TOOLS FOR THE MITIGATION OF THE URBAN HEAT ISLAND

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ABSTRACT

This paper explores various methods of mitigating the urban heat island effect in a hot dry climate by the use of tools like computer simulation programs and thermal imaging. Many of the outdoor urban surfaces such as sidewalks and building surfaces use low albedo materials that also have high thermal capacity. The aggregation of such high surface temperatures is the prime cause of the urban heat island. Our understanding of this phenomenon has been hampered because the physics of radiant heat exchange (direct solar, long wave re-radiation from building materials, time lagged heat release) are so complex that it can only be modeled accurately at the urban scale by computer simulation.

The study models the entrance of an educational building located on the campus of Arizona State University using a simulation program called RadTherm to optimize the interaction between building materials, surface properties, adjacencies (view factors) and resultant surface temperatures.

The thermal performance of the entrance of the building is compared with thermal images generated using an infrared camera to demonstrate the possible application of the simulation program for developing urban design guidelines to mitigate the urban heat island. At the same time Sol-air calculations were also performed in order to create a bench mark to compare the results from the simulation runs and the thermal imagery.

The primary focus of this paper is to try and develop a tool for professionals to use to make an informed set of decisions regarding material selection for the mitigation of urban heat island effects.

1. INTRODUCTION

The summer temperature in urban areas are typically higher than their adjoining rural surroundings, this phenomenon is called the urban heat island (UHI). Higher temperatures result in increased energy usage to support air conditioning. Increased energy production increases emissions of greenhouse gases, which contribute to global climate change. This cycle serves to increase the frequency and duration of extreme temperatures. The UHI can also cause the increase formation of harmful smog, as ozone precursors such as nitrous oxides (NO_x) and volatile organic components (VOCs) combine photochemically to produce ground-level ozone.

Researchers have discovered that the primary factors for this phenomenon in urban areas are the climate, topography, weather patterns, surface properties and vegetation. The last two factors constitute the majority of heat accumulation that is attributable to human activities. Urban design guidelines often neglect these aspects.

The adverse effects of the UHI can be reduced by designing an external environment that minimizes the excess heat gains to the urban environment. Increasing the albedo of the urban streetscape surfaces, reducing the radiation striking buildings and reducing the heat capacity of building surfaces can all contribute to mitigating the UHI effect.

The thermal properties of surface materials, self-shading, shading by adjoining buildings and foliage, all form the setting for the study of the urban heat island. This requires an understanding of the physics of radiant heat exchange which involves the direct solar, long wave re-radiation from building materials and the heat capacity of the material.

All these, along with building layouts and street orientations form a complex interaction that can only be accurately captured by computer simulation. One simulation program that potentially can accomplish this is called RadTherm, which was developed by ThermoAnalytics Inc.

2. EVALUATION TECHNIQUES

2.1 Computer Simulation

2.1.1 About the Tool

RadTherm was developed for the defense and automotive industry to aid in the analysis of the thermal behavior of their designs. It is a windows-based cross-platform thermal modeling tool, which can be used to model objects with complex surface geometry. RadTherm models 3D conduction, convection and multi-bounce radiation. The output from RadTherm generates a user-friendly graphic temperature map of the object's surface temperatures.

