Simulated Solar Light Set of Investigating the Commercial Roof and Insulation Types in Tropical Humid Country

Sumol Sae-heng Pisitsungkakarn[1,*] and Kanokkarn Jirakulsomchok[1]

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ABSTRACT

This research investigated Roof Thermal Transfer Value (RTTV), energy consumption, and economic analysis of roofs and insulation through the experiment by setting the heat flux at 500, 700, and 900 W/m^2 respectively. Five roof types were investigated, namely the transparent roof, corrugated ceramic roof tiles, the corrugated metal sheet roof, corrugated and slope concrete roof tiles which were installed at the angle 15° and 45°. The results showed that all types of roofs installed at an angle of 45 had less energy consumption than those at an angle of 15. When comparing the corrugated concrete roof tiles with the metal sheet roof which were most often selected for house and industry roof construction, it was found that the metal sheet roof had a steady temperature whereas the concrete roof tiles had continuous heat accumulation. Installing the fiberglass insulation under both roof types can significantly reduce RTTV and energy consumption about 38% and 98% respectively as compared to the absence of insulations.

1. INTRODUCTION

Nowadays, the world is warming since humans have destroyed nature by deforesting and creating environmental pollution that has resulted in the greenhouse effect [1]. Many countries, especially tropical humid countries, suffer from the destruction of the nature and environment. At the present, the seasons are different from the past. The temperature of the weather during the summer is higher than usual, and it rains less in the rainy season. These variations in climate are caused by global warming which is difficult to curb [2]. This accounts for why the world's environmental and energy problems are very important in that they should be eliminated and solutions are to be found. Energy-saving is an issue of interest due to the unbalance of energy consumption resulting in climate change which is challenging to be solved [3, 4].

For that reason, smart technology to increase energy efficiency is more important for inventing various innovations [5]. This is the source of research about energy saving in buildings for consumers to control the on-off operation of home appliances [6]. Previous research showed that the growth of smart technology is still in the start phase. As the design has not taken into account the behavior and perception of a sufficiently large group of people, it cannot be used effectively [7]. It requires further developments in smart technology in the future. However, the designs of the house and the roofs are an alternative to reduce energy consumption. The enveloped structure of the building is the most bearable part, which directly affects the thermal and energy consumption of the building [8]. It is strongly believed that if the roof of the building is properly designed, this directly affects the reduction of energy consumption of indoor air conditioners.

Previous research showed efficiency in reflecting solar radiation and roof heat absorption in comparing terracotta tiles uncoated with terracotta tiles coated with white engobe glaze and colors by using silicon carbide as a binder. The results demonstrated that the binder did not affect the appearance and reflection of solar radiation because chemical characteristics were similar to clay, which was a substrate used in tile material and was more efficient than organic binders such as an acrylic matrix. It was also found that terracotta tiles coated with white engobe glaze had the best solar reflectance rate [9], resulting in better cooling of the room and reducing the lifespan of the roof by 37%. The relationship between the effect of solar reflection and the service life of various glazed tiles within 3 years showed that coating can significantly reduce indoor energy consumption because it has good energy absorption [10].

In addition, types of roofs affect cooling load and energy consumption within the building [11] such as clay tile roofs [12], horizontal flat roofs [13], and concrete cool roofs [14]. There are many types of roofs. To exemplify, a green material roof uses plants and soil moisture as a heat shield from solar radiation and is environmentally friendly [15]. A heat absorbing material roof is a glazed roof with several

[1]*Research Centre for Combustion Technology and Alternative Energy (CTAE), College of Industry Technology (CIT), King Mongkut's University of Technology North Bangkok (KMUTNB), Bangkok, Thailand.*

**Corresponding author:* Sumol Sae-heng Pisitsungkakarn; Phone: +66-810-677-779; Email: sumol.s@cit.kmutnb.ac.th.

layers coated to increase heat capacity and save energy up to 47.5% [16]. A concrete roof employs concrete compounds and reinforcement [17, 18]. An insulant material roof utilizes insulation or air vents under the roof to reduce its temperature [19]. A reflective material roof uses a solar reflective material [20]. A metal material roof can help control the amount of heat radiation generated within the roof [21].

The thickness of the roof and the angle of roof installation affected by the heat generated by the temperature varies with the thickness of the roof [22, 23], and the angle of roof installation affects the amount of energy consumption [24, 25]. It was found that the energy consumption increased when the roof angle was acted on the flat ground by 20°, while that decreased when the roof angle acted on the sloping floor was adjusted by 10° [26]. It was discovered that increasing the thickness of the phase change layer and glazing layer can improve the thermal insulation performance of the roof [27].

The concept of reducing roof heat transfer by using a variety of roofs and insulation materials is to increase solar reflection and reduce energy consumption within the building [28]. The present study was intended to study the total heat transfer through a roof and insulation [29], along with energy consumption in an air-conditioned room under each type of roof and insulation by using a heat transfer testing prototype with the latter at different heat flux values and different roof angles. The results can be drawn on to develop energy-saving roof innovations in the future and provide more choices of construction materials [30].

2. MATERIALS AND METHODS

2.1. Types of Roofs and Insulation

The sample in this experiment consisted of five roof types and three insulation types, which were investigated in a cross-sectional area as shown in Fig. 1. The five roof types without insulation were: type 1 corresponding to the corrugated concrete roof tiles (30 mm thickness and size 440 mm×320 mm), type 2 corresponding to the slope concrete roof tiles (30 mm thickness and size 440 mm×320 mm), type 3 corresponding to the corrugated ceramic roof tiles (30 mm thickness and size 440 mm×320 mm), type 4 corresponding to the transparent roof (0.28 mm thickness roof and size 1,040 mm×650 mm), and type 5 corresponding to the corrugated metal sheet roof (0.35 mm thickness and size 1,040 mm×650 mm).

