J. King Saud Univ., Vol. 21, *Arch. & Planning* (1), pp. 1-7, Riyadh (2009/1430H.)

Measured versus Calculated Roof Peak Sol-air Temperature in Hot-arid Regions

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(Received 3/9/1428H.; accepted for publication 16/12/1429H.)

Abstract. Energy conservation within buildings in hot-arid regions is an issue of great importance. Careful design of the building envelope is essential in order to minimize external thermal impact on walls and roof. Roof color plays an important role in determining the value of sol-air temperature, and therefore, the amount of heat penetrating into the building. Sol-air temperature is a fictitious temperature equivalent to outside temperature that will cause the same rate of heat flow at the surface and the same temperature distribution through the material as current outdoor air temperature.

The first main objective of this study is to measure and compare sol-air temperature variations between different horizontal roof colors. The second objective is to verify ASHRAE estimates that are used to determine horizontal roof peak sol-air temperature with those measured values, within hot-arid environment. Field measurements of sol-air temperatures that were collected for various colors showed notable differences. Comparison between measured temperature readings and those calculated ones under the same climatic conditions showed that there are considerable differences between measured and calculated values of peak sol-air temperatures for various roof colors. Measured temperatures were found lower than that calculated ones by almost 10^{o}C.

The outcomes of this study will help architects and engineers to correct the estimates of cooling loads with regard to roof color.

Introduction

The outer surface of any building represents the first line of defense against external thermal forces. External envelope of low-rise buildings represents a major source of thermal load. Roof area in low-rise buildings represents a major portion of the envelope area and in many buildings might exceed 50% of the envelope area. While the surface temperature of the building is usually higher than that of the air , careful treatment of the roof surface is essential in order to reduce heat gain. The selection of absorptivity and emissivity characteristics of roof materials in the defense against solar radiation impacts are also very important. Absorptivity of any surface determines its response to solar radiation. The absorbed part of the striking solar radiation on the surface will raise its temperature and consequently increase the amount of heat that penetrates into the building spaces. Therefore, materials that reflect radiation and emit the absorbed heat readily will cause lower temperatures within the building to prevail. Emissivity, however, is independent of the color and related mainly to the nature of the surface. Olgay (1973) mentioned that the thermal exchange with the surrounding consists of longer infra-red wave lengths (over 2.5, usually from 5 to 20 microns). The characteristics of materials with regard to reflectivity of long wave infrared heat depends more on the density of surface and on molecular composition than on color. The following table tabulates the characteristics of some typical materials.

From Table 1, combined effect of reflectivity and emissivity must be considered when selecting roof material and color. White marble , for example, is a cooler surface than polished aluminum because white marble has bigger value of emissivity and therefore, capable of releasing absorbed heat to the sky more than the polished aluminium.

Berdahl and Bretz (1997) reported quantities and values of solar reflectance of some types of roofing materials and discussed also the effect of material properties such as composition, roughness, purity etc. on solar reflectance. They also illustrated strong correlation of roof temperature with solar absorptance and demonstrated the effects of infrared emittance and convection.

Table 1. Reaction of materials to solar and thermal radiation

Surface	Percent of Reflectivity Solar Radiation	Percent of Emissivity Thermal Radiation
Silver, polished	93	2
Aluminum, polished	85	8
Whitewash	80	-
Copper, polished	75	15
Chromium plate	72	20
White lead paint	71	89
White marble	54	95
Light green paint	50	5
Aluminum paint	45	55
Indiana limestone	43	95
Wood, pine	40	95
Asbestos cement, aged 1 year	29	95
Red clay brick	23-30	94
Gray paint	25	95
Galvanized iron, aged (oxidized)	10	28
Black matte	3	95

The outer thermal forces acting on buildings consists of incident solar radiation, radiant heat exchange with sky and other outer surroundings, and convective heat exchange with outdoor air. According to ASHRAE Fundamentals (1997), the heat balance at a sunlit surface gives the heat flux into the surface q/A as:

$$q/A = \alpha I_t + h_o (t_o - t_s) - \varepsilon \Delta \Re$$

Where :

t_s = surface temperature;

t_o = outdoor air temperature;

ε = hemispherical emittance of surface;

$\Delta\Re$ = difference between long wave radiation incident on surface from sky and surroundings and radiation emitted by black body at outdoor air temperature;

α = absorptance of surface for solar radiation;

I_t = total solar radiation incident on surface; and

h_o = Coefficient of heat transfer by long wave radiation and convection and outer surface.

