Asian Fisheries Science **28** (2015): 71-82
©Asian Fisheries Society
ISSN 0116-6514

Efficiency of Monitor Roof in Maintaining the Thermal Conditions of Indoor Air and Water in a Medium Scale Enclosed Tropical Prawn Hatchery Building

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Abstract

This paper investigated the effects of roof design on the thermal conditions of indoor air and larviculture tank water of a tropical freshwater prawn *Macrobrachium rosenbergii* (de Man 1879) hatchery building. The research method was through a simulation study, using Integrated Environmental Solutions Virtual Environment (IES VE) software and the building modelled was based on an existing medium scale enclosed freshwater prawn hatchery. Monitor roof (vented ridge) was compared with the existing pitched roof design. The results showed the vented monitor roof design provided a considerable improvement to the indoor thermal environment of the prawn hatchery. The indoor air temperatures recorded under the monitor roof was close to the upper human acceptable thermal limit (34.0 °C) and some of the thermal readings were adequate for humanly comfortable condition. The indoor air temperatures became totally acceptable for the occupants during daytime through the installation of reflective aluminium foil (RAF) to the monitor roof. Therefore, the combination of monitor roof and RAF was recommended to achieve acceptable indoor air thermal condition for occupants while successfully maintaining the water thermal requirement for optimal prawn larval growth.

Introduction

Indoor thermal condition of a building in a warm and humid climate can be improved through thermal insulation (D'Orazio et al. 2010), proper roof orientation (Jayasinghe et al. 2003) and roof design (Kindangen et al. 1997). The introduction of natural air ventilation system into the building can further enhance its indoor performance. Several passive cooling mechanisms can be applied to induce outdoor air into the building.

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However, the modification on the roof seems to be more preferred due to its higher contribution to indoor heat gain than other parts of the building (Al Homoud 2005). Most tropical farmhouses are built with a monitor roof to reduce the accumulated hot air inside the roof by allowing hot air to escape through the roof vents by stack effect (Choiniére et al. 1992; Mutaf et al. 2004). The small openings at the peak of the roof and large sidewall openings are two important elements for this roof design, to generate better indoor air exchange and minimise the usage of mechanical ventilation (Barnes and Mander 1991). The air intakes should be as low as possible on the wall, and the building should have enough height to create excellent air pressure (Hassan and Ramli 2010). This approach is found to be effective to sustain the coolness inside the building.

An enclosed aquaculture hatchery in tropical regions is built to sustain the optimal thermal requirements for larval production inside the building. The ideal water culture temperature range for the rearing of freshwater prawn larvae is 28-30 °C (Tayamen 2001). However, an extreme high or low indoor air temperature could cause an increase or decrease of water temperature (greater than 33 °C or lower than 24 °C) will reduce the growth rate of the prawn larvae and even cause mass mortality (Valenti 1985; Tayamen 2001). Moreover, indoor air temperature below 24 °C or over 34 °C can create an unacceptable working thermal condition for the hatchery workers (Mallick 1996; Wijewardane and Jayasinghe 2008) and affects their working performance (Lan et al. 2009). In Malaysia, the recommended upper limit thermal comfort for humans is 30.7 °C (Ibrahim and Hazrin 2009). This study was conducted to evaluate the effect of monitor roof on the indoor thermal condition of a medium scaled tropical enclosed giant freshwater prawn hatchery building in relation to acceptable thermal conditions for humans and prawn optimal growth.

Materials and Methods

The case study building

This study focused on a typical medium size giant freshwater prawn *Macrobrachium rosenbergii* (de Man 1879) hatchery in Malaysia. The chosen building is located at Kampung Kepayang, Ipoh, Perak, Malaysia (latitude 4° 29.774'N, longitude 101° 6.729'E). The 24.4 m x 24.4 m building was constructed using building materials as shown in Table 1. The hatchery comprised of three main spaces (Fig. 1):

a) The roofed but without wall portion three sides of the building (plan size 10.6 m x 24.36 m). There was no roof light installed on the roof.
b) The enclosed hallway, office and storage portion of the building on the front of the building (16.12 m x 4.95 m). There were three smaller roof lights installed on the roof, each one measuring 0.53 m x 1.8 m.
c) The enclosed hatchery portion (16.12 m x 19.43 m), housing the culture room, is installed with nine long strips of roof lights (0.53 m x 16.16 m) at 1.91 m intervals. There were 28 rectangular fiberglass tanks (0.6 m x 0.9 m x 1.8 m) in this room.

