Calculated MRT vs. Measured MRT in Experimental Buildings

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Abstract. Three room-sized building chambers were constructed in Elhasa, Saudi Arabia during the summer of 1988. These test chambers were identical except for the manner in which they were insulated. One was uninsulated (U), another had insulation on the exterior surface of the envelope (E), and a third had insulation on the inside surface (I) of the envelope. Hypotheses were developed and tested based upon an equation expressing the anticipated relationship of surface-weighted calculated mean radiant temperature (CMRT) and measured mean radiant temperature (MMRT). Floating temperatures were used in these calculations and measurements.

Keywords: Mean radiant temperature, black globe temperature, external insulation, internal insulation.

Introduction

Since the 1973 energy crisis, the notion of covering external surfaces of a building envelope with thermal insulation has gained the attention of building scientists and engineers. Combining a high thermal mass with building external insulation improves the thermal performance of buildings in some climates [1]. Building materials with high thermal mass have the ability to store energy; and insulation has the ability to slow its transfer. A building envelope with mass on the inside and insulation outside reduces the amplitude of the inside-air-temperature oscillation during the diurnal temperature cycle [2]. Consequently the maximum temperature and the peak energy load for cooling or heating are reduced. It also reduces energy consumption as the size of cooling or heating equipment [3]. It improves thermal comfort by creating uniform room air and surface temperature, and brings the mean radiant temperature as close as possible to the room air temperature

[4]. Consequently, thermal comfort will result in increasing productivity in the workspace [5,6].

The present paper may give a first start to compare the measured and calculated mean radiant temperatures. These values were field measured and compared with the real surface-based calculated mean radiant temperatures. Floating temperatures were used in these calculations.

Calculation of Mean Radiant Temperature

Mean radiant temperature can be best estimated by the empirical expression given by Oleson, plane radiant temperature for radiant heat flow from plane surface to perpendicular surface or to parallel plane surface are given by [7].

$$T_{pr}^4 = (T_1^4 \bullet F_{p-1}) + (T_2^4 \bullet F_{p-2}) + - - - - - + (T_n^4 \bullet F_{p-n}) \tag{1}$$

where

T_{pr} = plane radiant temperature

T_n = absolute temperature of surface n in K, (K= $^\circ$C + 273)

F_{p-n} = angle factor between a small plane element and surface n

$\sum F_{p-n} = 1$

If there is a small temperature difference between the surface of the room, i.e., $\leq$ 10 K, equation (1) can be simplified by the following linear expression:

$$t_{pr} = (t_1 \bullet F_{p-1}) + (t_2 \bullet F_{p-2}) + - - - - - - + (t_n \bullet F_{p-n}) \tag{2}$$

where

t_{pr} = plane radiant temperature in $^\circ$C

t_n = temperature of surface n in $^\circ$C

All temperature units are in $^\circ$C. The plane radiant temperature is calculated as the mean value of surface temperature weighted according to the fraction of the angle factors of each surface. For an object in the center of an enclosure the mean radiant temperature can be simplified further with fairly accurate results according to Szokolay forms (3).

$$MRT = \sum(t \bullet s) + \sum s \tag{3}$$

where

MRT = mean radiant temperature
t = temperature in $^\circ$C
s = surface area in m^2

Hypotheses

1. The building with externally applied insulation will experience the lowest MRT as measured by the black globe temperature.

2. The building with internally applied insulation will experience MRT as measured by the black globe temperature greater than the externally insulated building and less than the uninsulated building.

3. The uninsulated building will experience the highest MRT as measured by the black globe temperature of the buildings.

4. The average of measured mean radiant temperature (MMRT) will not differ from the average of calculated mean radiant temperature (CMRT) for all experimental buildings.

5. Similarly, hypotheses 1, 2, and 3 were formulated for calculated MRTs.

Experimental Facilities

Three test chambers (that are identical in size, color, shape, and orientation, one-room buildings) were constructed in the hot-arid climate of Elhasa (25° 18' N and 170 meter above sea level), Saudi Arabia (see Fig. 1). Before insulation, each building measures 3.24 m long by 3.04 m wide and 3.0 m high (see Table 1). The materials consisted of a 0.15 m reinforced concrete roof slab and 0.2 m thick concrete blocks. These particular materials were selected because they are widely used in hot-arid climates and have high thermal capacitance.