Sol-air temperature is a fictitious temperature [*Stephenson*] which represents as defined by ASHRAE the temperature of the outdoor air that , in the absence of all radiation changes , gives the same rate of the heat entry into the surface as would be the combination of incident solar radiation , radiant energy exchange with the sky and other outdoor surroundings , and convictive heat exchange with the outdoor air .

When expressing the rate of heat transfer in terms of sol-air temperature t_e , the rate of heat transfer will be:

$$q/A = h_o (t_e - t_s)$$

and sol-air temperature therefore will be :

$$t_e = t_o + \alpha I_t / h_o - \varepsilon \Delta \Re / h_o .$$

It is clear from the above equation that the sol-air temperature is equal to the sum of air temperature plus the effect of incident radiation absorbed by the surface minus the effect of emitted radiation to the sky and surroundings.

ASHRAE Fundamentals for the purpose of calculating sol-air temperature for horizontal surfaces suggests according to Bliss (1963) that the term $\varepsilon \Delta \Re / h_o$ for all types of surfaces equals 3.9 ^{o}C. The suggested value considers that the hemispherical emittance (ε) for all types of surfaces and materials is constant while it is actually variable because emissivity is a volume characteristics and the long wave radiation depends upon the temperature of the body (Thakur 1989).

ASHRAE Fundamentals on the other hand suggests certain values for the term α / h_o (0.026 for light colors and 0.052 for dark colors).

Problem Statement

The estimate of $\varepsilon \Delta \Re / h_o$ by ASHRAE does not differentiate between various climates, especially with regard to sky cover and air moisture content, pollution, etc. that influence long-wave radiative exchange process. Bliss (1963) mentioned in this regard that values of the net long wave radiation exchange implies 20% uncertainty. Also ASHRAE estimates of α / h_o are limited to two horizontal roof color categories (light, dark) and does not count for the specific value of absorptance of other colors.

Due to the fact that the atmosphere in hot-arid regions is characterized by few clouds and low humidity, it is expected that the specified values by ASHRAE (1997) for $\varepsilon \, \Delta \Re / h_o$ is lower than the reality. Horizontal roof sol-air temperature, therefore is expected in actual to be lower than values estimated using ASHRAE Fundamental Formula.

Objectives

The ultimate goal of this research paper is to verify and validate experimentally ASHRAE estimates of horizontal roof sol-air temperatures .

However, the specific objectives of the research are:

1. To measure horizontal roof sol-air temperatures for one year for various colors;
2. To compare calculated peak values of sol-air temperatures according to ASHRAE Fundamentals estimates with measured peak values;
3. To suggest corrections for ASHRAE Fundamentals estimates applicable for hot-arid regions; and
4. To build statistical models to calculate sol-air temperature for various roof colors for the city of Riyadh region.

Research approach and nature

Experimental approach was adopted to conduct the research. Seven Octagonal colored concrete tiles (30cm x 30cm x 2 cm) (natural black, dark gray, natural white, white paint, white marble, red, green and dark gray) were used for conducting the measurements. Figure 1 shows how the tiles were placed individually and horizontally on a roof facing directly the sky. All tiles were isolated from the roof mass using 7 cm thick Polystyrene thermal insulation board. The purpose of the thermal insulation is to block thermal effects of the mass. Measurements of sol-air temperatures were taken from the middle of each tile using thermo couples, that were fixed 2 mm underneath the surface of each tile.

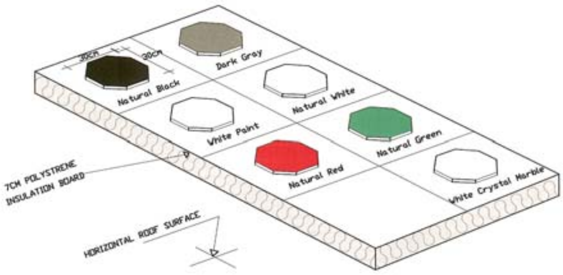

Fig. 1. Roof tiles arrangement.

Figure 2 shows how the sensors were fixed and connected. Measurements of sol-air temperature were recorded on hourly basis for one full year. Weather elements such as; air temperature, relative humidity, solar radiation, wind speed and direction, were simultaneously measured and recorded along with the sol-air temperatures measurements. Comparative and statistical analysis of the measurements with the calculated values were thoroughly performed.