Thailand is one of the tropical humid countries where the concrete roof tiles in double corrugated standard is most often used in the construction house and the Aluzinc metal sheet roof is most frequently used in the construction of industrial plants. Consequently, this accounts for why both roof types with three insulation types under the roofs were investigated in relation to heat transfer as follows: type 1 corresponding to the fiberglass insulation within aluminium foil 75 mm thickness, type 2 corresponding to the bubble insulation within aluminium foil 20 mm thickness, and type 3 corresponding to the polyethylene foam insulation within aluminium foil 10 mm thickness.

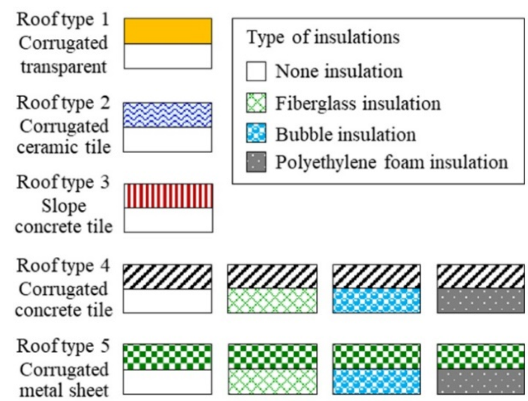

Fig. 1. Cross-sectional area of roof and insulation structure in the experiment.

This research took into consideration the most widely used variants of roofs in the residential building construction sector in a tropical humid country. The insulation types were made of three different materials, which are among the most available in the local markets and the most commonly used in constructions. The thermophysical properties of the materials are shown in Table 1 [31]-[37]. The abbreviations in the table have the following meanings: L is abbreviated from thickness, ρ from density, k from thermal conductivity, c from specific heat, α from solar absorptivity, σ as a symbol of solar reflectivity, and ε a symbol of surface emissivity.

2.2. Experiment and Measuring

The design was divided into two parts: an air-conditioned room and solar lights. The air-conditioned room was made of plywood with 10 mm thickness, which had a volume about 650 mm in width, 1040 mm in length, and 577 mm in height. The roof was designed for stacked 6 tiles in size 330 mm × 420 mm and can be adjusted to fit the experiment. The second part was a simulated solar light set assembled with the aluminum construction and the air-conditioned room, which was designed by using 6 spotlights and 500 Watt in each spotlight. The light fitted the entire roof area. The heat flux can be adjusted by three dimmers with 1,200 Watt. Each dimmer controlled two spotlights. The aluminum construction had a slide rail to facilitate adjusting the direction of the light distribution. The details are shown in Fig. 2a. The simulated solar light set assembled with the air-conditioned room was designed not only to fit experimental room for indoor testing but also to be easy to change the experimental materials and to control the room temperature.

The roof thermal transfer value (RTTV) and the total energy consumption were determined by adjusting the heat flux of the solar light unit according to the specified conditions at 500, 700, and 900 W/m^2, respectively.

Table 1. Thermophysical properties of the materials

Materials	L (mm)	ρ (kg/m³)	k (W/mK)	c (kJ/kgK)	α	σ	ε
Translucent fiberglass roof	1.20	1,700	0.181	1.880	0.18	0.36	0.59
Ceramic roof tile	10.00	2,100	0.338	0.800	0.70	0.86	0.90
Concrete roof tile	27.00	2,400	0.993	0.790	0.70	0.44	0.93
Metal sheet roof	0.35	2,672	211	0.896	0.75	0.67	0.20
Plywood	10.00	900	0.213	1.210	0.90	0.15	1.00
Air gap	-	1.225	-	1.020	-	-	-
Gypsum board	6.00	800	0.282	1.090	0.50	0.85	0.90
Fiberglass insulation	75.00	56	0.031	0.960	0.31	0.90	0.85
Bubble insulation	20.00	93	0.040	0.932	0.15	0.90	0.25
Polyethylene foam insulation	10.00	45	0.029	1.210	0.30	0.97	0.11

The solar power meter of CEM in model DT-1307 was used for measurement. The heat flux used in the experiment was simulated from the average solar radiation in Thailand; specifically, the summer season is very hot and has heat gain similar to the heat flux of about 900 W/m^2, while the winter season is very cool and had less heat gain similar to the heat flux of about 500 W/m^2, as well as the average heat flux of about 700 W/m^2.

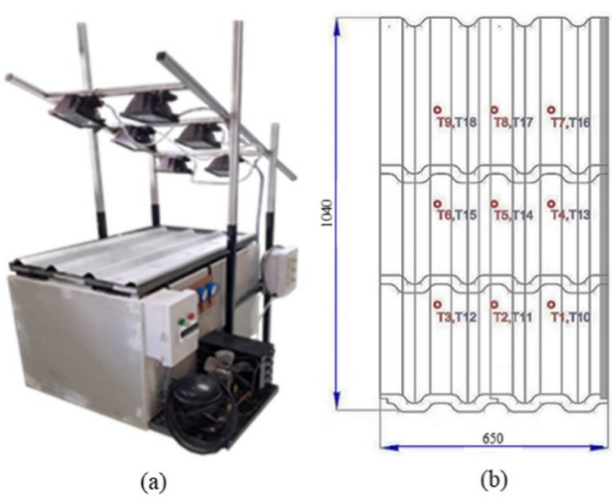

Fig. 2 Experimental setting (a) simulated solar light set assembled with the air-conditioned room and (b) location of measured roof temperature: outside and inside roof.