Table 1. Building physical characteristics

Building	Outer surface (m²)	Inner surface (m²)	Window area (m²)	Door area (m²)	Volume (m³)	Internal mass (kg/m²)
Uninsulated	47.5	35.9	0.42	1.616	19.7	171
Internal insulation	47.5	35.2	0.42	1.616	18.2	122
External insulation	50.0	35.9	0.42	1.616	19.7	220

Table 2. Building thermal characteristics

Building	Average decrement factor	Average solar absorption	Average R-value (m² .K /w)			
			wall	roof	window	door
Uninsulated	0.73	0.38	0.31	0.33	0.19	1.80
Internal insulation	0.62	0.38	2.38	2.40	0.19	1.80
External insulation	0.20	0.38	2.38	2.40	0.19	1.80

The buildings were of the same size to eliminate the need for thermal scaling. In addition to the basic materials, 0.05 m thick rigid polyurethane insulation boards were installed on the external surfaces of one module and on the internal surfaces of another. The third building was left uninsulated as a control. A 2.02 m by 0.8 m door and a 0.7 m by 0.6 m window were installed in the north wall of each module. For the externally insulated building, the insulation started 0.18 m below the floor level which was 0.4 m above the ground level. For the internally insulated building, the insulation started at the floor level. All the thermal insulation boards used in this experiment had the same thermal resistance value as determined by the manufacturer. Other thermal and physical characteristics are listed in Table 2. Tape was applied at the door and window perimeters to control the effect of infiltration and exfiltration. Thermocouple sensors were placed at the center of each wall and roof on the inside and outside surfaces. Black globe temperature, were taken at the center of each chamber (Fig. 1).

Temperature Measurement Locations

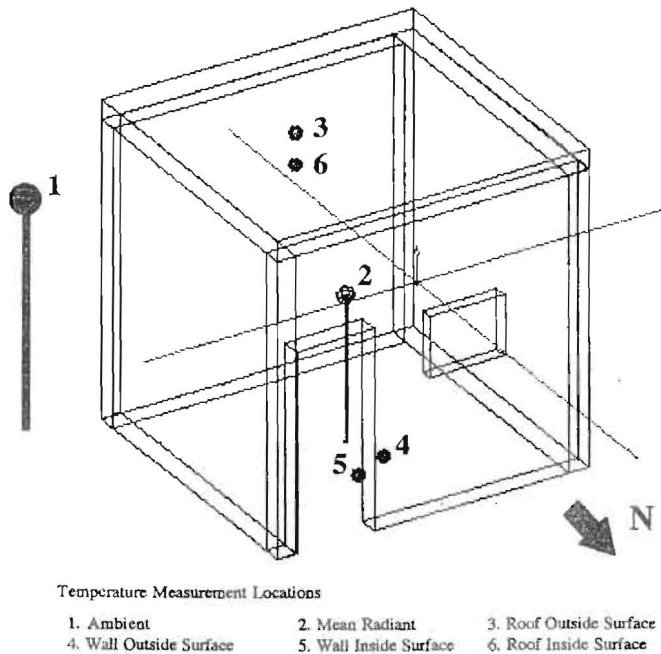| 1. Ambient | 2. Mean Radiant | 3. Roof Outside Surface |
| 4. Wall Outside Surface | 5. Wall Inside Surface | 6. Roof Inside Surface |

Fig. 1. The basic test module showing the location of sensors.

Each chamber has a 3-speed ventilation fan situated in the south wall 0.15 m below the ceiling. The rated air displacement volumes for the three speeds were 0.4, 0.51, and 0.69 cubic meters/minute. For this experiment the fan apertures in each building were operated at lower speed and the rate of air change was calculated to be 1.2 air change/hour (ACH).