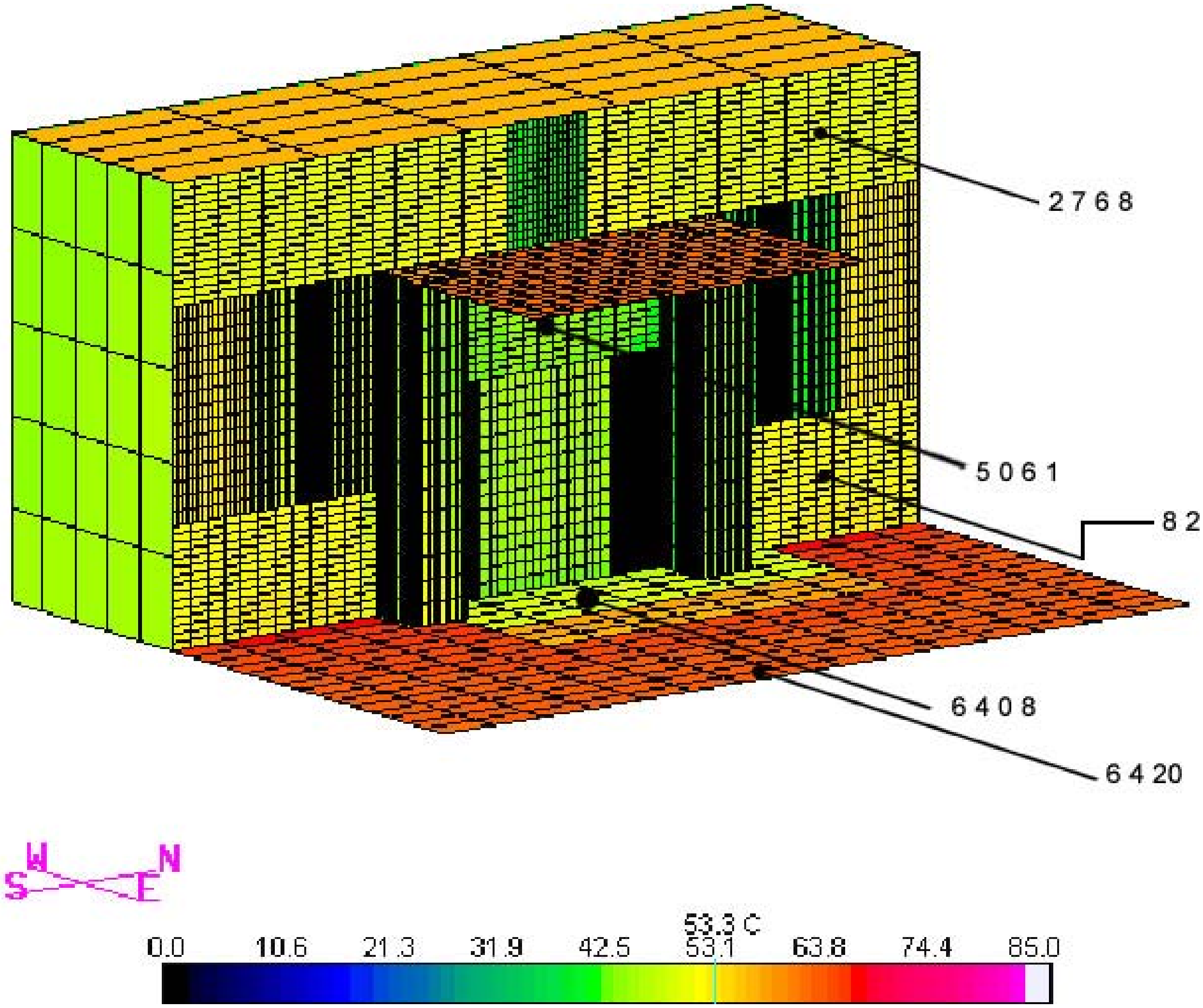

Fig. 1: RadTherm Results for Surface Temperatures (element no. analyzed)