The thermocouple with high thermal resistance in Type K was installed at 9 points on the roof, 9 points under the roof, 4 points on the ceiling, 4 points under the ceiling, 1 point within the air-conditioned room, and 1 point outside the air-conditioned room as shown in Fig. 2b. The experimental temperature profiles were recorded every 5 minutes in one hour by data loggers of Pico Technology in model TC08. However, the roof temperature gradually raised from the start-up to 20 minutes of the experiment, and after that, the system entered the steady state. The experimental results only during the steady-state period from 20 minutes onwards were presented. The air-conditioned temperature was set at 298 K, and the compressor's electric current was measured t by a digital clamp meter in model DT-600A.

In this research, the roof and luminaire angle were acted on the flat surface at 15° and 45° for the deviation of the construction error about ±5 degrees to cover the normal construction at 15° - 40°.

2.3. Economic Analysis

The measured temperature profiles were calculated in the total roof thermal transfer value to evaluate the heat transfer of each roof type. This value is widely used in Southeast Asia to estimate the amount of heat radiation transferred through the roof [38]. The RTTV equation is as follows [39]:

$$RTTV = (U_r)(1\text{-}SRR)(\Delta T) \tag{1}$$

where, RTTV is the roof thermal transfer value in the unit of W/m^2, U_r denotes the coefficient of opaque roof thermal transfer in the unit of W/m^2, SRR the ratio of transparent roof area per overall roof area, and ΔT the average temperature difference between the outside and inside roof in the unit of K.

In addition, the total energy consumption was calculated to evaluate energy-saving of each roof and insulation t from the following equation [40]:

$$ENC = ((PC_{onype} \times \%t_{on}) + (PC_{off} \times \%t_{off})) \times t \tag{2}$$

where, ENC stands for energy consumption in the unit of kWh, PC for power consumption in the unit of kW, PC_{on} for power consumption in compressor working in the unit of kW, PC_{off} for power consumption in compressor not working in the unit of kW, $\%t_{on}$ for percentage of the compressor working time in the unit of minutes, $\%t_{off}$ for percentage of the compressor not working time in the unit of minutes, and t for operating time in the unit of minutes.

The electricity cost was determined from the following equation [40]:

$$ELC = ENC \times ENP \quad (3)$$

where, ELC is abbreviated from the electricity cost in the unit of Baht and ENP from energy price in the unit of Baht/kWh.

To evaluate an investment cost, the payback period was taken into consideration from the following equation [39]:

$$PBP = INV / ELS \quad (4)$$

where, PBP is abbreviated from the payback period in the unit of years, INV from an investment cost in the unit of Baht, ELS from electricity saving in the unit of Baht.

In this research, energy consumption was calculated at an hourly rate per day so that it can be easily applied different operating times in the actual period. The parameters used in the calculations for RTTV, the energy consumption, and economics, namely the electricity cost and payback period, are shown in Table 2.

Table 2. Parameters used in the economic calculations.

Parameters	Value
Total operating time per year	365 days/year
Energy price	4.5 Baht/unit
Translucent fiberglass roof, cost	472 Baht/m^2
Corrugated ceramic roof tile, cost	513 Baht/m^2
Slope concrete roof tile, cost	199 Baht/m^2
Corrugated concrete roof tile, cost	137 Baht/m^2
Corrugated metal sheet roof, cost	27 Baht/m^2
Fiberglass insulation, cost	125 Baht/m^2
Bubble insulation, cost	196 Baht/m^2
Polyethylene foam insulation, cost	106 Baht/m^2

3. RESULTS AND DISCUSSION

3.1. Effect of Heat Flux

In the roof test with varied heat fluxes, the test results of a ceramic roof at the heat flux of 500, 700, and 900 W/m^2 are illustrated in Fig. 3. The temperature values were measured at locations as follows: the inside roof, the outside roof, on the ceiling, and under the ceiling. In Fig. 3a, 3b, and 3c, the result revealed that a heat flux at 500 W/m^2 had roof temperature less than that at 700 and 900 W/m^2 respectively.

The average temperature difference between the outside roof and the inside roof of the ceramic roof with an angle of 45° was approximately 12.43 K, 15.58 K, and 16.42 K at a heat flux of 500, 700, and 900 W/m^2 respectively. It should be noted that the inside roof temperature increased in all cases. Because the heat flux of 900 W/m^2 was comparable to the very hot weather in Thailand's summer, the outside roof had the highest temperature. It indicated that the higher temperature of a ceramic roof was proportional to the increasing heat flux.

3.2. Effect of Roof Angle

In terms of roof installation tested with the varied angles, the test results of a ceramic roof with the heat flux of 700 W/m^2 are displayed in Fig. 4. The roof temperature was measured every 5 minutes. The temperature inside the air-conditioned room was set up at 298 K while the roof angle was set up at 15° and 45°.