Data Collection

Data for this experiment were collected three times per hour from five inside surface temperature sensors and one mean radiant (black globe) temperature sensor for each of the three chambers. The 8 days experiment consisted of 10,368 observations. The experiment was conducted on clear sky days. The effect of solar radiation was reflected on the MRT readings. It should be noted that windows were not protected from direct solar radiation and they were exposed 4.5 hours each day early morning and late afternoon. The calculated MRTs are the surface weighted temperature of five inside surface temperature for each calculated MRT. The following relationship was used:

$$CMRT = \sum(T_n * A_n) \div \sum A_n \qquad (4)$$

where

T_n = temperature of surface n, K

A_n = area of surface n, m^2

Analysis

Hourly averages were computed for each sensor and plotted as a function of time (see Figs. 2, 3, and 4). These graphs made it easier to visually compare the temperature regimes among the three buildings.

The overall average mean radiant temperature was computed for each building. The differences among these averages were tested for significance using Scheffe's method for multiple comparisons at a probability of 0.05 [8].

Minitab [9] was utilized to organize the raw data and to calculate the basic descriptive statistics. A spreadsheet was utilized to calculate the weighted MRTs from the measured surfaces' temperature of ceiling, north, south, east, and west walls. Since surface temperature of the floor is mainly affected by soil temperature, it is believed to have neutral effect on the CMRT, therefore; floor surface temperature was not measured. The same spreadsheet was used to average each hour's three readings for observed and calculated MRT. As a result, each variable, cases were reduced from 576 to 192 cases. According to Al-Mofeez, measured black-globe temperatures are a reliable estimate in range and average values for MRTs in un-air-conditioned space [10]. The black-globe temperature were used as the measured MRTs.
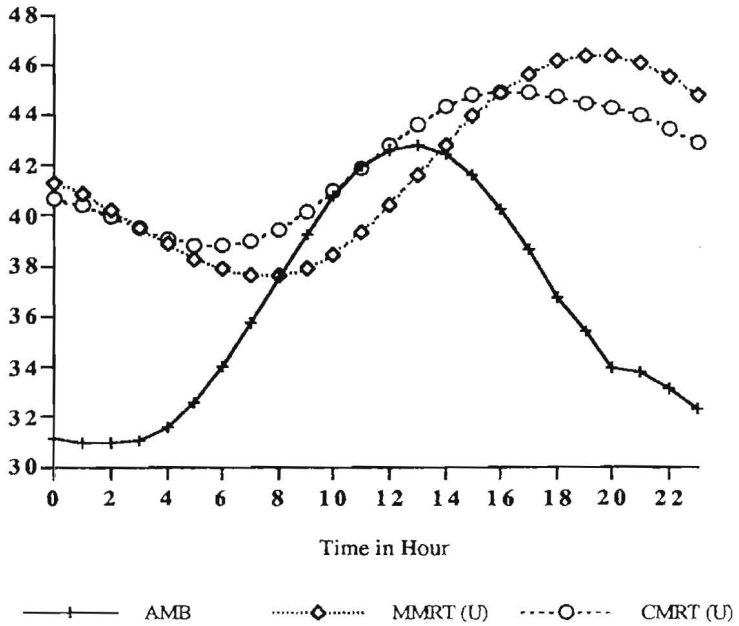
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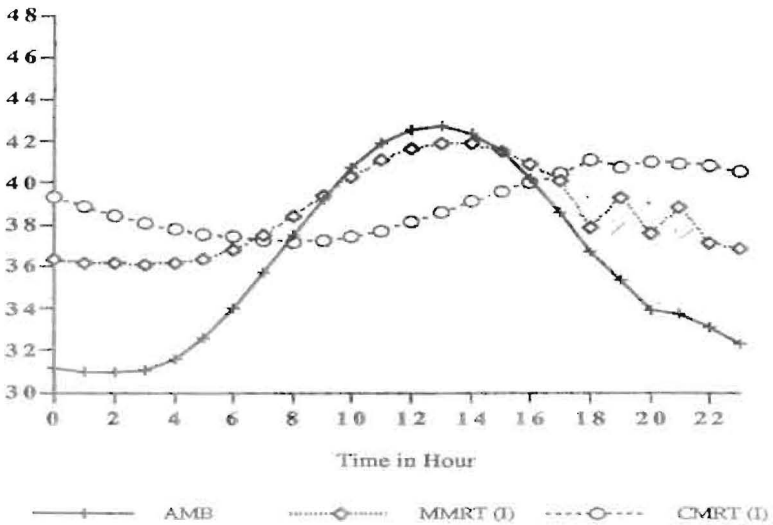Fig. 2. Temperature profile of the uninsulated building: 1.2 ACH.

