning, College of Design, Arizona State University, Tempe, AZ, USA.
2. Professor, College of Design, Arizona State University, Tempe, AZ, USA.
3. Professor, College of Design, Arizona State University, Tempe, AZ, USA.

ABSTRACT

One of the environmental consequences of rapidly growing urban areas such as Phoenix, Arizona, is its negative impact to the outdoor environment. On the pedestrian micro-scale, the effects are difficult to visualize. Design decisions such as street and sidewalk widths, shading structures, materials, landscaping, building heights, and air flow have a significant impact on the pedestrian thermal comfort and subsequently on the use of the urban environment. This paper discusses visualization of human thermal comfort on the micro-scale, using various mitigating strategies that can create a more thermally comfortable pedestrian environment in downtown Phoenix.

INTRODUCTION

The City of Phoenix, Arizona, as other cities in the hot-arid American Southwest, is dealing with the lack of pedestrian activities in its downtown core. Currently, the downtown is largely a vehicular environment, and the pedestrian activity is almost non-existent on the exposed concrete sidewalks. To achieve a downtown that is more “lively, inviting and comfortable”, the current pedestrian-hostile urban environment has to be transformed to become pedestrian-friendly. Past research has typically focused on separate phenomenon analysis, such as wind and air movement in urban canyons (Oke 1988) and rarely on the combined effect of the various physical and climatic factors on human thermal comfort. However, since it has become apparent that urban geometry is a major factor in the urban heat island effect, by impacting air flows and mean radiant temperatures (Oke 1987, Golden 2004), the approach to this outdoor thermal comfort research became more interdisciplinary. The interface between the macro and micro scales is the urban street network which links the “parts” of the city, and where various civic activities and functions occur (Ali 2005). Some of the previous studies have shown that through an integrated approach, an acceptable level of thermal comfort can be achieved (Bryan 2001, Chalfoun 2001).

This paper describes the use of the ENVI-met climate model to help in making decisions about the design of urban spaces with enhanced thermal comfort in downtown Phoenix. The specific aim of the study is the simulation of the outdoor thermal conditions at a location between Monroe and Adams, 1st Avenue and 2nd Avenue in downtown Phoenix, Arizona. The paper’s goal is to enhance the understanding of outdoor comfort factors and issues in an urban desert hot arid environment which has the potential to reduce some of the downtown core vehicular traffic and induce people into more civic participation and outdoor activities.

OUTDOOR COMFORT:

Human thermal comfort is not easily quantifiable even in a controlled indoor environment. The outdoor environment is even harder to quantify as it includes multiple factors that affect the pedestrian and cannot be described using a single factor such as ambient air temperature. As argued by Jeffrey Cook outdoor comfort criteria cannot be compared to indoor criteria. The outdoor criteria should be benchmarked by different parameters, and the benchmark of the individual’s comfort level outdoors is much higher than the one for indoor environment (Cook 2001). Therefore, past outdoor comfort research usually cites a certain thermal index which combines a number of factors affecting comfort as a benchmark for the study. The critical factors for outdoor comfort may include air temperature Ta, relative humidity RH, air movement v, and mean radiant temperature MRT. However thermal comfort is also dependent on the person’s clothing CLO, activity level MET, psychological and other factors. The person is not actually experiencing the ambient temperature; instead the pedestrian’s comfort is affected by the heat lost/gained from the body. The general public’s typical misunderstanding is that the most important factor for their thermal comfort is the ambient air temperature. But, especially in outdoor conditions, MRT is as, if not more, important in the level of comfort. MRT and ambient temperature are interconnected to a certain extent; for example, a 1°F increase in air temperature can be counterbalanced by a decrease of 1.39°F in MRT (Emmanuel et.al. 2006). During the summer, in the hot-arid southwest Phoenix built up urban environment, most of the heat absorbed by a person standing in an outdoor space comes via the short wave and long wave radiation fluxes. Past research in this environment has repeatedly shown the dominant role of the mean radiant temperature (Bryan 2001). This fact alone indicates the critical importance of shading as an approach for attempting to reach an acceptable thermal comfort level in a hot arid setting such as Phoenix. Shading helps in a number of ways; it shields the pedestrians from direct solar exposure and reduces the temperature of the shaded surfaces, thereby reducing the radiative exchange with the pedestrian's body.