This room had no auxiliary fan, as the owner wanted to maintain a high water temperature in the larviculture tanks during the night.

Table 1. Details of the construction materials used in the giant freshwater prawn hatchery.

Structural parts	Description of materials[a] from exterior to interior	Thickness (m)
External wall	-Concrete blocks (medium)	0.1050
	-Cement plaster-sand aggregate (ASHRAE)	0.0100
Internal partitions	-Cement plaster-sand aggregate (ASHRAE)	0.0100
	-Concrete blocks (medium)	0.1050
	-Cement plaster-sand aggregate (ASHRAE)	0.0100
Ground floor	-Stone chippings	0.0100
	-Cast concrete (dense)	0.1000
	-Screed	0.0050
Door	-Wood HF-B7	0.0350
Roof	-Lightweight metallic cladding	0.0008
Ceiling	The building has no ceiling	
External window	-Clear float 4 mm	0.0040
Roof light	-Acrylic 3 mm clear	0.0030

[a] Construction materials provided in the simulation software

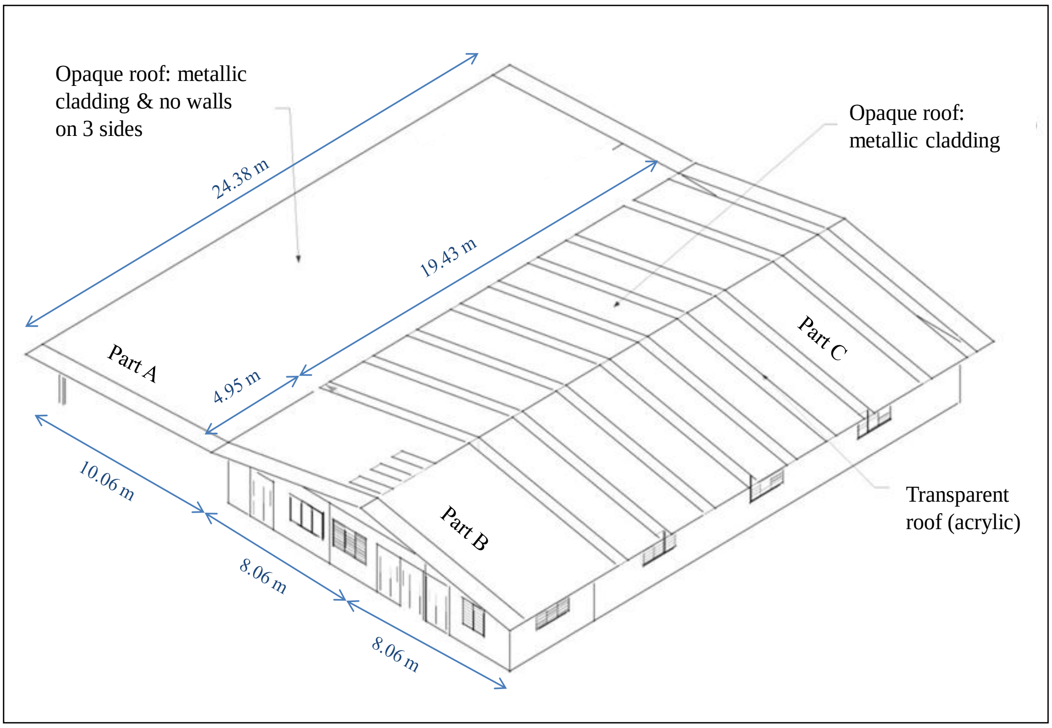

Fig. 1. Original roof design of the freshwater prawn hatchery building showing measurements of the plan.