Fig. 3. Temperature profile of the internally insulated building: 1.2 ACH.
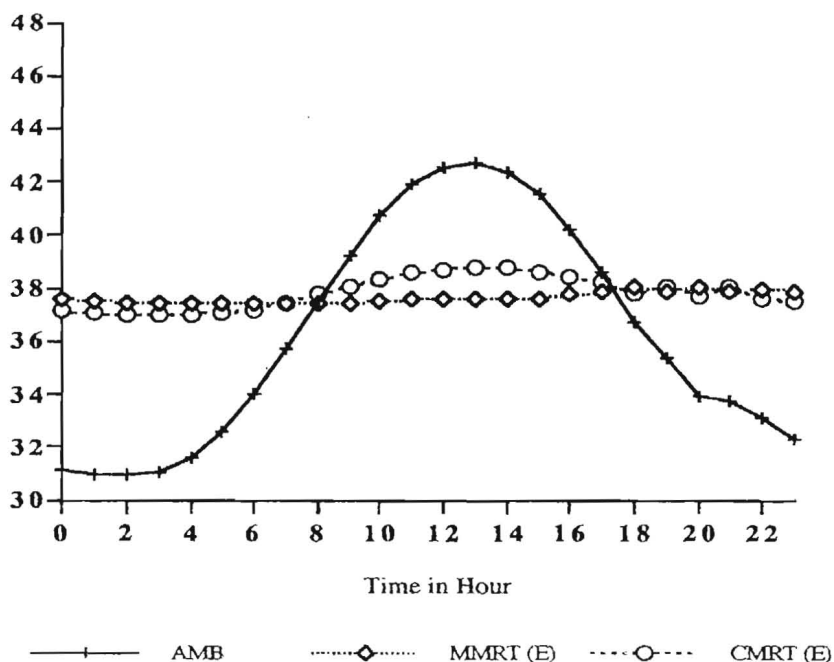
Fig. 4. Temperature profile of the externally insulated building: 1.2 ACH.

Results

Descriptive
Averages

Based on 192 measurements of the internal surfaces temperature of the three buildings which are the basis of the surface weighted (calculated) MRT, the observed values of measured MRT were very close to the calculated MRT (see Table 3).

The uninsulated building indicated on average (0.29)°C differences between calculated and measured MRT means. The internally insulated building showed (0.4) °C difference between calculated and measured MRT means. The externally insulated building showed the smallest differences in means (0.16) °C among the three buildings. The systematic differences in favor of the calculated MRTs can be explained by the omission of floor surface temperature which may lower the calculated MRT since earth is a very good heat sink.

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Table 3. Basic descriptive statistics of MMRT and CMRT

	MMRT (U)	CMRT (U)	MMRT (I)	CMRT (I)	MMRT (E)	CMRT (E)
No. of cases	192	192	192	192	192	192
Minimum	35.31	34.67	34.95	36.01	34.95	34.52
Maximum	49.22	49.18	44.53	42.26	39.95	41.02
Range	13.22	13.51	9.58	6.25	5.00	6.51
Mean	41.46	41.75	38.47	38.87	37.62	37.78
Standard deviation	3.58	2.79	2.49	1.52	0.85	1.27
Std. error	0.15	0.12	0.10	0.06	0.04	0.06
Skewness (G1)	0.18	-0.01	0.54	0.22	0.00	0.15
Kurtosis (G2)	-1.06	-0.72	-1.11	-1.02	-0.24	-0.59
Sum	34.121	34.29	32.4	32.63	31.91	32.00
C.V.	0.06	0.05	0.04	0.03	0.02	0.02
Median	41.11	41.68	37.38	38.78	37.62	37.60
Uncertainty of sensors	± 0.14	± 0.45*	± 0.14	± 0.33*	± 0.25	± 0.48*

*Based on the means of uncertainty of individual sensors.