Furthermore, there are numerous unquantifiable factors affecting outdoor comfort such as the contrast in temperatures and time of exposure. Contrast is the concept that outdoor comfort is affected by moving from an extreme environment to a less extreme environment. So if a person is experiencing a large amount of heat gain standing in an exposed asphalt parking lot and moves into the shade of a tree, his/her feeling of comfort is improved by the contrast (Yoklic 2001). For the design of the outdoor comfort features at the EXPO 92 in Seville, the measure of outdoor comfort was set by the amount of a person's sweating. In fact, most of the evaluation studies for the various cooling subsystems designed were shown through graphs expressed through grams/hours of sweat (Rowe 1991). The human organism regulates its heat exchange with the surroundings by the amount of sweat produced. So ideally the comfort would be such that no sweat is produced.

The human energy balance (Fig 1) shows the various factors affecting human outdoor comfort. Out of these heat gain/loss factors, the most significant one is the total radiation, which can amount to up to half the total heat gain on the subject. On the other end of the spectrum is the ambient temperature, which accounts for only 7% of the heat gain (Rowe 1991). Therefore, lessening the exposure to and reducing the temperature of the surrounding surfaces (i.e., MRT) is the most effective means to achieve outdoor thermal comfort for pedestrians in urban spaces (Bryan 2001). This is especially true in hot-arid climates such as Phoenix, Arizona. The relative humidity is typically low (average 12%-15% from data collected by author in June 2007) which assists comfort by rapidly evaporating sweat. Allowing breezes (typically dry) will also assist in the swift evaporation of sweat and thereby aiding in improving the comfort conditions.

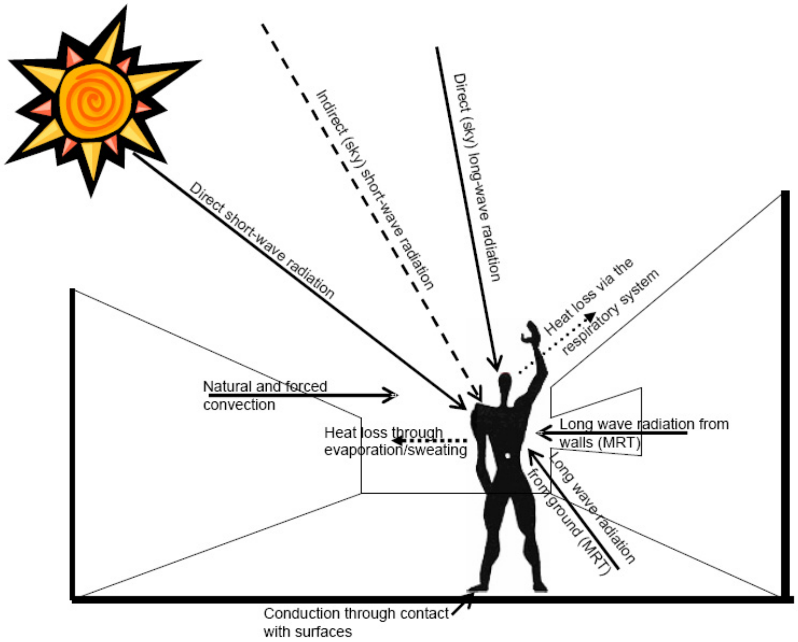

Figure 1: outdoor human energy balance.