Thermal comfort simulation

The thermal conditions in the building were studied using IES VE version 5.6 simulation software (Integrated Environmental Solutions Limited, UK). The simulation was focused on the enclosed culture room (16.12 m x 19.43 m). The thermal characteristics were:

- Roof; zinc and transparent roof: U = 7.0 W m^{-2} K^{-1}
- External wall; concrete wall: U = 2.57 W m^{-2} K^{-1}, zinc wall: U = 5.79 W m^{-2} K^{-1}
- Ground floor: U = 3.29 W m^{-2} K^{-1}
- Internal partitions: U = 2.03 W m^{-2} K^{-1}
- External windows: U = 5.57 W m^{-2} K^{-1}

The construction properties were:

- Absorptance for solar radiation: 0.55 (external wall and internal partition); 0.4 (roof)

- Emissivity: 0.9 (opaque external wall and internal partition); 0.2 (roof)
- Air infiltration: 0.2 ach
- Cooling mechanism: natural ventilation
- Incoming air: natural (external air)
- Building orientation: 82 °

The simulations were performed using Kuala Lumpur/Subang weather data obtained from the IES VE software library. The hatchery operated daily for 12 hours (0700 to 1900 h). The internal gains of the building for two occupants were due to:

- Max. sensible gain: 90 W per person (90 W x 2 persons = 180 W)
- Max. latent gain: 60 W per person (60 W x 2 persons = 120 W)
- Percentage presence: 84 % (constant)

Internal gain due to occupants were:

Sensible heat: 180 x 0.84/301.9= 0.5 W m^{-2}

Latent heat: 160 x 0.84/301.9= 0.45 W m^{-2}

For tank water-air temperature relationship, the following linear equations were used:

a. Rising T_w = 0. 0.1516 T_i + 25.89 (R^2 = 0.6407)
b. Cooling T_w = 0.1307 T_i + 26.907 (R^2 = 0.4402)

where T_w = tank water temperature and T_i = indoor air temperature

The correlation was built up based on the *in situ* data measurements of the hatchery building including the air temperature (inside and outside of the hatchery building) and the water temperature inside the rearing tanks (Kamarudin et al. 2013). Lighting, which was another potential heat source, was kept at very minimal usage and was considered negligible.

Monitor roof, with or without RAF, was proposed for the hatchery (Fig. 2) and compared with the existing roof design. The measurement scale for air temperature is shown in Table 2.