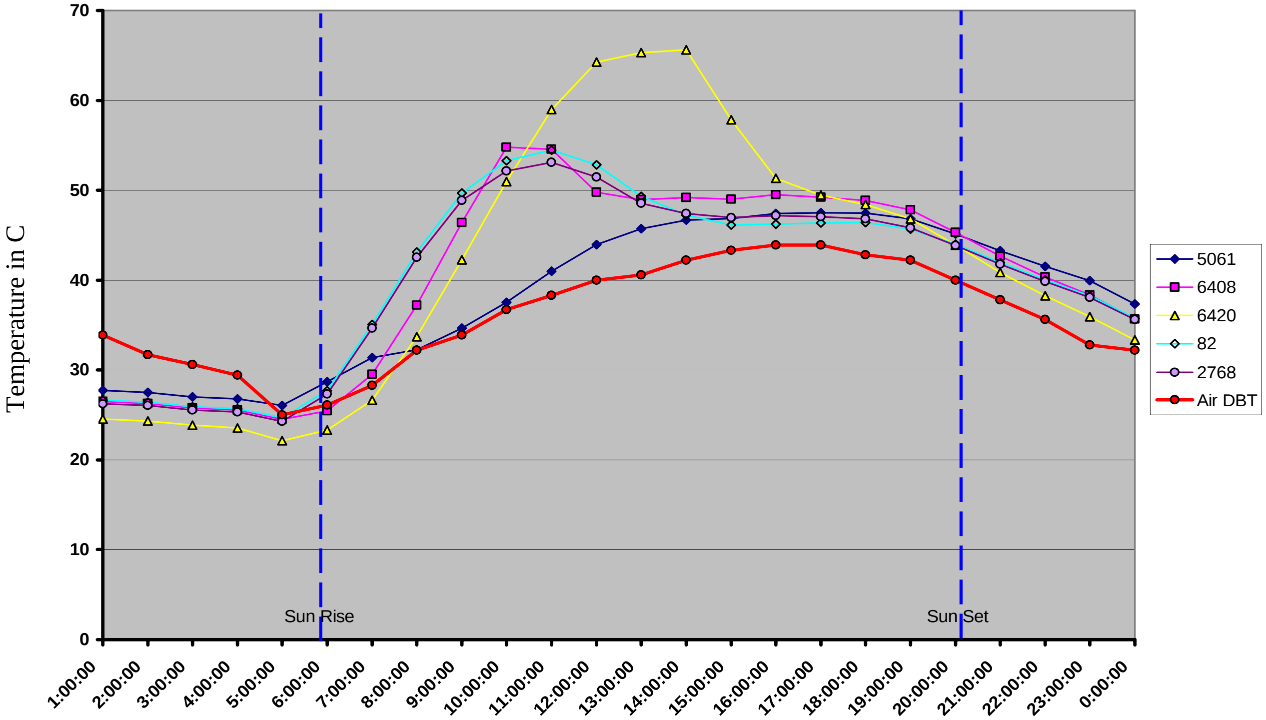

Fig. 2: RadTherm Results Surfaces Temperature Profiles

2.1.2 Model Setup

The simulation model used for the study is the entrance of an educational building located on the campus of Arizona State University (Figure 1). The building geometry was imported from AutoCAD and further additions were done using the RadTherm interface. Surface material properties and thickness for elements were assigned as close as possible to the actual buildings used for the study.

The weather data was taken from the TMY2 file for Phoenix and converted to a format that is compatible with RadTherm. The sky data was modeled using RadTherm's sky modeling routines to calculate long wave infrared radiation based on geographic location. The solar data is structured to take inputs for total Solar and direct solar radiation values from the weather file. Convection was calculated for all outside surfaces by using wind data from the weather file. The solution time was set up every 60 minutes. The model was run for 20 days for initialization so that the steady state solution was reached for June 26th. The default value of 20ºC (initial temperature) was input as a boundary condition during model set up to accelerate convergence of the model. This is used as the numerical seed value when solving the steady state solution. The temperature entered as the initial temperature may not be the temperature of the part when the model is converged. Thermal models in RadTherm are organized into a hierarchical arrangement of nodes, elements, parts and assemblies. Elements are isothermal surfaces that are modeled with geometry. Each element in a model has a unique element number. A number of elements were selected for analysis to compare their thermal behavior in relation to dry bulb temperature. Figure 2 shows surface temperature profiles for the selected elements.

2.2 Thermal Imaging

2.2.1 About the Technique

Thermography is the use of an infrared imaging and measurement camera to see and measure thermal energy emitted from an object. Thermal, or infrared energy, is light that is not visible because its wavelength is too long to be detected by the human eye. Unlike visible light, everything with a temperature above absolute zero emits heat. The higher the object's temperature, the greater the IR radiation emitted. Infrared thermography cameras produce images of invisible infrared or heat radiation and provide precise non-contact temperature measurement capabilities.