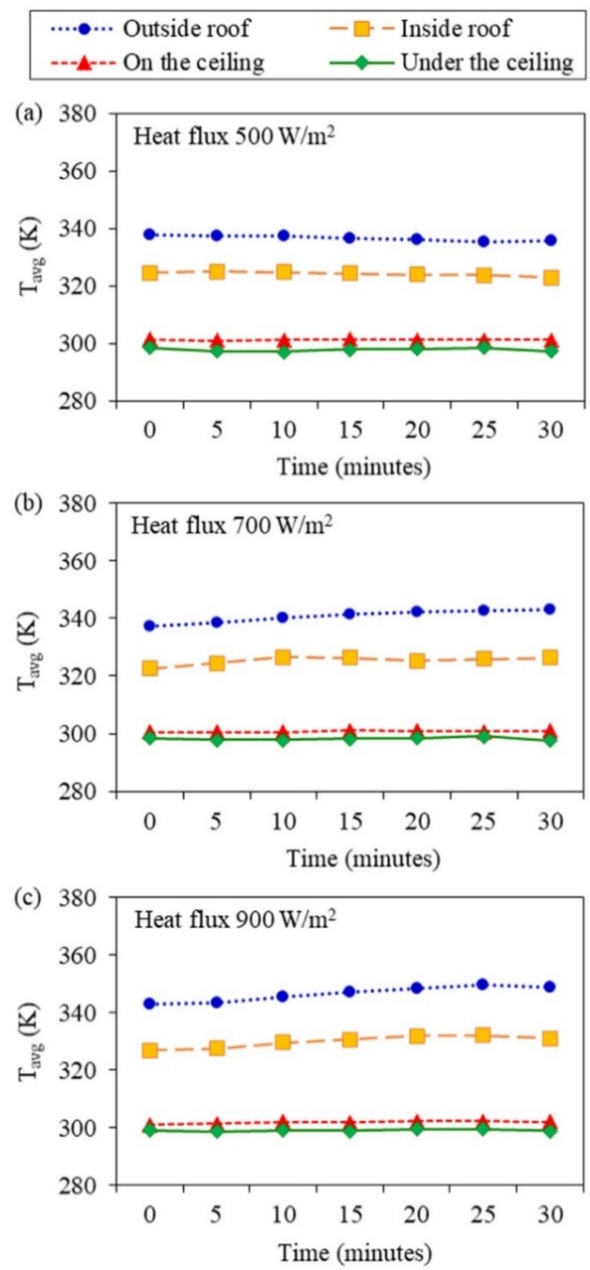

Fig. 3 The measured temperature of the ceramic roof with an angle of 45° at different heat fluxes: (a) 500 W/m^2, (b) 700 W/m^2, and (c) 900 W/m^2.

From the ceramic roof with the heat flux of 700 W/m², the result revealed that the roof installed at the angle of 15° had an average temperature difference between the outside and inside roof of approximately 8.91 K. It was less than that at an angle of 45° with an average temperature difference between the outside and inside roof of approximately 15.44 K. This was due to the fact that the 45° roof angle had more attic gaps than the 15° roof angle, thus having less roof heat transfer. As a result, adjusting the angle of the roof with more air gaps affected more heat reduction of the roof. Considering testing with other roof types and adjusting the heat flux values, it was found that changing the angle of the roof to widen the attic gap can decrease the heat transfer under the roof.

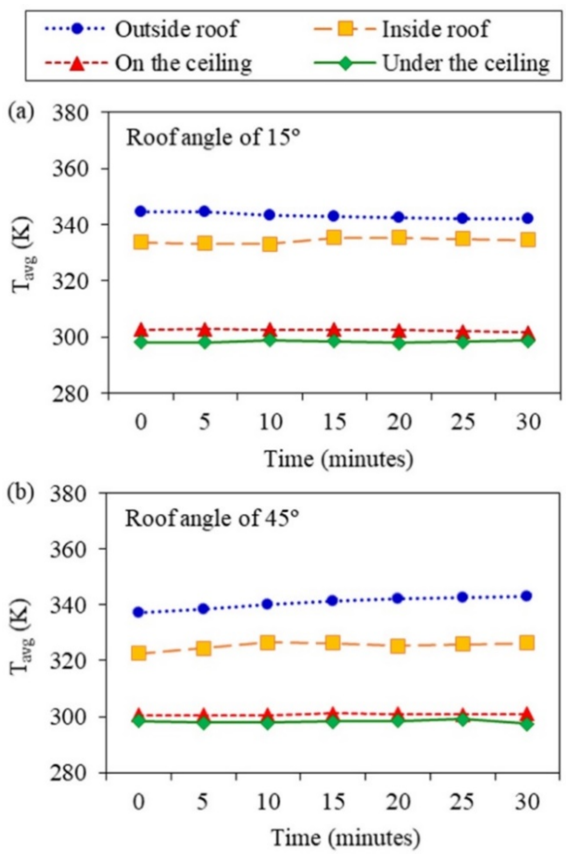

Fig. 4 The measured temperature of the ceramic roof at the heat flux of 700 W/m² with different roof angles: (a) roof angle of 15° and (b) roof angle of 45°.

3.3. Energy Consumption of Roofs

In this section, the five roof types were selected to investigate the energy consumption. As shown in Fig. 5, the highest energy consumption of all roof types was at 900 W/m², while the lowest was at 500 W/m². Both graphs indicated that the corrugated and slope concrete roof tiles were the same materials, so their energy consumption was similar. The roof installed at an angle of 15 illustrated that the transparent roof had a significant maximum value of energy consumption, which was higher than the corrugated ceramic roof tiles, the slope concrete roof tiles, the corrugated concrete roof tiles, and the corrugated metal sheet roof of about 35.79%, 33.39%, 30.14% and 32.88% at the heat flux of 900 W/m² as evidenced in Fig. 5a. Considering roof installation at an angle of 45, the metal sheet roof and the transparent roof had higher energy consumption than corrugated ceramic roof tiles, slope concrete roof tiles, and corrugated concrete roof tiles. The slope concrete roof tiles had the least energy consumption, which was less than the transparent roof of approximately 33.33% at the heat flux of 900 W/m² as shown in Fig. 5b.