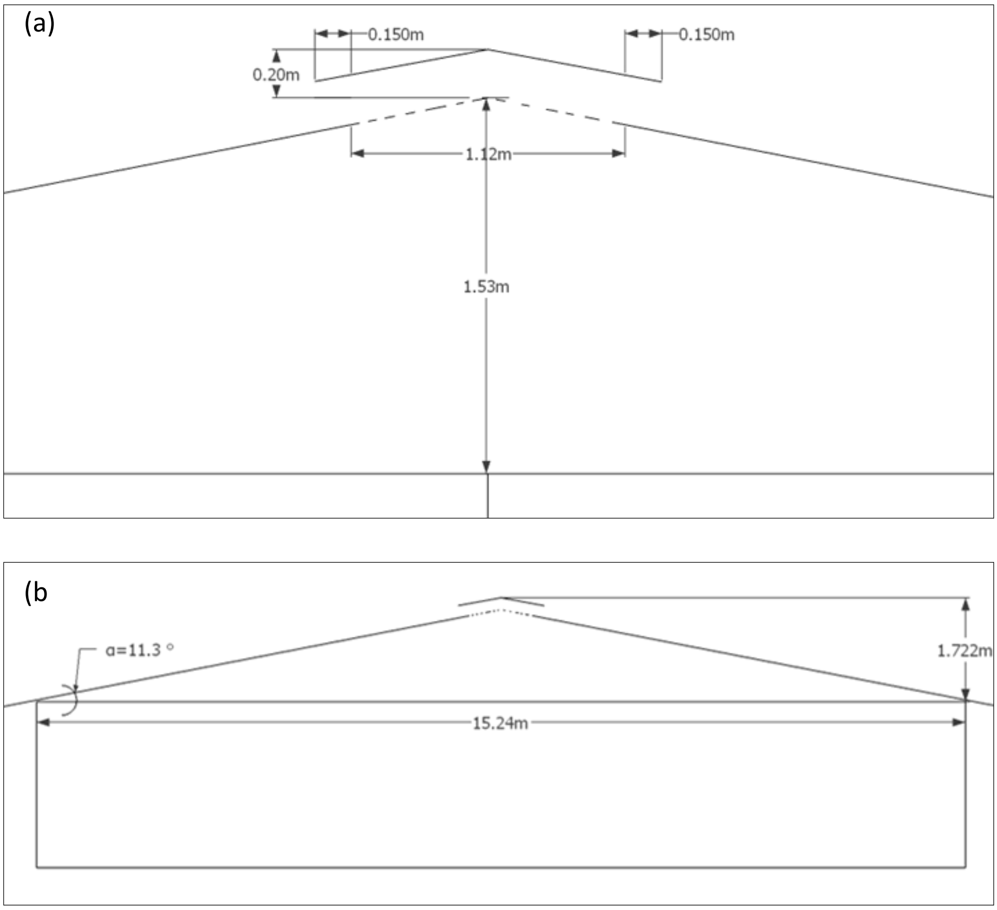

Fig. 2. The measurement of the monitor roof design of the freshwater prawn hatchery building. (a) small opening of the roof, (b) front view of the hatchery.

Table 2. The scale of measurement for temperature (Abdul Rahman 1995)

Scale	Description	Celcius
0	Cold	Less than 16
1	Cool	16-25.5
2	Comfort	25.5-28
3	Warm	28-32
4	Hot	32-40
5	Extremely hot	Above 40

Indoor air temperatures

The daily average indoor air temperatures of the culture room in the hatchery building during the warmest month (March), coolest month (December) and annual overall are shown in Fig. 3. The indoor air temperature under the existing roof ranged 24.6-40.6 °C during the warmest month and 24.1-36.6 °C during the coolest month. The temperatures measured between 0645 and 1545h were significantly reduced under the monitor roof without RAF (warmest month: 24.6-34.2 °C; coolest month: 24.1-31.8 °C) and roof installed with RAF (warmest month: 24.8-33.4 °C; coolest month: 24.3-31.3 °C).

The results showed that both new roof systems successfully reduced the indoor air temperature closer to the comfortable and acceptable thermal limit for humans by 2.7-3.5 °C for monitor roof without RAF and -0.6 - 0.2 °C for monitor roof with RAF.