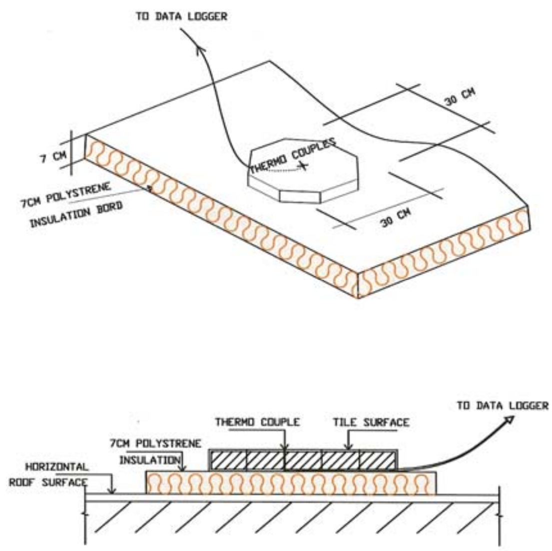

Fig. 2. Details of thermal sensors fixation.

Instrumentation and data recording

Figure 3 shows the instrumentation system which consists of four main parts: First; thermal sensors (8 thermocouples, type T), were used to measure Sol-air temperatures of tested roof tiles. Second; a complete weather station consists of:

1. A Met One anemometer, type 014A-U is used to measure ambient wind speed;

2. A perineometer, model LI-COR, type LI2003S, is used to measure the total solar radiation intensity on the horizontal plan. The output is read in micro-volts and converted into Watts/m^2; and
3. A probe manufactured by VAISALA, type HMP35C, is used to measure outdoor dry bulb air temperature and relative humidity. This probe is shielded against solar and reflected radiation from surrounding surfaces.

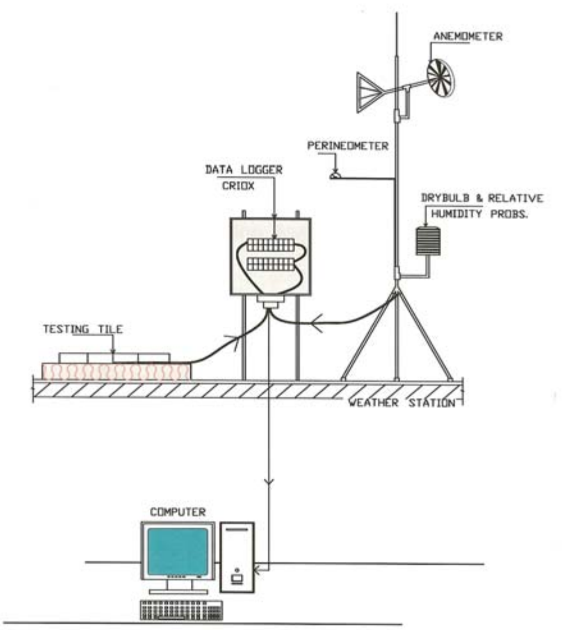

Fig. 3. Complete diagram of measurements instrumentation and data acquisition system.

Third; a data acquisition system is used to receive data from the sensors and send them to a computer. It consists of hardware and software. A data Logger type: "CR10X" were used, to receive and collect readings from the weather station and the 8 thermocouples. A software program "PC208W" were used to run the process of the data acquisition system. Fourth; an IBM compatible PC is used to receive and save the collected measurements from the CR10. A spreadsheet program "Microsoft Excel" were used to perform statistical analysis and produce graphs.

Analysis

Sol-air temperatures for various colored horizontal roofing tiles where measured hourly for one year. In addition, ambient air temperature, solar radiation and wind speed were recorded for the same period. A large number of recorded readings were analyzed using Excel program.

Figure 4 shows an example of curves of daily readings of horizontal roof sol-air temperatures for various colors. Ambient air temperature is shown also on the same figure. The figure shows the variation exists between black roof and white roof sol-air temperatures and with ambient air-temperature. Most of the variation, however, occurs during hours of peak solar radiation (mid-day). Figure 5 shows curves of daily peak sol-air temperature for various roofs colors plotted for one year together with the daily peak ambient temperature. The variation clearly exists through the whole year.

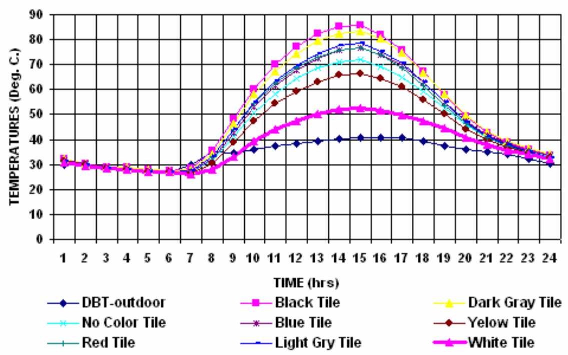

Fig. 4. Sol-air temperatures of various horizontal colors for July 4th, Riyadh.