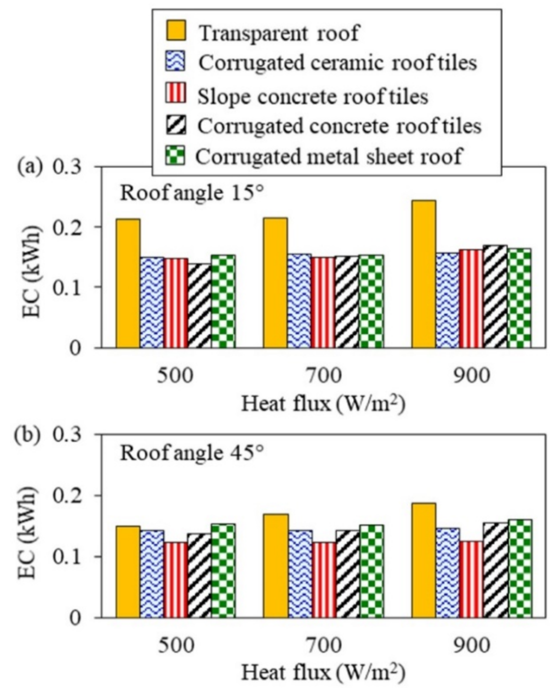

Fig. 5 The energy consumption at the heat fluxes of 500, 700, and 900 W/m² of different roof types by using different roof angles: (a) roof angle 15°, and (b) roof angle 45°.

It can be concluded that the roof installed at the angle of 45 had less energy consumption than that at 15. For all types of the roofs, the attic space affected heat transfer. As the results showed, the transparent roof had the most heat transfer from the ambient to space under the roof. The corrugated metal sheet roof had the highest energy consumption of the opaque materials in this experiment, while the slope concrete roof tiles had the least energy consumption and heat transfer. However, the corrugated roof was well-drained and easier to install and cost less than the sloping roof; given that the corrugated roof was bent to increase strength, the thickness of the corrugated roof was not required to be equal to that of the sloping roof. Consequently, the corrugated concrete roof tiles and the corrugated metal sheet roof are most preferable for house and industry construction in Thailand. This research selected both roofs to study the effects of different insulations under the roof in the next section.

3.4. Effects of Insulations under the roof

In this section, the corrugated concrete roof and the metal sheet roof were selected to investigate the effect of insulations under the roof. Three types of insulations such as fiberglass, bubble, and foam insulation, were studied and compared with the roof without insulation. Figure 6 shows the measured temperature of the different insulations under the corrugated concrete and metal sheet roof at the heat flux of 700 Wm^{-2} and the roof angle of 45°. The result revealed that the temperature of the concrete roof and the metal sheet roof without insulation had similar trends as shown in Figure 6a and 6e. It can be noted that the metal sheet roof had higher solar reflectance than the concrete roof tiles, which can be observed from the temperature of both outside and inside roof temperature.

In respect of the concrete roof, the results revealed that the outside roof temperature without insulation was stable, while the outside roof temperature increased with the time for installation of all insulation types. The heat flux had simulated stable heat of solar radiation, and then insulations had continuous heat accumulation as shown in Figure 6b, 6c, and 6d, so the maximum temperature of the outside roof was investigated, along with that of the inside roof and under the ceiling to explore the effect of insulations under the concrete roof.

The concrete roof without insulation had the lowest temperature difference between the outside and inside roof of approximately 5.23 K, while the fiberglass insulation installation under the concrete roof had the highest temperature difference reached about 42.91 K, which was higher than the case of bubble insulation and foam insulation of approximately 12% and 38.08% respectively. The results pointed out that the insulation can reduce heat gain dramatically. On investigation of the insulation types, it found that the fiberglass insulation was the most effective insulator, followed by the bubble insulation and the foam insulation which was regarded as the least effective insulator for the concrete roof in this heat transfer test. Considering this fact, the thermal resistance of the bubble insulations had the highest heat transfer coefficient about 3.18 m^2K/W, which was higher than the fiberglass insulation of about 25%, but the fiberglass insulation had the most thickness, which was about three times thicker than the bubble insulations. On the contrary, the polyethylene foam insulation had the least thickness and thermal resistance about 10 mm and 0.34 m^2K/W respectively. Thus, a part of the thermal resistance of the insulation was a significant factor, and the thickness of the insulation was one of the factors to reduce the amount of solar radiation through the building.

As regards the metal sheet roof, the results revealed that the outside roof temperature of the metal sheet roof without insulation was slightly higher than the inside roof temperature, while the temperature of the outside roof with all insulation types was significantly higher than that of the inside roof as the thermal insulation can reduce roof heat transfer. Apart from that, the metal sheet roof had high solar reflectance and was unable to accumulate more heat continuously; thus, the temperature was steady as shown in Fig. 6f, 6g, and 6h. The maximum temperatures were similar to the average temperature, and it was used to investigate the results. The metal sheet roof without insulation had the lowest maximum temperature difference between the outside and inside roof approximately 10.45 K, while the fiberglass insulation installation had the highest temperature difference between the outside and inside roof approximately 33.30 K, which was higher than the roof with bubble insulation and polyethylene foam insulation of approximately 15.65% and 30.03% respectively. The results confirmed that the fiberglass insulation was the most effective insulator for the metal sheet roof in this test, in line with the results of the concrete roof.

When the temperature difference between the outside roof and under the ceiling was compared, it was found that the metal sheet roof without insulation had the lowest maximum temperature difference about 30.40 K, while that installed with the fiberglass insulation had the highest maximum temperature difference approximately 36.59 K, which was higher than the temperature difference between the outside and inside roof of about 65.63% and 9% respectively. With respect to bubble insulation and polyethylene foam insulation, the temperature difference between the outside roof and under the ceiling of the roof was higher than that between the outside and inside roof of approximately 18.96% and 26.38% respectively. These results were akin to the case of the concrete roof.