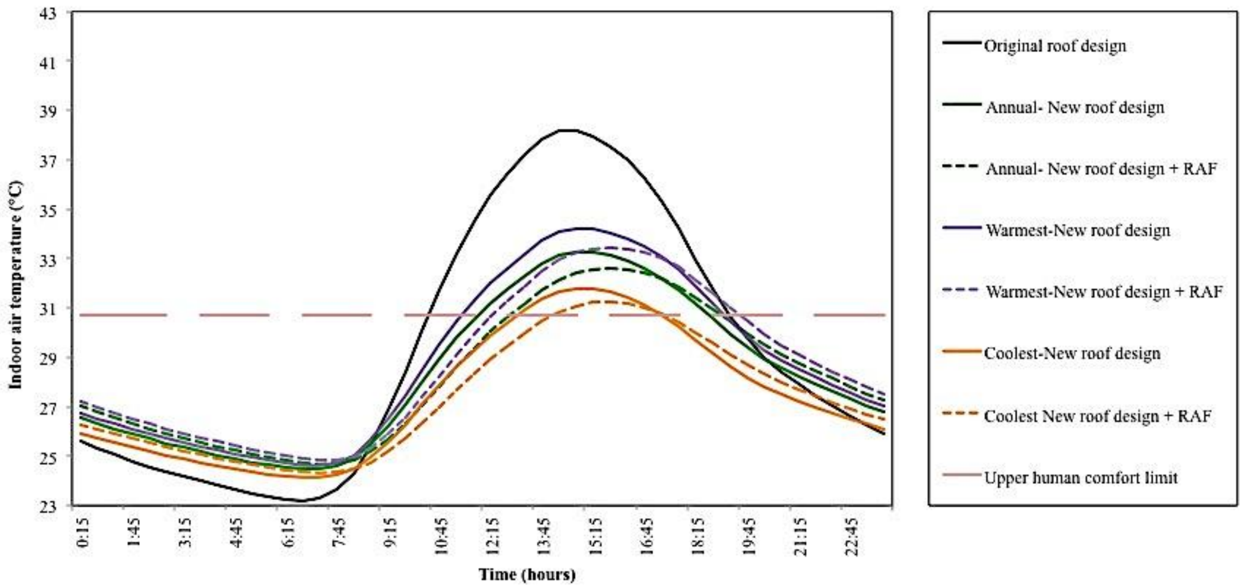

Fig. 3. Daily average indoor air temperature of the freshwater prawn hatchery building during the warmest month, coolest month and annual overall.

The annual daily average data portrayed clearer view of the indoor air temperature pattern in the culture room. The annual indoor air temperatures for the existing roof design were lowest at 23.2 °C at 0645 h and peaked at 38.2 °C at 1415 h. However, the maximum and minimum air temperatures fluctuated between 24.5 and 33.3 °C under monitor roof without RAF. Similarly, the maximum and minimum of air temperatures were also reduced to between 24.7 and 32.6 °C under monitor roof with RAF. These readings mostly fell below the acceptable human indoor thermal upper limit of 30.7 °C (between 1900h to noon) but peaked to 1.9-2.6 °C higher than the human upper thermal comfort limit between noon to 1900 h.

The indoor thermal conditions of the hatchery clearly influenced the indoor working condition of the workers (Fig. 4). The average daily data showed that during working hours (0700-1900 h), the workers felt thermally comfortable for only 2.75 h (warmest month), 3.75 h (coolest month) and 2.5 h (annual average) under the existing roof design.

The thermal comfort durations, however, were increased under the monitor roof without RAF [4.5 h (warmest month); 6 h (coolest month); 5 h (annual average)] and with RAF [5.25 h (warmest month), 7.25 h (coolest month) and 5.75 h (annual average)].

Thermally acceptable duration is the extent of warmest condition that the workers can tolerate. However, the workers felt 4.5, 7 and 5.25 h of acceptable durations during the warmest month, coolest month and annual average, respectively under the existing roof design (Fig. 4). The indoor duration of the acceptable thermal conditions of the hatchery building increased to 11-12 h under monitor roof system installed either without or with RAF.

