

Thermal Performance of Industrial Buildings with Low Slope Metal Deck Roofs in Tropical Climates

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Abstract: Roofs are a very significant component of the building envelope especially for tropical climates. Being the part most exposed to the sun, it can cause excessive heat gains which will consequently exert a considerable influence on a building's cooling energy consumption. A recent survey has shown that most industrial buildings in the Klang Valley, Malaysia use low slope metal deck roofs. A study is being conducted to investigate the performance of this type of roof under tropical climatic conditions. Field measurements were conducted on the temperature differences of an existing low slope metal deck roof construction, the heat flux and simultaneous outdoor climatic parameters. The data were analyzed and used to simulate various configurations of the roof construction to obtain the optimum thermal performance. The cooling load of a typical industrial building and the estimated energy savings obtained by using the most favorable roof configuration were also calculated. Results of this study would be an important input to the existing Malaysian building codes as well as future building codes for tropical climates.

Keywords: Thermal performance, Metal deck roofs, Tropical climates, Building simulation

NOMENCLATURE

Symbol	Description [Units]
T _a	Outer ambient air temperature (°C)
T _i	Internal surface temperature (°C)
T _o	External surface temperature (°C)
T _{dif}	Measured temperature difference (°C)

1. INTRODUCTION

The Klang valley, located in the state of Selangor, Malaysia is hot and humid typical of tropical region. The daily temperature exceeds 25°C, 58% of the time, with a mean annual humidity of 83% with a high level of global solar radiation ranging from 12MJ/m²/day to as high as 21MJ/m²/day [1]. Consequently, non-domestic buildings in the country consume about 80% of the total energy needs with almost 50% for air-conditioning alone [2].

The structure most exposed to the sun is the roof. Therefore in a hot environment, one of the biggest heat gains is from the roofs, making the roof the most important structural element of a building [3]. Thus, there is a great theoretical potential for saving energy and electricity for buildings with insulation in the tropical region.

Metal deck roof constructions are very popular with wide ranging applications, from warehouses to factories. The study is one of a series of studies meant to investigate the performance and

characteristics of metal deck roofing in order to find ways to improve its thermal properties to reduce heat gain.

2. OBJECTIVES

The aim of the study is to investigate the most favourable roof configuration for low slope metal deck roofs, that can give optimum thermal and economic performance. The study involves both field experiments and computer simulations. using the Energy-10 software. The measurements obtained from the field experiments are then used as inputs for the simulations, to find ways to improve the roof thermal performance.

The effect of various configurations of roof construction, namely insulation thickness and its placement in the roof assembly, on its thermal performance will also be investigated using the computer simulations. Investigations are also made on its economic viability, such as the incurred energy expenses, cooling loads and payback period.

3. METHOD

The study was conducted on an existing building located inside the campus of Universiti Teknologi MARA, Shah Alam, Selangor. The building is identified as Block E and is being used as the Electrical Engineering Laboratory.

3.1 Field Measurements

Temperatures across the metal deck roof construction were measured along with heat flux and simultaneous solar irradiation and outside ambient air temperature. Figure 1, below, shows the set-up of the data acquisition system used.

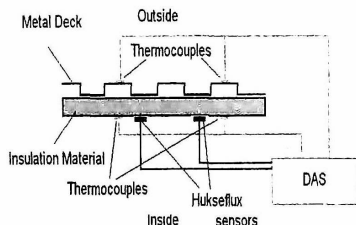


Figure 1: Diagram of Data Acquisition Set-up

Temperature readings, by means of Kx-type thermocouples with sensitivities of $\pm 2^\circ\text{C}$, were taken simultaneously at two points on the outer (top) surface of the roof (T_o) and at corresponding points directly below, on the lower (internal) surface of the insulating material (T_i). Two heat flux sensors (called hukseflux) were also placed on the lower surface of the insulating material to measure the heat flux passing through the roofing materials. The readings were logged using the Campbell CR10X data logger which collected data every 10 seconds and calculates the average value over a period of 10 minutes. Four more pairs of temperature readings across the roof were also taken using the K-type thermocouple to monitor any lateral heat transfer. Corresponding temperature difference values (T_{diff}) across the roofing materials during the observation period were also measured. The data used in the study were collected in the month of June.