LANDSCAPE:

Landscaping can have a significant effect on tempering the outdoor temperature. If used on a large scale it can even have a measurable effect in moderating the urban heat island effect (McPherson et al. 1994, Akbari et al. 1995, 2001). However, there are few studies on the effects of the vegetation on outdoor thermal comfort, especially within an urban context (e.g. Shashua-Bar and Hoffmann 2000). Vegetation contributes to the modification of urban climate in primarily providing shading, evapotranspiration and directing wind, either as a windbreak or as a wind funnel (McPherson et al. 1994). The most important property of the tree is its potential as a shading device. In this respect, the significant characteristic of the landscape element is its shape, volume and leaf density. Shashua-Bar and Hoffman, (2000) studied the tempering effects of trees in planted urban streets at various locations in a hot arid urban location. In their study, they found that the tempering effect of planted urban streets was about 1 -3 K. Their conclusion, which is repeated in other similar studies, is that the local cooling effect is ascribed mainly to the shading properties of the vegetation rather than to evapotranspiration. The vapor pressure measured within the vegetated areas was insignificantly higher relative to an adjacent non-vegetated area. This was justified by the lack of irrigation of the soil leading to low evapotranspiration rates (Shashua-Bar and Hoffman, 2000). Therefore, in hot-arid climates, the optimal use for vegetation is for its shading properties to abate the short wave solar radiation in the summer, in addition to blocking the long wave radiation coming off of the various surfaces. The tree's shade also reduces the materials' heat absorption and stored energy and thereby reducing the amount of radiation it emits back onto the street pedestrians. In a paper presented at the "Cooling Frontiers" Symposium at Arizona State University in 2001, 'Radiative exchange analysis between a tree and a west wall', Puja Manglani reports on her experiments focusing on the shade tree's role in lowering the surface temperature of a tree shaded wall. The tree is effective, not only due to blocking solar radiation, but also due to a radiative exchange between the tree and the surface of the wall. In her results, she found that at 3:00 pm in the summer the difference between an exposed wall (104 °F) and a shaded wall (84 °F) is 20 °F. The cooling effect of evapotranspiration is insignificant due to the rapid dissipation of any "cooler air" through air turbulence in a hot summer street (McPherson and Simpson 1995). Evapotranspiration is effective only in situations where significant irrigation occurs such as in agricultural fields. However, it also has a significant effect in residential areas with large areas of vegetation such as parks. There, the cooling effect of trees due to evapotranspiration can be up to 10°F (McPherson and Simpson 1995). In an urban context, the effect of the vegetation is dependent on the amount of the planted area as related to the urban built-up area. It is also dependent on the size and location of the tree, and on its LAI (leaf area index) and LAD (leaf area density).

Individual trees spaced with large intervals, as is usually the case in an urban street, do not have a significant cooling effect. Therefore, it has been recommended that it is more effective for urban sites to use several smaller groups of trees (McPherson 1992, McPherson et al. 1994). In a dense urban environment, trees can be located in various locations such as in rows along the sidewalks, in parking areas and at street intersections. However, in order to achieve these benefits of urban vegetation, we have to pay particular attention to the requirements of appropriately planting and maintaining healthy mature trees in an urban setting to produce the desired shading and cooling effects. Professor Chris Martin of ASU's Department of Applied Biological Sciences has put forth recommendations specific for factors influencing tree growth and health in the Phoenix urban core (Martin 2006). The main aspect that influences the growth and health of urban trees is the condition and scope of the tree's root zone. Tree roots need adequate air, water and space below ground (6" to 30" in depth) for health and strong growth. The root system of a healthy tree is 1 to 3 times larger in diameter than the tree canopy. If this space and access to air and water is not available (as is the case with most of the trees currently in the Phoenix urban core) tree roots will not grow and this results in shorter tree life spans, smaller tree crowns and consequently in less shading potential (Martin 2003, 2006).