It can be concluded that the outside roof temperature of the metal sheet roof was slightly lower as it had higher solar reflectance than the concrete roof. Installing the insulation under the roof can significantly reduce heat gains when compared to those cases without insulation. The corresponding values indicated that the fiberglass insulation was the most effective insulator in both roof tests, whereas the polyethylene foam insulation was the least effective insulator in both roof tests. In addition, the installation of the ceiling can reduce heat gains less than that of insulation under the roof.

3.5. RTTV and Energy consumption

The roof thermal transfer value (RTTV) and energy consumption in an hour of both roof types at the angle 45° and the heat flux of 700 W/m^2 were compared as displayed in Fig. 7. The results illustrated that the concrete roof tiles and the metal sheet roof without insulation had the highest RTTV about 28.598 W/m^2 and 43.003 W/m^2 and the highest energy consumption about 0.1428 kWh and 0.1507 kWh respectively. It could be confirmed that the insulations increased the protection of solar radiation through the roof.

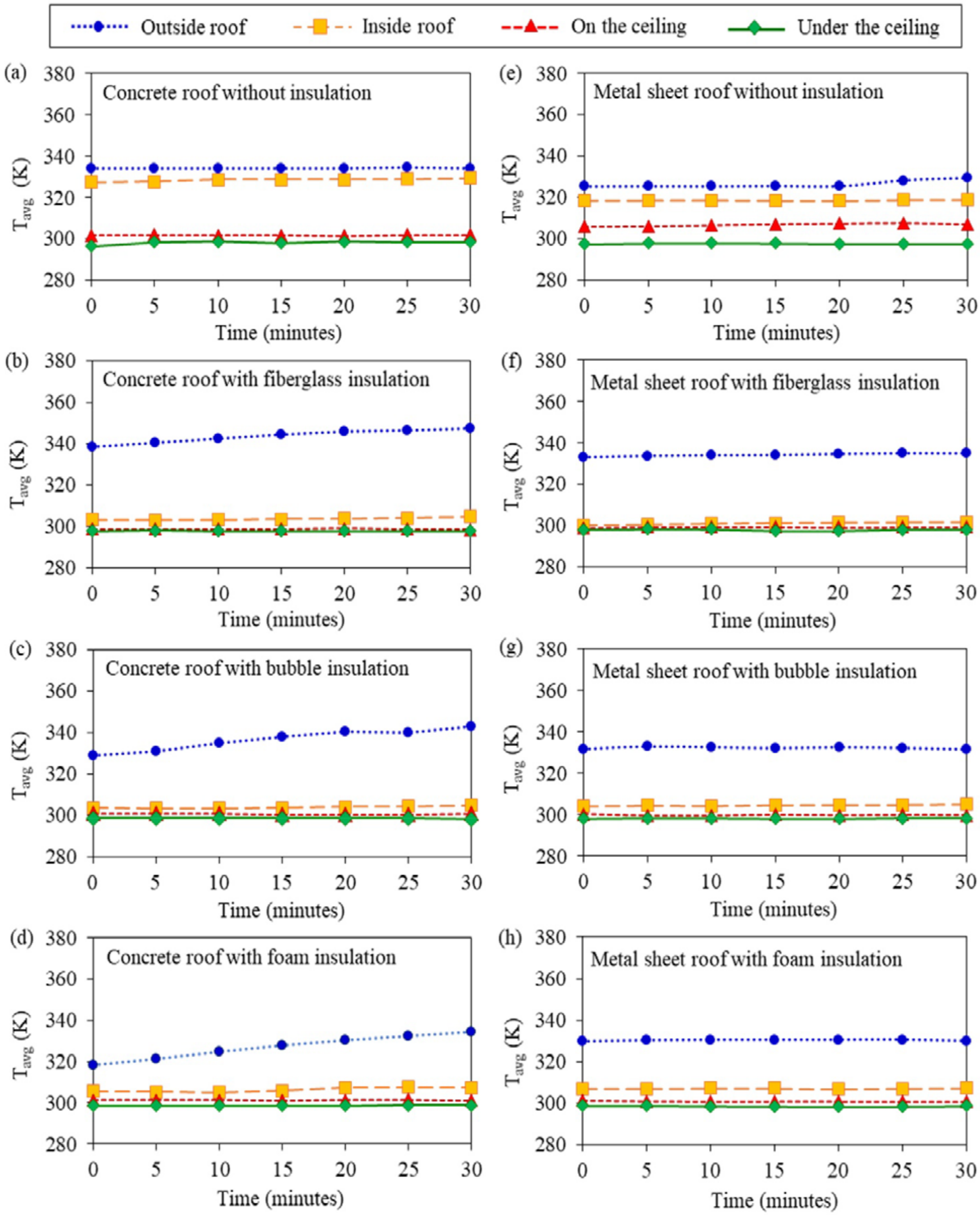

Fig. 6. The measured temperature at the heat flux 700 W/m^2 and roof angle of 45° of the roofs with different insulations: (a-d) the concrete roof and [22] the metal sheet roof, different insulations: (a and e) roof without insulation, (b and f) roof with fiberglass insulation, (c and g) roof with bubble insulation, and (d and h) roof with polyethylene foam insulation.

As insulation types under the concrete roof tiles were compared, it was found that the fiberglass insulation installed under the concrete roof tiles had the lowest RTTV and energy consumption approximately 0.542 W/m^2 and 0.0901 kWh respectively, which were lower than the roof with the bubble insulation of about 33.25% and 1.85% respectively.