2.2.2 Tool Used

For the purpose of the study thermal images of the case study building were taken by a ThermaCAM P60, an infrared thermal imaging camera made by FLIR Systems. The FLIR software package was used for reporting, analyzing and organizing IR images and data captured with

Fig. 3: Thermal Image on June 26th, 2004 at 9:41:55 PM

ThermaCAM infrared cameras. The software allows interpretation of calibrated infrared camera images to render temperature measurements. (Figure 3)

2.3 Surface Temperature Calculation

2.3.1 The Procedure

The procedure selected based on calculating outdoor surface temperature known as Sol-air temperature using equations provided by ASHRAE (2001). The calculation was made for horizontal surface as well as for other orientations on vertical walls. The calculation was done based on location specific data; the day of the year, latitude and longitude as well as clearness number "CN" for the City of Phoenix, Arizona. The date selected for calculation was JUNE 26th. The following is sol-air temperature equation used for analysis in this paper.

$$\textbf{Sol-air Temperature} = t_o + ((\alpha/h_o)\, E_t) - ((\varepsilon / h_o)\, \Delta R)$$

Where t_o is the outdoor ambient air temperature F°, α is the absorbance of surface for solar radiation, h_o is the coefficient of heat transfer by long wave radiation and convection at outer surface (Btu/h.ft^2.F°), E_t is the total solar radiation incident on surface in Btu/h.ft^2.F°, ΔR is the difference between long-wave radiation incident on surface from sky and surroundings and radiation emitted by a black body at outdoor air temperature (Btu/h.ft^2) and finally, ε is the hemispherical emittance of the surface. As indicated above on the Sol-air temperature equation, the overall value $(\varepsilon / h_o)\, \Delta R$ is known as long-wave correction term which represent the amount of temperature drop due to long-wave radiation to the sky. An empirical value for temperature drop was suggested by Givoni (1997) for use based on climate condition. A value of 11F° were suggested for arid climates with clear skies, 7F° for humid climates with clear skies and zero for cloudy skies conditions (Givoni 1997). Since vertical surfaces receive almost nothing from long wave radiation emitted to the sky, it is common practice to assume $\Delta R = 0$ for vertical surfaces. For ground/horizontal surfaces, a value of 20 Btu/h.ft^2 was suggested as an average value for ΔR. (ASHRAE, 2001)

2.3.2 Sensitivity of the Parameters

2.3.2.1 Surface Absorbance and Reflectivity

A materials reflectivity is a measure of visible light reflectance. Albedo (â) is the measure of incident light and solar reflectivity of a material or surface. Albedo is described as a ratio and is measured on a scale of 0.0 to 1.0. Materials or surfaces on the low end of the scale 0.0 absorb solar radiation. While those at the high end of the scale, reflect solar radiation.

High albedo materials reflect more of the solar heat. Buildings treated with high albedo materials absorb much less heat to store and to transfer inward towards interior systems or to air near to the surface. Due to the high reflectivity of light color walls, the effect of surface orientation can be minimized where a very small amount of long-wave radiation will be absorbed by the surface. A series of calculation were performed to investigate surface temperature change due to albedo change. Albedo values used for analysis starting from zero (perfect absorber) to 1.0 (perfect reflector). The calculations were performed for every 0.05 albedo. Based on published data, albedo values for common materials were used for reference.

2.3.2.2 Surface Heat Coefficient

One of the important parameters for calculating surface temperature is the outdoor surface heat transfer coefficient $\mathbf{h_o}$, where it represents the rate of surface heat loss by convection and radiation for outdoor surfaces. The surface heat transfer coefficient is estimated based on ASHRAE recommendation for winter condition as a maximum of 5.1 Btu/ft2 for 15 mph wind speed and as low as 1.2 Btu/ft2 for still air condition. A linear equation was performed to estimate $\mathbf{h_o}$ values due to local wind speed condition for Phoenix, Arizona. A value for surface heat coefficient transfer loss was concluded of 0.278 Btu/ft2 for every increase of one mile per hour wind speed. Givoni (1997), a value of 6 Btu/h.ft^2.F^o or 20 w/m^2.C^o was suggested as an average value for use with wind speed of 7.8 mph or 3.5m/s. The values for $\mathbf{h_o}$ will be used based on ASHRAE standards values.