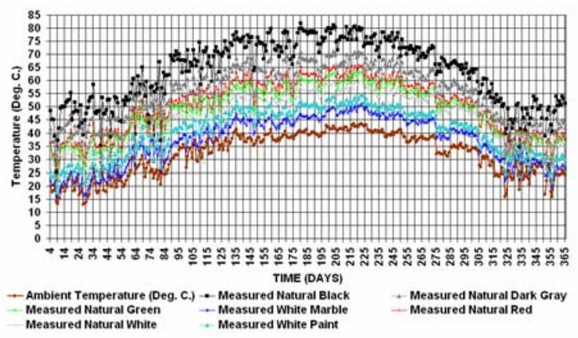

Fig. 5. Daily maximum sol-air temperature for various roof colors.

The continuity of variation of peak sol-air temperatures with peak ambient temperature is influenced by the prevalence of sun most of the year. Strong correlation therefore, is expected between peak sol-air temperatures and peak ambient temperature. When plotting peak sol-air temperature readings against ambient air temperature readings for various colored roof tiles, as in Fig. 6, it proves the linear relation with ambient temperature.

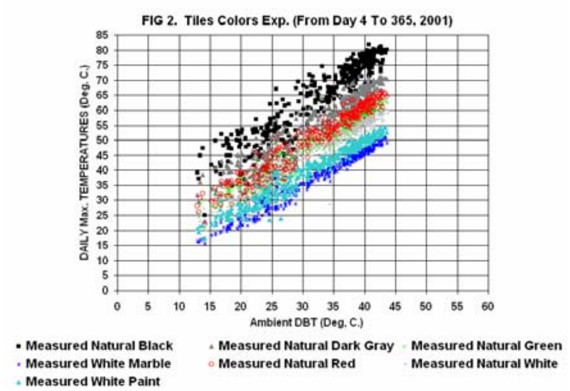

Fig. 6. Scatter plot of peak sol-air temperature against ambient temperature.

When correlating sol-air temperature for various roof colors with ambient temperature, the researcher found that there are very strong correlations. Table 2 shows values of correlation coefficients for various roof colors.

Table 2. Correlation coefficients for various colored horizontal roof tiles

Roof tiles color	Correlation Coefficient (R-value)
Natural Black	0.93
Natural Dark Gray	0.94
White (natural)	0.98
White (painted)	0.98
White Marble	0.98
Natural Green	0.96
Natural Red	0.95

Therefore, in hot-arid climates where clear sky conditions prevail most of the year, the peak sol-air temperatures can be predicted directly as a function of the ambient temperature.

By simply regressing sol-air temperature reading with ambient temperature readings, the researcher has achieved several formulas that can be utilized to predict sol-air temperature as a function of ambient temperature for the central region of Saudi Arabia. The formula as follows:

$$\text{Sol-air temp.} = C + (a \times \text{Ambient temp.})$$

Values of (C) and (a) are tabulated in Table (3) for various colors

Table 3. (C) and (a) values for various roof coloring

Roof color	(C)	(a)
Natural Black	17.5	1.44
Natural Dark Gray	12.37	1.33
White (natural)	6.7	1.215
White (painted)	3.97	1.148
White Marble	0.25	1.15
Natural Green	8.07	1.26
Natural Red	8.5	1.30

When applying measured peak ambient temperature and solar radiation to ASHRAE Fundamentals equation, it has been able to calculate peak sol-air temperature values for the whole year for both black and white colored horizontal roofs. The equation, as mentioned before, uses certain values to estimate reflectivity and emissivity components. Figures (7, 8) shows scatter plots of measured sol-air temperature values and ambient temperature and calculated sol-air temperature values and ambient temperatures for black and white colored horizontal roof. It is evident from the figures that calculated values of sol-air temperatures according to ASHRAE estimates are bigger than that measured ones. Both plots are almost parallel in shape, when plotting sol-air temperatures generated by the regression models against those generated using ASHRAE estimates as in Figs. (9, 10), the researcher has found that ASHRAE values for sol-air temperature are 10 ºC above those generated through regression of measurements.

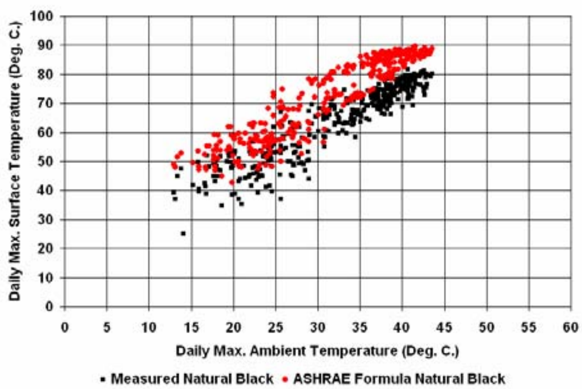

Fig. 7. Scatter plot of measured and calculated sol-air temperatures of black roof against ambient temperatures.