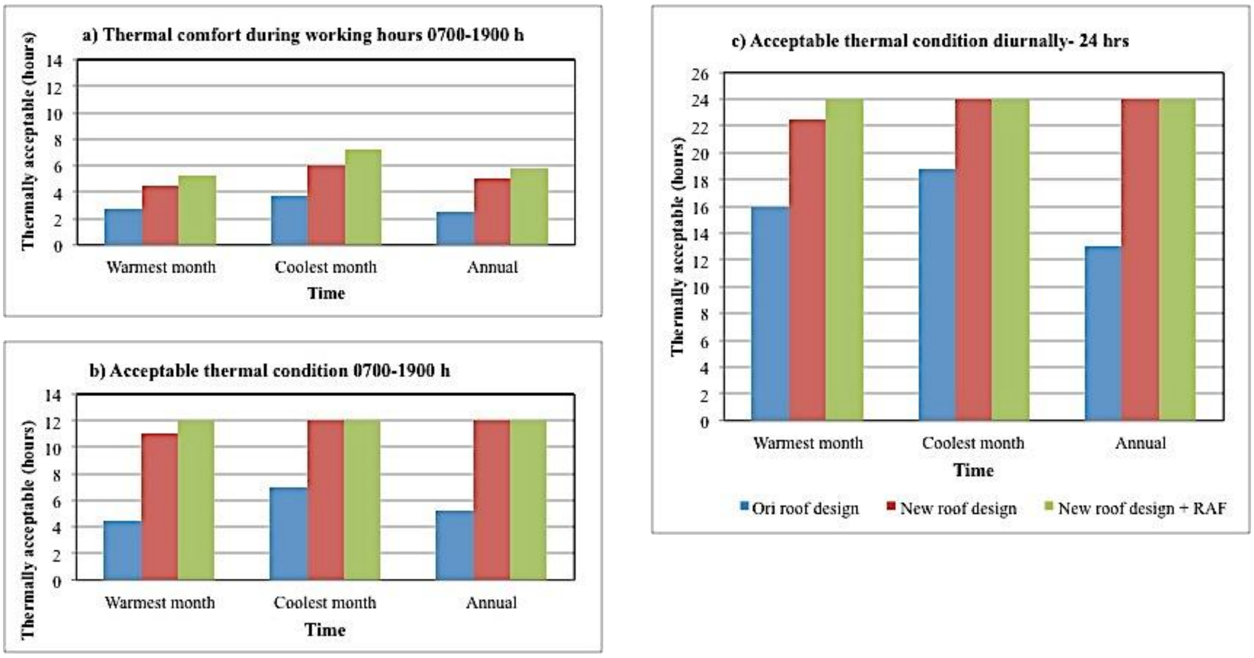

Fig. 4. Indoor thermal condition of the hatchery: (a) Working hours thermal comfort (0700 –1900 h), (b) Working hours acceptable thermal condition (0700-1900 h), (c) Acceptable thermal condition (diurnally - 24 h).

The diurnal indoor thermal pattern for 24 h showed that the shortest thermally acceptable durations were recorded under the existing roof design (warmest month: 16 h, coolest month: 18.75 h, annual average: 13 h). Longer durations of accepted thermal conditions were obtained under the monitor roof for 22½ hours (warmest month) and 24 h during the coolest month and annual average. The monitor roof with RAF recorded the best thermally acceptable results where the indoor air temperatures did not fall below 24 °C or higher than 34 °C in 24 h at all times.

Water temperatures

Figure 5 shows the daily average water temperature in the larviculture tanks during the warmest month, coolest month and annual average. The water temperature ranged 29.6-32.0 °C, 29.6-31.1 °C, and 29.7-31.0 °C under the existing roof design, monitor roof without RAF and with RAF, respectively.

Lower readings were recorded in the coolest month (existing roof: 29.5-31.4 °C; monitor roof: 29.6-30.7 °C; monitor roof with RAF: 29.6-30.6 °C) between 0915 h to 1815 h. The annual average data showed that the water temperature ranged from 29.4-31.7 °C under the existing roof, followed by the monitor roof without RAF (29.6-30.9 °C) and with RAF (29.6-30.8 °C) at 0915-1815 h.