The collected data were then imported into a personal computer and analysed. Simultaneously, external ambient air temperature (T_a) data were collected, and total solar irradiation recorded, using a Licor Pyranometer placed outside the building.

3.2 Simulation Work

The data were analysed and used to simulate various configurations of the roof construction to obtain the optimum thermal performance using the Kuala Lumpur yearly weather data. The cooling load of a typical industrial building and the estimated energy savings obtained by using the most favourable roof configuration were also calculated. The Energy-10 software (version 1.6) was used as the simulation software in the study.

4. RESULTS AND ANALYSIS

4.1 Thermal Performance Data

4.1.1 Building Description

The building investigated is a 30-year old, single storey rectangular shaped building, with a length of

61.5 m and a width of 12.3 m. Its walls are made of concrete and bricks with a thickness and height of approximately 0.14 m and 4.3 m respectively. The total window area is estimated at 127.8 m^2 with single glazing.

Its roof is constructed of metal deck and mineral wool insulation, with an estimated thickness of 0.5 mm and 45 mm respectively. The respective stated thermal conductivity of the metal deck and insulation material are approximately 50 W/mK and 0.04 W/mK. The roof has an air gap estimated at 1 cm thick. The roof's construction is of double pitched, at a slope of approximately 5° with an average attic space height of 0.92 m. The ceiling is of gypsum board estimated at 1 cm thick. The side of the roof monitored is generally facing the North-West direction.

4.1.2 Temperature Variation

Average "time of day" temperature values were calculated from the temperature readings within the observation period and plotted as in Figure 2.

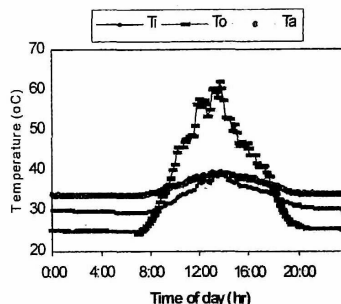


Figure 2: Variation in Internal temperature (T_i), Outside temperature (T_o) and, Outside ambient air temperature (T_a) for time of day.

During the daylight hours, it was observed that the internal temperature (T_i) rises and approaches the air temperature (T_a) due to the solar gains. However, during the night, the internal temperature is consistently above the ambient air temperature.

Generally, T_i is comparatively stable and varies within a 10°C margin. This shows that the insulation material is effective in reducing heat transfer through the roof.

Within the observation period, the ambient temperature is also quite stable with a minimum of 33.8°C to a maximum of 39.5°C .

On the other hand, the external temperature (T_o) rises to more than 60°C during the day, but falls below both T_i and T_a during the night. This characteristic may be caused by external influences such as the wind; and moisture from the air. Similar results were obtained by Harimi et al.^[4] in their study on concrete tiled roofs. Table 1 summarises the temperature variation of internal (T_i), outer surface (T_o), ambient air (T_a), and the measured temperature difference (T_{diff}).

Table 1: Average, minimum and maximum values of internal (T_i), outer surface (T_o), ambient air (T_a), and measured temperature difference (T_{diff}).

	T_i (°C)	T_o (°C)	T_a (°C)	T_{diff} (°C)
Average	32.5	34.3	35.6	2.1
Minimum	29.7	24.7	33.8	-5.3
Maximum	39.2	61.9	39.5	23.2

4.1.3 Heat Flux and Solar radiation

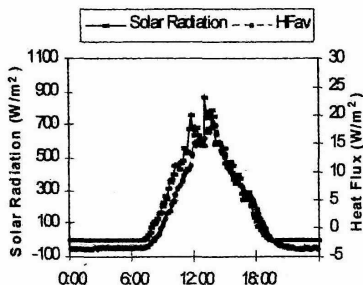


Figure 3: Average 'Time of day' solar radiation and heat flux.

The average 'time of day' heat flux follows closely the variation in solar radiation with a small time-lag. This result showed that the roof has a small thermal mass consistent with a low-weight roof.