SIMULATION PROCESS:

The ENVI-met software was used to simulate the impact of certain urban design strategies on thermal comfort at a location between Monroe and Adams, 1st Avenue and 2nd Avenue in downtown Phoenix. The ENVI-met software uses input values for buildings, vegetation, ground surfaces, climatic conditions, soils, and then simulates the modifications from the proposed building form, additional shading, alternative orientations, etc. ENVI-met is a three-dimensional computer model which analyzes micro-scale thermal interactions within urban environments. The software uses both the calculation of fluid dynamics characteristics, such as air flow and turbulence, as well as the thermodynamic processes taking place at the ground surface, at walls, at roofs and at plants. ENVI-met takes into account all types of solar radiation (direct, reflected and diffused) and calculates the mean radiant temperature. The calculation of radiative fluxes includes the plant shading, absorption and shielding of radiation as well as the re-radiation from other plant layers (Bruse 2007). In calculating MRT, ENVI-met takes into account all radiation fluxes, direct, diffuse and reflected solar radiation as well as the long-wave radiation fluxes from the atmosphere, ground and walls and is capable of producing MRT values for each cell of the model environment at varying heights above the ground surface (Ali 2005, Emmanuel & Fernando 2007).

ENVI-met has two basic steps before the simulation is run. The first is editing the input of the urban area to be tested. For this task, one needs the horizontal and vertical dimensions of the architectural environment along with any specific design features such as open breezeways, overhangs, horizontal surface materials, ground cover, vegetation size and coverage, etc.

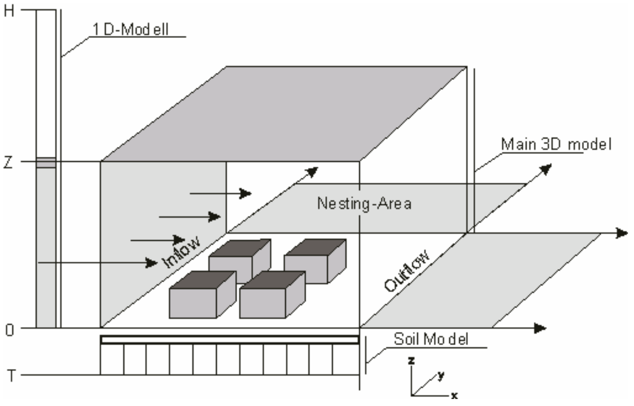

Figure 2: Basic layout of the fluid dynamics of the ENVI-met model. (Source: Bruce 2007)

The input is designed in a 3D setting where the buildings, trees/vegetation, and the various surfaces are placed. These elements are represented by various size grid cells. The smaller the cell is, the finer the resolution (as small as 0.5 meter). The cell area can be designated at any dimension from 0.5 meters to 10 meters. For example, a 100 x 100 meter area can be represented in a 100 x 100 grid cells of 1 x1 meters each, or it can be represented by a 20 x 20 grid cells of 5 x5 meters each, depending on the size of the test area and the desired resolution. To minimize boundary effects which may distort the output data, the model uses an area of nesting grids around the core of the model to move the model boundary away from the area of interest (Bruse 2007).

The second step is editing the configuration file, where the information about the site location, temperature, wind speed, humidity, PMV parameters, and databases for soil types and vegetation are entered. The simulation is then processed using both the input and configuration files. ENVI-met outputs binary files (.EDI/.EDT) which have to be imported into a visualization program - LEONARDO 3.0. Each output file has a multitude of information which has to be translated into different visualization layers. The following main layers are typically used to visualize the output data:

- Data layer: Displays continuous data (e.g. temperatures)
- Special layer: Displays singular data (e.g. buildings, plants)
- Vector layer: Displays vectors such as wind

Visualization is then configured to display the urban environment with the desired section of data cut horizontally (plan view), vertically (section view), or in a 3-D axonometric view.

SIMULATION LIMITATIONS:

ENVI-met however has certain limitations. The tools to create the urban environment are limited to buildings, soils/pavement materials and trees/vegetation. There are no tools to create any other objects such as shade structures independent of the building blocks. Another significant limitation is that the building blocks have no thermal mass and only a single constant indoor temperature. ENVI-met cannot simulate water turbulent mixing so the use of water strategies is limited to still water bodies. Therefore, ENVI-met is unable to simulate fountains or water spray type systems. Water bodies are inputted as a type of soil, and the processes are limited to the transmission and absorption of shortwave radiation (Bruse 2007). Furthermore, the albedo and thermal resistance of the building surfaces is constant and cannot be varied (Emmanuel & Fernando 2007). Therefore, to test for the effect of materials' mass characteristics the team used software called Radtherm, which is specialized in radiant heat transfer analysis software able to incorporate the materials' mass in its calculations.