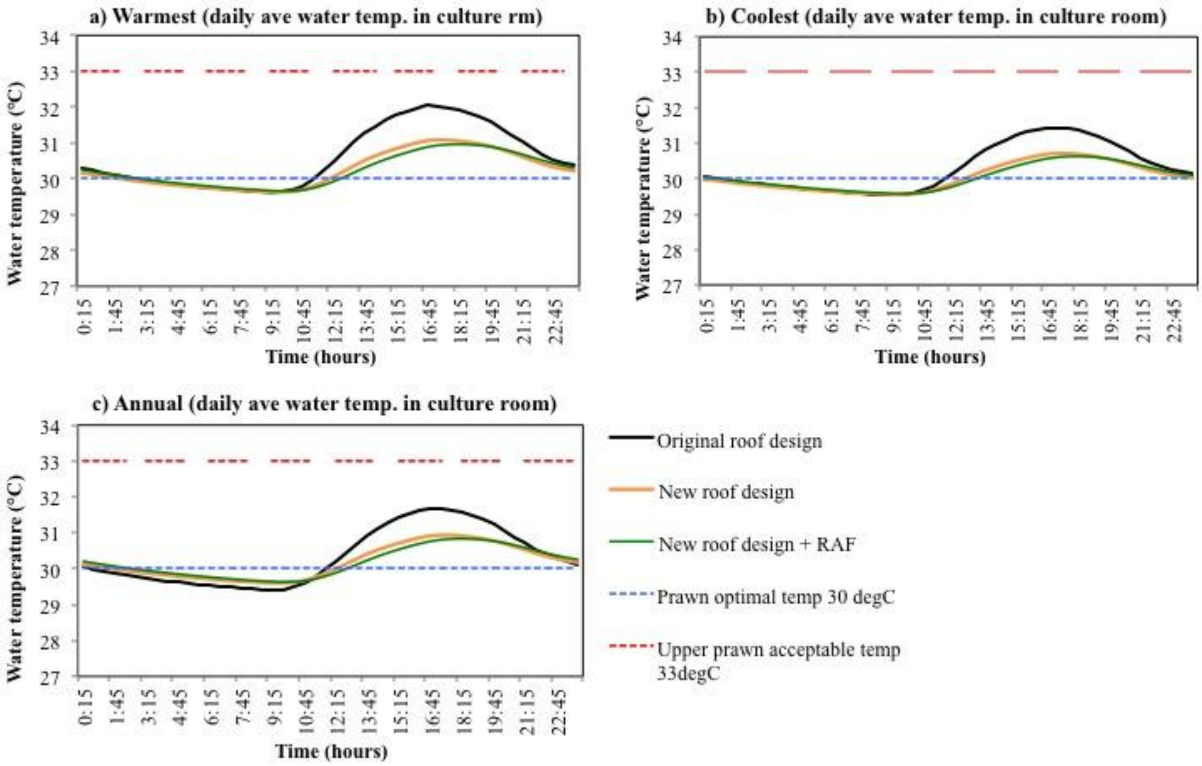

Fig. 5. Daily average water temperature in the culture room of the freshwater prawn hatchery building: (a) warmest month, (b) coolest month, (c) annual.

Discussion

The monitor roof design provided a considerable improvement to the indoor thermal environment of the prawn hatchery building. During the daytime, the indoor air temperature under monitor roof showed significant thermal reduction close to the upper human acceptable thermal limit (34.0 °C) and even some of the peaks were lower. The installation of RAF to the roof further reduced the indoor air temperature to an acceptable level for workers during the day. At night, the monitor roof provided an equal indoor temperature or slightly higher than the existing design roof.

The findings of this study were in agreement with earlier studies on other farm buildings (Shklyar and Arbel 2004; Katsoulas et al. 2006). Katsoulas et al. (2006) concluded that the best ventilation performance of the greenhouse is achieved when an opened roof (roof ventilation) is combined with the side ventilation. Low ventilation rate is produced by the side or roof ventilation alone. In the present study, the windows of the monitor roof building were opened (side ventilation) to create better indoor air movement before the air temperatures were measured. Shklyar and Arbel (2004) observed the role of the monitor roof and side vents for inducing ventilation rate of a greenhouse. Wind direction and opening angle of the vents are two key elements to determine the ventilation rate inside the building. The ventilation rate is 4 to 4.5 times greater under a perpendicular directed wind (90°) to the side vents compared to a parallel one. The monitor roof in the present study was designed with two openings placed side by side to maximise the flow rate of the indoor hot air to the outdoor environment.

The warm air buoyancy and differential air pressures called stack effect (Bradshaw 2006) were believed to cause a tremendous temperature drop in the indoor warm air of the studied prawn hatchery building. When the outdoor air temperature is lower than the indoor temperature, cooler outdoor air leaks into a building through openings at the lower level of the building, and warmer indoor air escapes through the openings at the higher level (Awbi 1991). Therefore, when parts of the roof are opened, it will allow the excessively warm indoor air to move out of the building and the cooler indoor air is sustained for a certain period. However, this effect is not significant during summer because the temperature and the density differences are relatively small (Bradshaw 2006). In contrast, the results in the present study showed that the indoor air temperature in the hatchery was significantly higher than the outdoor environment for most times. Therefore, the air buoyancy effect had significantly developed inside the prawn hatchery.