4.2 Input for Energy-10

For simulation purposes the building is considered as a single zone shoe-box shaped building with four internal walls. While maintaining other aspects of the building, various different configurations of the roof construction were simulated.

Local material and local construction library supplied with the software are used, with the application of local electricity tariffs. In the calculation of the payback period, the local price of related materials and labour charges are used.

4.3 Comparison of various roof configurations

Simulations on the effect of various insulation thicknesses are compared with two base case references i.e. the non-insulated roof, and the actual roof setup.

4.3.1 Comparison to the non-insulated roof.

Simulations were conducted using the non-insulated roof as a reference, for 3 cases i.e. Case A: Different insulation thicknesses on the roof only; Case B: Different insulation thickness on the ceiling only and Case C: Roof insulation thickness fixed at 5cm, but with different ceiling insulation thickness. Tables 2, 3 and 4 summarizes the results of the simulations for Cases A, B and C respectively. T_1 refers to insulation

thickness on the roof and T_2 , insulation thickness on the ceiling. The corresponding R-value is denoted as R, Energy expense as E, Savings as S, Payback period as P and Cooling load as C.

Table 2: Simulation results for Case A: Insulation on Roof

T_1 (cm)	R (m ² · K/W)	E (RM*)	S (RM)	P (Yrs)	C (kWh)
0	0.37	21519	0	0	137114
5	1.66	20607	912	5.48	127512
10	2.84	20319	1200	7.92	126595
15	4.00	20167	1352	10.36	125976
20	5.18	20070	1449	12.77	125535
25	6.36	20003	1516	15.17	125263

(*RM: Malaysian Currency)

Table 3: Simulation results for Case B: Insulation on Ceiling

T_1 (cm)	T_2 (cm)	R (m ² · K/W)	E (RM*)	S (RM)	P (Yrs)	C (kWh)
0	5	0.37	21519	0	0	137114
0	10	1.53	20652	867	5.77	130859
0	15	2.70	20338	1181	8.04	128612
0	20	3.87	20178	1341	10.44	127263
0	25	5.05	20079	1440	12.85	126446
0	30	6.22	20006	1513	15.20	125875

Table 4: Simulation results for Case C: Insulation on Roof and Ceiling

T_1 (cm)	T_2 (cm)	R (m ² · K/W)	E (RM*)	S (RM)	P (Yrs)	C (kWh)
0	0	0.37	21519	0	0	137114
5	5	2.82	20317	1202	7.9	128446
5	10	3.99	20166	1353	10.35	127164
5	15	5.16	20068	1451	12.75	126390
5	20	6.34	20002	1517	15.16	125826

For every additional 5 cm of mineral wool insulation, the corresponding amount of cost incurred is estimated at RM4000. Labour charges are estimated at RM1000 for the first layer, with an increase of RM500 for each additional layer. Comparing that to the amount of energy expenses saved, it was found that 5 cm of insulation on the roof has the shortest estimated simple payback period of 5.48 years for a non-insulated building (see Table 2). This result shows that roof insulation can substantially

reduce energy usage of a building in the tropics. Similar results were also obtained in another study conducted on the effect of roof insulations in warm climatic conditions, which showed a relatively high energy consumption reduction when compared to that of cold climates^[5].

As would be expected, the simulations indicated that additional layers of insulation will increase R-values and reduce energy costs. However, this would also increase the payback period since the resulting improvement in energy savings would be offset by the increase in incurred cost.

Results also predict that in terms of investment over payback period, it is better to insulate the roof rather than the ceiling (see Tables 2 and 3). The same thickness of insulation on the ceiling produces a much higher cooling load.

Insulating both the ceiling and roof will require the highest initial investment and payback period, but the best in terms of energy expense savings as shown in Figure 4. However, effectively it can be seen that the total insulation thickness of both the roof and ceiling give almost the same results as having insulation only on the roof (compare Tables 2 and 4).

Additionally, comparing insulation thickness of 5cm between all the cases, it was found that only by insulating both the ceiling and roof would comply with the minimum R-value of 2 m²K/W as stipulated in the Malaysian Standards^[6].