MEASUREMENT:

The ENVI-met software requires climactic data input for the site being simulated. These inputs were collected at the site and used in lieu of typical meteorological year data. Collection of data was achieved in a series of sessions between May 2007 and September 2007. The climate stations collected the following data: dry-bulb temperature, relative humidity, solar radiation, wind speed, and globe temperature (MRT). Vertical and horizontal surface temperatures were collected using an infrared thermal gun. The measurements were taken on average between the hours 11:00 AM to 2:00 PM covering the time in which typically most intensive outdoor activity occurs. This data was then averaged and used as simulation input start values. A black globe thermometer was used for measuring the mean radiant temperature (MRT), stabilizing it for approximately an hour at each location. The sky view factors were recorded and quantified by means of fish-eye photography.

SCALE OF CASE STUDIES:

The simulation was being run on different scales. First the various forms were tested for an entire grouping of urban blocks (roughly an area of 300'x300'/block) at the reference location between Monroe and Adams, 1st Avenue and 2nd Avenue downtown Phoenix. The urban block form was tested based on effective air flow at the mesoscale, street shading potential, orientation, street canyon proportions, and sky view factors that were conducive to releasing the evening heat.

Wind is an overlooked resource in cooling the Phoenix urban environment. As mentioned previously, the urban form's adverse impact on local wind patterns is one of the contributing factors in the increased UHI effect. Wind helps distribute the cooling effect of urban parks and helps clear up the pollutants that trap the heat in the urban fabric. We started by simulating various urban block scenarios to gain an understanding of which combination of building massing, height, orientation and open space optimized air movement.

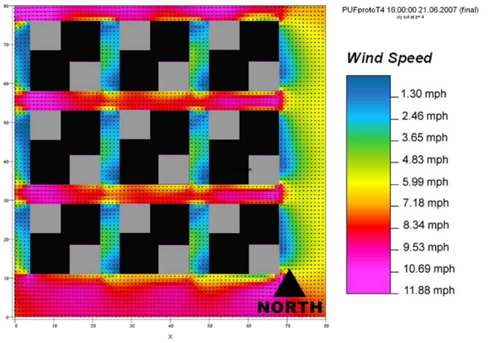

Figure 3: Example of a scenario testing urban form's effect on wind direction.

Based on the simulation results, the optimal massing at this scale was characterized by having maximum lot coverage of 80% (or 20% open space) not including alleys, and a building base of 8 stories. Above the 8th story the coverage was reduced to 50%. The tower placement alternated in a checkerboard pattern (Fig 3). This standard was also based on average street canyon proportions of 1:1.5. This was similar to an existing four block area between Monroe and Adams, 1st Avenue and 2nd Avenue.