The effectiveness of stack ventilation principle for thermal comfort depends on the thermal buoyancy inside the building (Andersen 2003; Hussain and Oosthuizen 2012). Sidewall openings and the openings at the peak of the roof are two main approaches to accelerate air ventilation in the building, which can influence thermal buoyancy. Nonetheless, the sizes of the opening and the height of the room area must also be considered for better comfort results (Chenvidyakarn and Woods 2005). The influence of the prevailing wind entering the building should be highlighted as it creates the necessary airflow for the indoor thermal comfort (Gladyszewska-Fiedoruk and Gajewski 2012). However, for a single-sided ventilated building, the prevailing wind can reduce the stack effect and consequently, lower the air exchange rate (Caciolo et al. 2011). In the present study, the hot air inside the culture room area of the hatchery accumulated at the existing rooftop creating a high temperature on the roof surface and in the culture room area as the building had no wall apertures to allow outdoor air entering into the building to induce natural ventilation. The extremely low and high indoor air temperature can also create uncomfortable indoor conditions for workers, thus affecting their working performances (Lan et al. 2009). The modification of the roof into a monitor type plus window opening successfully reduced the unbearable daytime indoor air temperature to the acceptable limit for workers.

Nonetheless, the measurement of the opening should be determined. An over-sized opening provides an excessive air flow into the building, which could accelerate evaporation of the culture water in the prawn tanks, thus reducing the culture water volume at a faster rate (Tang and Etzion 2004). The optimal opening measurements for indoor thermal comfort via naturally ventilated approach have been studied and determined for other farm buildings (Foster 1987; Mutaf et al. 2004).

Installation of insect net or pivot to the openings should also be considered to ensure the biosecurity of the building when monitor roof system is used. However, such covers could reduce the air ventilation and movement in a building (Katsoulas et al. 2006; Parra et al. 2004) and a further study on their impact on the hatchery should be conducted.Besides passive ventilation system, the introduction of ventilation device is necessary to enhance air movement for a better and constant indoor thermal comfort.

There is a wide range of ventilation devices with different operation and engagement modes with the air, from the traditional passive practices such as atria and courtyard, wing walls and wind tower, to the modern active ventilation devices such as rotating chimney cowl and turbine ventilators (Khan et al. 2008). However, those devices need additional installation to the present building, which would incur additional costs and maintenance.

Many researchers have confirmed the effectiveness of RAF as roofing thermal insulation, especially in hot humid climate (Al-Homoud 2005; Medina 2000; Soubdhan et al. 2005). The sheet material provides low emittance and absorptance (good reflector) to resist the heat transfer by radiation from the sun. Al-Homoud (2005) strongly recommended the reflective foil to be installed underneath the roof of buildings located in the hot and humid climatic regions to gain better indoor thermal performance. In the present study, the building is located in a tropical hot humid climate of Malaysia and therefore, the installation of RAF was recommended.

Larval rearing is a very crucial process because it is the most sensitive life form in freshwater prawn growth cycle. Any inefficient activity during larval rearing such as larval feeding, water quality monitoring and larval screening could affect the larval growth performance and also can cause mortality. Tayamen (2001) stated that the lethal temperature for freshwater prawn larval growth is below 24 °C and above 33 °C while Malecha (1983) and Ra'anan and Cohen (1982) reported that a lower temperature limit of below 20 °C can cease larval growth and cause mortality. Although there was a large reduction of indoor air temperature in the prawn hatchery with a monitor roof, the water temperature was successfully maintained at the optimal range for prawn larval growth.

Conclusion

This study indicated that the application of monitor roof and RAF into the roof system of a tropical prawn hatchery building successfully improved its indoor air temperature to the acceptable indoor human thermal limit while maintaining the optimal indoor water temperature for prawn larviculture. Nevertheless, the combination of monitor roof and RAF was not able to lower the indoor thermal condition to the human thermal comfort limit (30.7 °C) during the daytime. Other additional compatible approaches to improve the indoor thermal conditions of the tropical hatchery building should be further explored, such as optimising the use of window and ridge openings and ventilators.

Acknowledgement

The authors would like to thank Mr. Ridzuan bin Mat Husein, the owner of Kampung Kepayang Prawn Hatchery and his staff for their assistance. This study was funded by the Malaysian Ministry of Science, Technology and Innovation through E-Science Grant 03-01-01-SF0037.

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Received: 15/04/2015; Accepted: 24/05/2015 (MS15-35)