Considering that the insulation material is marketed in thickness of 2.5 or 5.0 cm and the price differences between both thicknesses are very marginal, therefore, it can be deduced that the optimum thickness is taken as 5.0 cm.

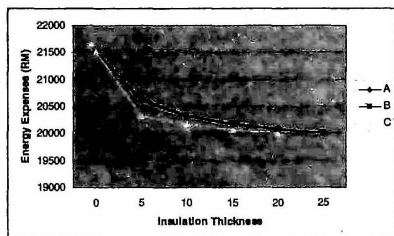


Figure 4: Comparison of Energy Expenses (E) for Cases A, B, C

4.3.2 Comparison to the actual roof.

Simulations were conducted using R-values measured from field data of the actual roof set-up, referred to as Case D. It must be noted that the R-value measured from field data was only for the metal deck roof and the insulation. This value is then added to the R-values due to the external air film, the ceiling air, the ceiling (of gypsum board) and the internal air film^[7]. Combining all these values, the final R-value is found to be 1.68 m²K/W which is very close to the theoretical value of 1.66 m²K/W for similar roof configuration with 50 mm of mineral insulation, as shown in Table 2. Thus, using the field measurements produced consistent results with that of the simulations. With the actual roof setup of 45mm

of insulation thickness as the base case reference, simulations were then conducted using increased thickness of insulations.

T (cm)	R (m ² · K/W)	E (RM*)	S (RM)	P (Yrs)	C (kWh)
0	1.68	20625	0	0	128940
5	2.86	20331	294	17.01	127512
10	4.02	20174	451	21.06	126595
15	5.20	20072	553	25.32	125976
20	6.38	20003	622	29.74	125535
25	7.56	19956	669	34.38	125263

Table 5: Simulation results for Case D: Actual Roof Set-up

The results of the simulations are as tabulated in Table 5. Looking at the payback period, it can be concluded that it is not economical to further increase the insulation thickness of the current roof. Also, again, R-values obtained from field data shows a lower value than the minimum imposed in the Malaysian Standards^[6]. As the roofing configuration of the buildings studied are representative of the current typical metal deck roof construction for Malaysian buildings, there must be urgency for further investigations and improvements on current roofing configuration and assembly of these buildings.

5. CONCLUSIONS

The temperature profiles and heat flux of an existing low slope metal deck roof, under tropical climatic conditions, were investigated and analysed. Simulation work was also carried out to obtain the optimum thermal performance by simulating various configurations of the roof construction, under the Kuala Lumpur yearly weather data, using the Energy-10 software. The results were then used as an input for the design of a new building or to improve the thermal performance of existing buildings in the tropical region.

From this study, the following conclusions may be made based on the predictions of the simulations:

1. It is important that the roof of any new building be installed with a layer of insulation on the roof. Simulations showed that roof insulation has a substantial potential impact in reducing the cooling energy cost of the building. The most economical is found to be a 5 cm layer of mineral wool which is estimated to have a simple payback period of less than 5 years.
2. It is economically better to insulate the roof rather than the ceiling
3. Insulating both the ceiling and roof will require the highest initial investment and payback period, but the best in terms of energy expense savings.
4. Current R-values of industrial buildings with low slope metal deck roofs does not comply with the

minimum standards of 2 m²/KW as stipulated in the Malaysian Standards.

Research on thermal performance of roofs is especially vital for tropical climates as it has a substantial impact on energy consumption and cooling loads. It is important that localized research be conducted to obtain realistic results. Further studies needs to be done to determine the impact of lowering heat gains through roofs on energy savings by modifying the roof assemblies or types of insulation as well as other radiant heat retardant roofing systems specially developed for tropical climates.

Improving the thermal performance of roofs will have a great impact on reducing overall energy cooling needs and consequently, greater environmental benefits. While monetary gains remain an important factor and incentive to encourage energy efficiency awareness, it must be emphasized that it should not be at the expense of environmental degradation. The overall economic viability should be inclusive of un-quantifiable benefits such as environmental protection and contribution to the reduction in scale of climate change.

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