Standard deviation (STD DEV)

Based on 192 cases (readings) of the internal surfaces of the three buildings which are the basis of the surface weighted MRT, except floor surface's, the observed values of MMRT (STD DEV) were very close to the CMRTs.

The uninsulated building indicated (3.58) °C for observed MMRT and (2.79) °C for CMRT. The results were expected because the standard deviation of CMRT resulted from five surface temperatures. The internally insulated building showed similar results. The externally insulated building showed unexpected results; this may be attributed to the effect of floor surface temperature. The standard deviation of the CMRT is higher than MMRT (1.2 vs. 0.85) °C (see Table 3).

Standard error of the means

The means showed low uncertainty, (standard errors). They were between (± 0.15) °C for means of measured MRT for uninsulated building to (± 0.04) °C for the measured means of the externally insulated building. In contrast, the uncertainty (standard errors) of individual sensors were higher in most readings. They were between (± 0.48) °C, highest and (± 0.14) °C for black globe temperature of internally insulated building (see Table 3).

Ranges

Ranges of calculated and measured MRT were different among buildings. The expected trend among building was observed. The highest range was observed in the case of the uninsulated building and the lowest was observed in the case of the externally insulated building (see Table 3).

Inferences

Mean difference in MMRTs

The analysis of variance table shows that building envelop design had a significant effect on (MMRT). The Scheff's pairwise comparison indicated significant difference at 0.05 level between MMRT (U) and MMRT (I) with (2.99) °C. It also indicated significant difference at 0.05 level between MMRT (U) and MMRT (E), with (3.84) °C. MMRT (I) and MMRT(E) had a (0.84) °C difference which was significant at 0.05 level. In other words, hypotheses 1,2,3 are accepted at the specified level of significance (see Tables 4 and 5).

Table 4. MMRT and CMRT analysis of variance

Source	DF	SS	MS	F	P
		MMRT			
Building	2	4860.3473	2430.1736	359.1180	0.00001
Error	1725	11673.1810	6.7671		
Total	1727	16533.5283			
		CMRT			
Building	2	4682.1468	2341.0734	289.4009	0.00001
Error	1725	13954.1792	8.0894		
Total	1727	608814.5265			

Table 5. Summary of least square means

	LS means	SE	N		LS means	SE	N
MMRT (U)	41.4603	0.1185	576	CMRT (U)	41.7525	0.1084	576
MMRT (I)	38.4672	0.1185	576	CMRT (I)	38.8659	0.1084	576
MMRT (E)	37.6241	0.1185	576	CMRT (E)	37.778	0.1084	576

Mean difference in CMRTs

The analysis of variance table shows that building envelope had a significant effect on CMRT. The Scheff's pairwise comparison indicated significant difference at 0.05 level between CMRT (U) and CMRT (I) with (2.89) °C. It also indicated significant difference at 0.05 level between CMRT (U) and CMRT (E) with (3.98) °C. CMRT (I) and CMRT (E) had (1.09) °C difference which was significant at 0.05 level. In other words, hypothesis 5 (similar to hypotheses 1, 2, and 3) were accepted at the specified level of significance (see Tables 6 and 7).

Table 6. Summary of Scheffe's matrix of pairwise mean differences

	CMRT (U)	CMRT (I)	CMRT (E)		CMRT (U)	CMRT (I)	CMRT (E)
MMRT (U)	0.0000			CMRT (U)	0.0000		
MMRT (I)	-2.9931	0.0000		CMRT (I)	-2.8866	0.0000	
MMRT (E)	-3.8362	-0.8431	0.000	CMRT (E)	-3.9747	-1.0881	0.0000

Table 7. Summary of Scheffe's matrix of pairwise comparison probabilities

	CMRT (U)	CMRT (I)	CMRT (E)		CMRT (U)	CMRT (I)	CMRT (E)
MMRT (U)	1.0000			CMRT (U)	CMRT(U)	1.000000	
MMRT (I) .000009	1.000000	CMRT (I)	CMRT(I)	.000009	1.00000	
MMRT (E).000009	.000003	1.00000	CMRT (E)	.000009	.000001	1.00000