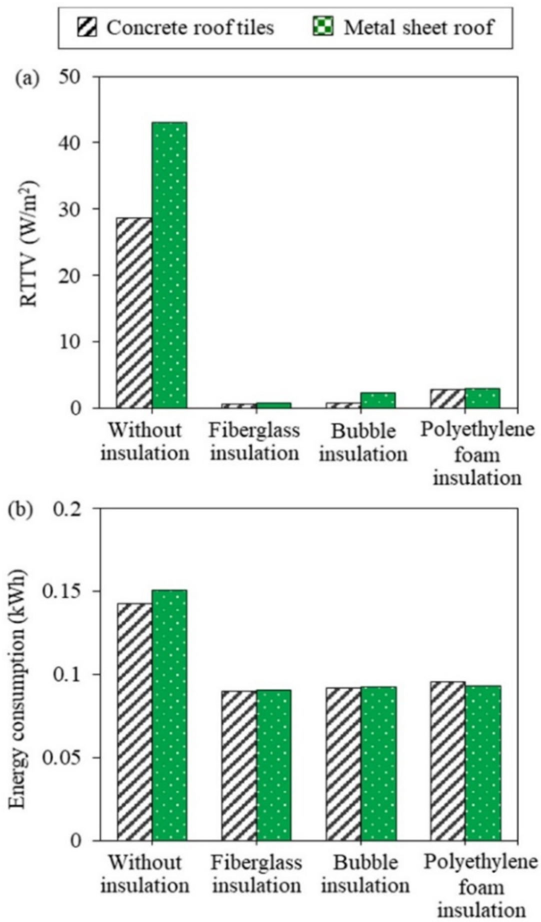

Fig. 7. Comparing the results between the concrete roof and the metal sheet roof with different insulations at the heat flux 700 W/m^2 and roof angle of 45°: (a) RTTV, and (b) hourly energy consumption.

This may lie in the fact that the thermal resistance of both insulations was similar, but the fiberglass insulation was thicker than the bubble insulation; as a result, the fiberglass insulation was most effective in reducing energy consumption for the concrete roof. On the other hand, the concrete roof tiles with polyethylene foam insulation had the highest RTTV and energy consumption approximately 2.804 W/m^2 and 0.0957 kWh respectively; this can be explained by the fact that the polyethylene foam insulator had the lowest thermal resistance and thickness.

When insulation types under the metal sheet roof were compared, it was found that that the fiberglass insulation installed under the metal sheet roof had the lowest RTTV and energy consumption approximately 0.699 W/m^2 and 0.0905 kWh respectively, which were lower than the roof with the bubble insulation of about 70.68% and 2.37% respectively. The metal sheet roof with polyethylene foam insulation had the highest RTTV and energy consumption approximately 2.895 W/m^2 and 0.0931 kWh respectively. These results were compliant with those of the concrete roof tiles in that installing fiberglass insulation under both roof types resulted in a significant reduction in energy consumption.

In addition, the results indicated that the RTTV and energy consumption of the metal sheet roof without insulation were higher than those of the concrete roof of about 33.5% and 5.24% respectively, and the metal sheet roof with fiberglass insulation had higher RTTV and energy consumption than the concrete roof of about 22.46% and 0.44% respectively. Despite being small in thickness, the commercially metal sheet roof is has high reflectivity, which significantly reflects the solar radiation.

3.6. Economic Analysis

This research presented an economic analysis to determine the optimal combination between the energy consumption and the payback period from the investment in roof construction and building renovation as shown in Table 3. ENC had the unit of kWh/year, ELC is abbreviated from the electricity cost in the unit of Bath/year, ENS from energy saving in the unit of kWh/year, ELS from electricity saving in the unit of Bath/year, INV from an investment cost in the unit of Bath, and PBP from the payback period in the unit of year. It can be noted that the total energy consumption and economic analysis of roof were shown at the heat flux of 700 W/m^2 and the roof angle 45º. For an explicit comparison, this analysis was divided into two parts. The first part concerned the yearly energy consumption and electricity cost, including the yearly energy saving and electricity saving as shown in the first four columns.

Firstly, the five roof types without insulations were investigated to consider the energy-saving roof. The results demonstrated that the transparent roof without insulation had the most yearly energy consumption and electricity cost, so it was defined as a reference case in comparison of all roof types. If the roof was changed from transparent materials to opaque materials, the corrugated metal sheet roof had not only less yearly energy consumption of about 11.51% but also less yearly electricity cost than the transparent roof at approximately 32.19 Baht. On the contrary, the slope concrete roof tiles had the least yearly energy consumption; the metal sheet roof cannot reduce solar energy absorption as its yearly energy consumption was about 10.53% higher than that of the concrete roof tiles. However, given that the metal sheet had the lowest thickness and weight, it can reduce the cost of roofs, beams, and piles, which were suitable for showrooms, coffee shops, and factory construction. Considering appearance, the yearly energy consumption and electricity cost of the corrugated concrete roof tiles without insulations were similar to those of the corrugated ceramic roof tiles and higher than those of the slope concrete roof tiles of about 13.72% and 32.19 Baht respectively. Nevertheless, the standard corrugated roof could help drain the rain well; thus, it was a preferable roof feature for house construction in Thailand.

Table 3. Total energy consumption and economic analysis of roof per year.