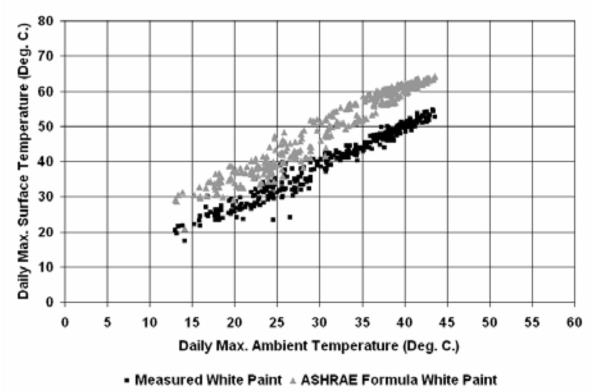

Fig. 8. Scatter plot of measured and calculated sol-air temperatures of white roof against ambient temperatures.

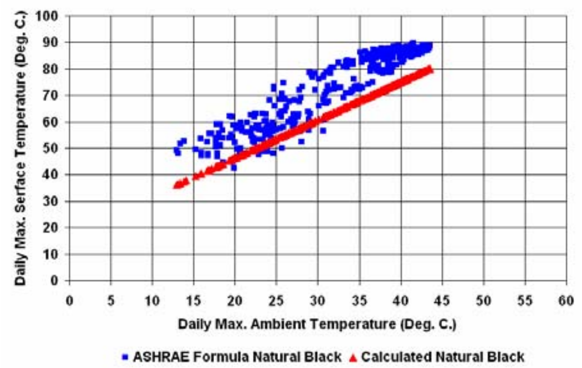

Fig. 9. Scatter plot of measured sol-air temperatures generated by the regression models against those generated using ASHRAE estimates for black roof.

Conclusion

The outcomes of this research challenges the applicability of ASHRAE Fundamentals values for various climates. However, a 10 ºC increase of peak roof sol-air temperature estimation has a significant impact on the estimation of thermal load coming through roof. Indeed, comprehensive field studies are necessary to reach reliable estimates to avoid over estimation of thermal loads and therefore bigger AC machines.

Acknowledgement. The author is indebted to his colleague Dr. Nassir Al-Hemiddi for his support which made this research possible.

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مقارنة الدرجة الذروية ا قاسة مع ا سوبة رارة ا واء الشمسية للأسقف الأقاليم ا ارة ا افة

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(قدم للنشر في ١٤٢٨/٩/٣هـ؛ وقبل للنشر في ١٤٢٩/١٢/١٦هـ)

ملخص البحث. يعتبر الحفاظ على الطاقة في المباني في الأقاليم الحارة الجافة من الأمور بالغة الأهمية . لذا فإن التصميم المتأني للأغلفة الخارجية للمباني يعتبر أمراً اساسياً لتقليل التأثير الحراري الخارجي على الحوائط والأسقف ويلعب لون السقف دوراً مهماً في تحديد درجة حرارة الهواء الشمسية وبالتالي كمية الحرارة النافذة إلى داخل المبنى. إن درجة حرارة الهواء الشمسية هي درجة وهمية تكافئ درجة حرارة الهواء الذي يُحدث نفس معدل التدفق الحراري من السطح ونفس توزيع درجات الحرارة داخل المادة.

إن الهدف الأول والرئيس لهذه الدراسة هو لقياس ومقارنة درجة حرارة الهواء الشمسية للألوان المختلفة للأسقف الأفقية. أما الهدف الثاني فهو للتحقق من تقديرات جميعه مهندسي التكييف والتدفئة الأمريكيين والواردة في مجلد الأساسيات والمستخدمة لحساب الدرجة القصوى لحرارة الهواء الشمسية مع تلك التي تم قياسها وذلك للبيئات المناخية الحارة الجافة.

لقد أثبتت قياسات درجات حرارة الهواء الشمسية لمجموعة من الألوان أن هناك تفاوتاً ملحوظاً بينها. أما المقارنات بين القياسات الحقلية والمحسوبة وفق تقديرات الجمعية فقد أظهرت فروقاً حقيقية. وقد ظهر بأن الدرجات التي تم قياسها أقل بعشر درجات مئوية عن الدرجات المحسوبة.

إن نتائج هذه الدراسة ستساعد المعماريين والمهندسين على اختيار لون السقف ومادته المناسبين وكذلك تصحيح تقديرات أحمال التبريد على المباني .