It is expected that with a given wind speed the actual speed next to wall is affected significantly by the urban structure. Where in a dense built urban area would be about one half of the measured wind speed in weather stations (Givoni, 1998). Since the rate of change for surface heat transfer coefficient depends mainly on wind speed, a series of calculations were made to investigate the amount of change in $\mathbf{h_o}$ rate and consequently the surface temperature change due to change in wind speed. The calculation was made using wind speed values starting from 7 miles per hour, to 15 mile per hour representing the maximum winter condition on one mile per hour increment.

3. COMPARATIVE RESULTS

By applying the procedure discussed previously, the Sol-air temperature on east wall was correlated linearly with the albedo change on its maximum value at 9 am. Where for every 0.05 rise in albedo, a surface temperature increase of 3C^o was observed (Figure 4). For example, a material has a surface albedo 0.2, such as common brick, will have higher surface temperature by about 18C^o than the same material with 0.5 surface albedo. Therefore, surface albedo for walls and building envelop will be an effective tool as an urban heat island mitigation strategy.

Unlike the procedure used for surface albedo correlation, the surface heat transfer coefficient was interrelated with a non-linear relation to surface temperature. As shown from (Figure 5), the surface temperature on east wall at 9 am on 26th of June was reduced by 5 C^o due to rise in

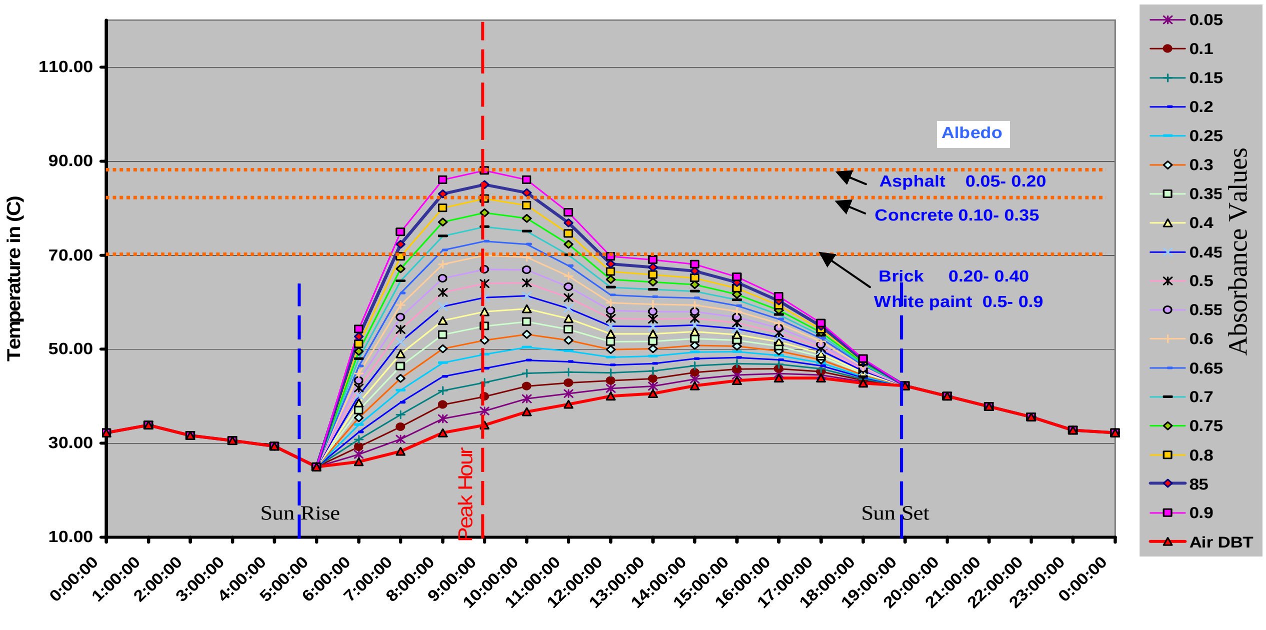

Fig.4: Sensitivity of Albedo on Surface Temperature,
East Wall, June 26th 04

wind speed from 7 mph to 8 mph where for wind speed rise from 14 mph to 15 mph only a drop of 1 C^o was observed.