Roof parameters	Insulation parameters	ENC (kWh)	ELC (Baht)	ENS (kWh)	ELS (Baht)	INV (Baht)	PBP (years)
Comparison of roof types							
Translucent fiberglass roof	none	62.16	279.72	-	-	392.52	0.000
Corrugated ceramic roof tile	none	52.27	235.21	9.89	44.51	426.61	9.584
Slope concrete roof tile	none	44.97	202.36	17.19	77.36	165.50	2.139
Corrugated concrete roof tile	none	52.12	234.55	10.04	45.17	114.00	2.524
Corrugated metal sheet roof	none	55.01	247.52	7.15	32.19	22.45	0.697
Comparison of insulation types under corrugated concrete roof tiles							
Corrugated concrete roof tile	none	52.12	234.55	-	-	114.00	0.000
Corrugated concrete roof tile	fiberglass	32.89	147.99	19.24	86.56	217.88	2.517
Corrugated concrete roof tile	bubble	33.51	150.78	18.62	83.77	276.92	3.306
Corrugated concrete roof tile	foam	34.93	157.19	17.19	77.36	202.08	2.612
Comparison of insulation types under corrugated metal sheet roof							
Corrugated metal sheet roof	none	55.01	247.52	-	-	22.45	0.000
Corrugated metal sheet roof	fiberglass	33.03	148.65	21.97	98.88	126.40	1.278
Corrugated metal sheet roof	bubble	33.84	152.26	21.17	95.26	185.45	1.947
Corrugated metal sheet roof	foam	33.98	152.92	21.02	94.61	110.60	1.169

For this reason, the corrugated concrete roof tiles and the corrugated metal sheet roof with three insulation types were analyzed. In terms of the corrugated concrete roof tiles, the results showed that installing the foam insulation achieved the highest yearly energy consumption and electricity cost, which was less than the absence of the insulation of about 32.98% and 77.36 Baht respectively. However, installing the fiberglass insulation resulted in the least yearly energy consumption, which was lower than the bubble and the foam insulations of about 1.89% and 6.22% respectively. In the same manner, the corrugated metal sheet roof installed with foam insulation achieved the highest yearly energy consumption and electricity cost, which were less than the absence of the insulation of about 38.22% and 94.61 Baht respectively. Nevertheless, installing the fiberglass insulation resulted in the least yearly energy consumption, which was lower than the bubble and the foam insulations of about 2.43% and 2.87% respectively. It could be concluded that all types of insulated roofs were dramatically energy-efficient and cost-effective as compared with the absence of insulations because these can reduce heat from solar radiation and prevent heat into the room. Hence, this finding emphasized that installing fiberglass insulation under both roof types was most energy-saving.

Secondly, the investment cost and payback period of the roof with insulations were analyzed as illustrated in Table 3. According to the comparison of roof types without insulation presented in the first section, the results indicated that the transparent roof and the corrugated ceramic roof tiles had the high investment cost and long payback period, which were not a favorable investment option. Considering energy saving, the slope concrete roof tiles were the most yearly energy efficient and cost effective, but it had a higher investment cost than the corrugated concrete roof tiles of about 31.12%. Taking into account the above reasons, the corrugated concrete roof tiles were studied in respect of installing insulation under the roof. On the contrary, the corrugated metal sheet roof had the cheapest investment cost and the fastest payback period; therefore; the corrugated metal sheet roof with insulation was investigated to compare the results.

From the comparison of insulation types under the corrugated concrete roof tiles, installing the polyethylene foam insulation had the cheapest investment cost, but with the additional investment of about 15.8 Baht to change from the polyethylene foam insulation to the fiberglass insulation, the fastest payback period would be 2.517 years and energy saving would rise about 10.63%. In contrast, installing the bubble insulations had a longer payback period than the fiberglass insulation of about 0.789 years, yet it only increased energy-saving by approximately 1.85%. It showed that the bubble insulation had the highest investment cost and longest payback period, and the polyethylene foam insulation had the highest yearly energy consumption and electricity cost. Thus, it was not suggested for investment. On the other hand, the fiberglass insulation not only had the shortest payback period but also was most energy-saving, regardless of the fact that it had a more expensive investment cost than the absence of the insulations of about 47.68%. However, it was most suitable for investment when considering the overall results.

In the same way, the corrugated metal sheet roof with polyethylene foam insulation had the cheapest investment cost and the fastest payback period. With the additional investment of about 12.5% to change from the foam insulation to the fiberglass insulation, energy saving and electricity cost saving would slightly increase about 2.79% and 4.27 Baht respectively; therefore the heat prevention of both insulators was similar. In contrast, installing the bubble insulations had the most expensive investment cost and longest payback period, which was more expensive and longer than the fiberglass insulation of about 31.84% and 0.669 years respectively, but it only increased energy-saving by about 2.37%. Thus, it showed that fiberglass insulation was most effective in reducing solar radiation for the metal sheet roof, while foam insulation was suggested for investment.

The optimal combination analysis between the energy consumption and the investment could be concluded that the fiberglass insulation was the best insulator for the corrugated concrete roof tiles as it was most energy-saving and had the shortest payback period, while the polyethylene foam insulation was the most suitable investment for the corrugated metal sheet roof as it had the shortest payback period, and the energy saving was slightly different than that of the fiberglass insulation. The bubble insulation was not recommended for both roof types as it had the longest payback period, and the energy saving was not different from the others. In terms of suggestions, the service life of each type of roof was not analyzed in this research as it depends on many variables such as selecting the quality of the material of the construction company, different methods to install the roof, and weather conditions affecting the installed roof. It requires an extended and more varied trial period.

4. CONCLUSIONS

In conclusion, the energy consumption can be ordered from ascending order as follows: slope concrete roof tiles, corrugated concrete roof tiles, corrugated ceramic roof tiles, the corrugated metal sheet roof, and the transparent roof. However, the corrugation of the roof is well-drained to be suitable for the rainy season in Thailand. In general, installing insulation increases heat prevention through the roof. The addition of fiberglass insulation to the corrugated concrete roof tiles and polyethylene foam insulation to the corrugated metal sheet roof could be considered as a promising alternative to the investment of house and industrial construction respectively.

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