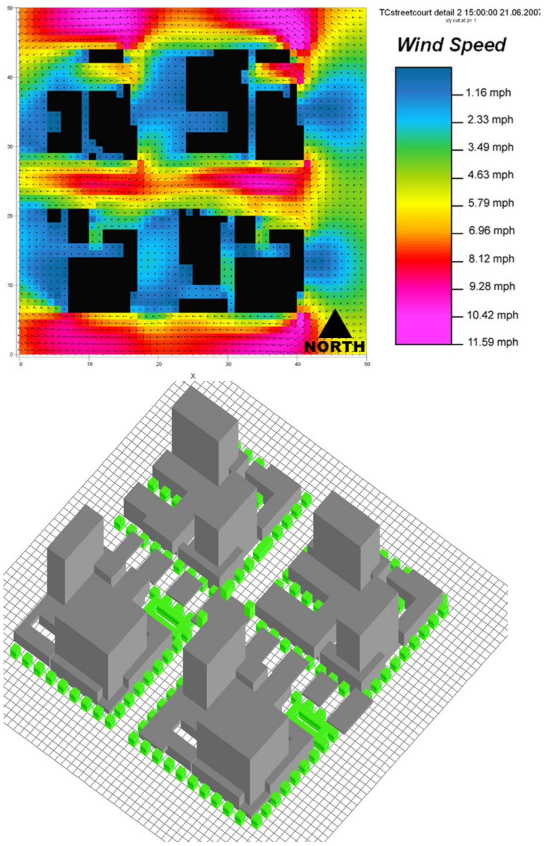

Figure 4: Optimal configuration – block scale. Plan view is cut at 5'-10" above ground surface.

Wind patterns are significant in affecting temperatures between the various urban spaces. In previous studies it was shown that cooling effects of urban parks for example, is increased or diminished based on the direction of the prevailing wind (Oke 1988). The simulation of this urban block massing (Fig 4) showed the most optimal air movement and decrease in ambient temperatures. Consequently, the open spaces at the street level of this block massing can be enhanced by adding shading devices, creating pocket parks, courtyards and pedestrian passageways connecting the various parts of downtown. However, from an economic point of view, the design could not “enhance” the all pedestrian paths with shading structures. Therefore, the design effort was directed to enhance “strategic” locations along the pedestrian paths such as street corners, openings/courtyards within the block structure and passageways within the block itself. The pavement of the street between the buildings is the largest contributor to the pedestrians’ MRT environment, and therefore test runs were simulated to gauge the effect of partially shading at least the east –west streets to reduce their MRT effect. The final block design was then also simulated to test the average radiant temperatures, ambient temperatures, wall/surface temperatures, and incident direct/indirect radiation.

MICRO SCALE SIMULATION:

The gathered data shows that the time of exposure outdoors is a critical factor in how pedestrians perceive whether they are within a comfort range. Therefore, the “strategic” enhanced spaces along the edge and within the urban block itself were designed to minimize the pedestrians’ exposure to the weather extremes for extended periods of time. These “cool pockets” were tested as areas of multiple applied cooling strategies in order to bring the environment into an acceptable range of thermal comfort. One such pocket, the U shaped courtyard space off the street within the urban block, was simulated in ENVI-met to investigate the micro-scale strategies. The basecase scenario was for a bare space with no additional shading (other than self shading), no landscape or water features and with a low velocity wind at 0.5 m/s. The simulation was run between 10:00am and 2:00pm. The output data used was between 12:00noon and 1:00pm, the time when the downtown outdoor environment is usually most active.

ESTABLISHING THE GOAL:

The (SET) index was chosen as the standard benchmark to set the goals for the outdoor thermal comfort in the space. It was deemed the most appropriate way of comparing thermal comfort and accounting for a broad range of environmental conditions. SET uses operative temperature (t_o) which is an average of ambient (t_a) and mean radiant temperature (MRT), weighted by air velocity and activity level to provide a dynamic equivalent index. This was established in the research by Gagge et al. where they defined 95F SET as an appropriate outdoor comfort metric (Gagge et al. 1973). Furthermore, according to the ASHRAE Handbook of Fundamentals, if humans are exposed to conditions of SET above 95ºF for extended periods of time, there is a danger of suffering heat stroke. Thus the maximum outdoor design criteria should be a SET of 95ºF (Bryan 2001). The strategies used to bring the environment within the 95 ºF SET were:

1. Provide horizontal shading (5’ deep) at the entire perimeter of the U shaped space.
2. Provide 2 rows of trees lining the U shaped space with grass planting beds.
3. Add air movement at 3 m/s (6.71 mph)
4. Add a linear water feature (still water)

RESULTS AND DISCUSSION:

Table (1) shows the values of the ambient and the mean radiant temperatures as simulated by ENVI-met in an incremental fashion. The strategies employed had a more significant effect on the MRT values while the ambient temperature showed less variation. The values were read at the midpoint of the eastern side of the U shaped space. Other “cool pockets” in the urban block were also simulated and showed similar patterns. Based on the incremental results, the most effective strategy was shading. There is a significant decrease in both ambient as well as in the mean radiant temperatures when shading was employed both as fixed horizontal shading devices and by placing shade trees in the space. The rest of the strategies showed incremental decrease in the temperatures but not as significant as the shading. The air movement, while decreasing the ambient temperature did little to decrease the MRT. Cumulatively, to bring the space within the acceptable 95º SET, the shading has to be combined with the air movement. The water strategy had little effect as it was simulated only as a still water body with limited evaporation into the air.

Strategy	**Ta ºF**	**Tmrt ºF**	**To ºF***	**SET ºF***	**Notes**
Basecase	102.3	157.8	120	106	no shade
Strategy 1	100.2	116.4	110	101	5' deep hor. shade
Strategy 2	101.4	106.5	102	97	2 rows of shade trees
Strategy 3	95.6	138.1	115	102	air movement to 6.71 mph
Strategy 4	102	157	119	106	linear water feature
* For methodology see (Bryan 2001)					

Table 1: Incremental results - showing ambient temperature, mean radiant temperature, operative temperature and standard effective temperature for the various strategies tested and simulated.

Strategy	**Ta ºF**	**Tmrt ºF**	**To ºF***	**SET ºF***	**Notes**
Basecase	102.3	157.8	120	106	no shade
Strategy 1	100.2	116.4	110	101	5' deep hor. shade
Strategy 2	98.9	100.2	100	96	2 rows of shade trees
Strategy 3	94.5	99.9	98	94	air movement to 6.71 mph
Strategy 4	94.3	99.8	97.5	94	linear water feature
* For methodology see (Bryan 2001)					

Table 2: Cumulative results - showing ambient temperature, mean radiant temperature, operative temperature and standard effective temperature for the various strategies simulated in descending order.

One of the factors investigated separately was the effect of the building and pavement materials on the average MRT in the space. The factors involved in assessing the MRT potential of various materials are surface temperatures and emissivity. The emissivity varies little as most materials' values are around 0.9. However, the surface temperatures were found to vary significantly between different materials. From a pedestrian thermal comfort perspective, high mass materials, such as concrete or brick perform much better than insulated low mass materials, such as exterior insulation finish systems (EIFS). The collected data show that even with full solar exposure concrete surfaces run 10-15 ºF lower than EIFS. Additionally, if the high mass materials are shaded and periodically wetted, their temperatures can run even lower. This results in cooler surfaces which emit less radiation onto the pedestrians in the outdoor space. High mass materials have been typically classified as detrimental to mitigating the urban heat island. However, the urban heat island effect in hot arid climates is a nocturnal phenomenon and therefore has less of an effect on pedestrian comfort which is a daytime activity. Therefore, when designing for pedestrian outdoor comfort, shaded high mass materials are preferable to low mass materials. This is one of the inevitable trade-offs between maximizing the outdoor pedestrian thermal comfort and mitigating the urban heat island effect.

CONCLUSION:

If implemented, the recommendations gained through the simulation model have the potential to enhance pedestrian activities in the Phoenix downtown streets and reduce the dependency on vehicular circulation. Furthermore, future work can focus on the possibility of adapting ENVI-met into a tool for establishing a performance based standard for the design of the pocket parks' micro climate. Climate simulations of this type are important to quantify the benefits of proposed urban design scenarios. The simulation output visualized in LEONARDO (Bruce 2007) can act as a basis for the architectural design and urban planning decisions. This climatic simulation allows planners to optimize the Phoenix urban form based on the harsh Phoenix climate and its specific desert environment. Basing design decisions on the output data, results in more specific/quantifiable recommendations for planning and urban form strategies, as opposed to importing zoning codes from other regions of the country.

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