Measured and Calculated MRTs (MMRT vs. CMRT)

The measured and calculated MRT's for uninsulated and externally insulated buildings indicated no significant differences in means at 0.05 level. The internally insulated building reversed the trend and indicated significant differences between CMRT (I) and MMRT (I) at 0.05 level. However, the apparent trend was that in all building cases, the MMRT is less than CMRT with a magnitude of (0.29) °C for the building with no insulation, (0.4) °C for the internally insulated building, and (0.16) °C for the externally insulated building. The result indicated that CMRT is very close to MMRT in the case of the last building. In other words, CMRT was a very good estimate of MMRT. The floor surface temperature in the internally insulated building reduced MMRT values. One may conclude that the thermal capacity of an internal layer of a wall may affect surface temperature measurements (see Table 8).

Table 8. Summary of paired sample T-test

	N	Mean	Std dev	SE mean	T=	P	Df	95% Ci diff. of means*
MMRT (U)	576	41.46	3.71	0.15				(-0.70
vs					-1.39	0.16	1141	,
CMRT (U)	576	41.75	3.40	0.14				0.12)
MMRT (I)	576	38.47	2.66	0.11				(-0.66
vs					-3.00	0.028	997	,
CMRT (I)	576	38.87	1.76	0.073				-0.138
MMRT (E)	576	37.62	1.84	0.077				(-0.399
vs					-1.23	0.22	1083	,
CMRT (E)	576	37.78	2.37	0.099				0.091)

*95% confidence interval (CI) of difference between paired means, when CI contains zero, there is no significant difference between the means.

Conclusions

The building experiment suggested that CMRT was a very good estimate of MMRT in values, ranges, and means. The calculated MRT means are constantly higher than measured MRT means in all chambers, this may be due to the omission of the floor surface temperature. The statistical analysis found no significant difference among MMRTs and CMRTs of the uninsulated and externally insulated buildings at 0.05 level with T=-1.39, p=0.16 and T=-1.23, p=0.22 respectively.

The statistical analysis indicated significant difference in MMRT's among the buildings. The same conclusion can be drawn in using CMRT's among the buildings. The temperature means differences between the insulated buildings and the uninsulated building were predicted due to the presence of high resistance PU insulation boards. More investigation is needed to include the measurement of floor surface temperature in the calculated MRT.

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معدل درجات الحرارة الإشعاعية المحسوبة والمقاسة
في المباني التجريبية

إبراهيم عبدالله المفيز

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(قُدم للنشر في ١٤١٥/٦/٢ هـ ؛ وقُبل للنشر في ١٤١٩/٥/٢٩ هـ)

ملخص البحث. تم تشييد ثلاث غرف صغيرة الحجم في منطقة الأحساء في المملكة العربية السعودية في صيف عام ١٤٠٨هـ الموافق ١٩٨٨م. بحيث تتشابه هذه الغرف في جميع الجوانب ما عدا طريقة العزل الحراري. قام المؤلف بتركيب ألواح العزل الحراري على الأسطح الداخلية لإحدى هذه الغرف ، كما قام بتركيب ألواح شبيهة بالأولى على الأسطح الخارجية للغرفة الثانية ، أما الغرفة الثالثة فتركت بدون عزل حراري.

قام الباحث بتطوير فرضيات لتحديد العلاقة المتوقعة بين معدلات درجات الحرارة الإشعاعية (mean radiant temperature) المقاسة والمحسوبة للأسطح الداخلية للغرف. استخدمت درجات الحرارة المتذبذبة (floating temperatures) في دراسة العلاقة بين درجات الحرارة المقاسة والمحسوبة.

توصل الباحث في نهاية البحث إلى أن المعدلات المحسوبة لدرجات الحرارة الإشعاعية للأسطح الداخلية قريبة جدا من معدلات درجات الحرارة المقاسة في القيمة الوسطية والمدى. أي أنه من الممكنة وإلى حد قريب التنبؤ بمعدل درجات الحرارة الإشعاعية الحقيقية بواسطة المعدلات المحسوبة لدرجات الحرارة الإشعاعية.