4. IMPLICATIONS

Although, the building was modeled as accurately as possible (material properties etc) to the actual building, large surface temperature differences were observed when the results of the RadTherm simulation were compared to that of the IR imaging and the Sol-air calculation. Three major causes seem to be responsible for these differences. First, the Sol-air calculation method is limited to a day time calculation and does not take into effect surface heat losses by night time radiation to the sky. Second, the effect of material thermal mass and its capability to store heat was not included. Third, the cooling effect through earth contact process known as earth coupling and heat released from surfaces in contact with the soil was not accounted for.

5. CONCLUSIONS

While preliminary investigation reflect the potential of using RadTherm and thermal imaging as design tools for mitigating urban heat island, more calibration and enhancement are needed for the process of material properties selection for walls and ground surfaces. Also since the urban heat island is such a crude phenomena we have based our analysis on a comparative methodology of various processes. A precise tool for this analysis can only be born of a combination of various processes as shown in this paper. So, the next step for this work would be to perform a controlled comparative study between IR imaging and RadTherm simulation compared to an hourly field measurement. This procedure would be more accurate methodology to enhance and calibrate results for future UHI mitigation studies.

6. REFERENCES

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(4) www.thermoanalytics.com

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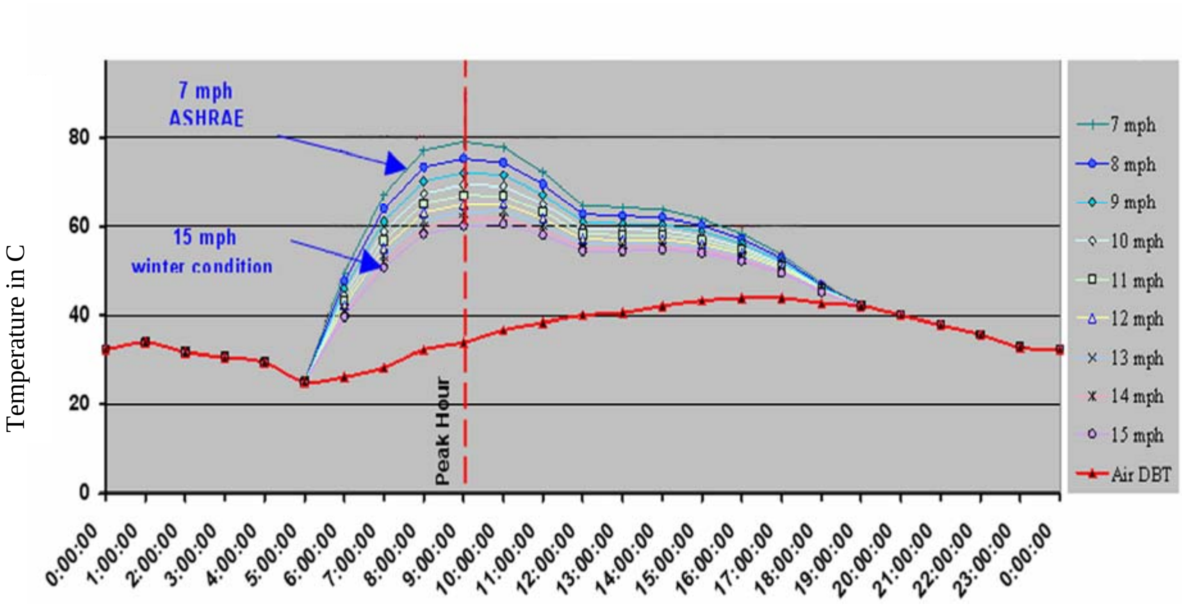

Fig.5: Sensitivity of Surface Heat Coefficient on Surface Temperature, East Wall, June 26th 04