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Solar Heating Systems for Recirculation Aquaculture

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Abstract
The literature over the past 25 years indicates that there has been a continued interest in using passive and active solar technologies to reduce the conventional energy required to maintain water temperatures in small recirculation aquaculture systems. Although all of the experimental systems reviewed report favourable results, there is little information available to guide system designers. This paper describes the use of a simulation model to predict the annual conventional energy consumption of a 10.6 m^3 RAS enclosed in a double layer polyethylene greenhouse in two different climates. The water was maintained at 22.5^0C and the recirculation rate was 10% of tank volume per day. Simple unglazed solar collectors have also been combined with the greenhouse to further reduce energy consumption. The effect of increasing collector area on the solar fraction and utilization of useful energy was predicted. Finally, the model was used to investigate the relationship between the occurrence of condensation on the inner cover, ventilation rates and energy use.

It was found that in a hot dry climate, the greenhouse alone was sufficient to reduce the conventional energy requirements by 87%; while in the cooler temperate climate reductions of 66% were possible. When solar collectors were added to the system, conventional energy requirements were reduced further and depended on the area of collector used. For example, in the temperate climate location, conventional energy requirements were reduced to 23% of a RAS enclosed in a non-solar building when 26 m^2 of solar collector inclined at the optimum angle for winter energy collection were used. Although condensation could be successfully reduced by ventilation of the greenhouse, this increased conventional energy requirements because the potential for evaporation was increased. Covering the tanks at night was found to be a more effective strategy because it reduced condensation and conventional energy use simultaneously.

Keywords: recirculation aquaculture, solar energy, water temperature, condensation, ventilation

1. Introduction

There are many examples of using passive and active solar technology to reduce water heating costs in both open and recirculation aquaculture systems. In passive systems, where natural convection and direct solar absorption by the water body are the principle heat transfer mechanisms, greenhouses are the main technology used. Brown *et al*. (1979) reported air temperatures of 7.8^0C above ambient when using a single layer 36 m^2 greenhouse covering a 18 m^3 system in Arlington, USA. A parabolic mirror, inclined at 60^0, was located internally on the north (solar) face. On average 26% of the solar radiation entering the structure was stored in the water and rises in water temperature of almost 3^0C were measured following three days of full sun. Van Toever and Mackay (1980) installed two 2.0 m^3 tank modules in a solar greenhouse in which they hatched and raised various salmonids. Measurements over the Canadian winter (November-March) indicated that the water temperatures in the aquaculture tanks were in the range 7^0-14^0C despite subzero external ambient air temperatures. Yuschak and Richards (1987) successfully used a passive solar greenhouse to heat the water in four 1.7 m^3 tanks to rear marine organisms in a tidal bay system in Connecticut, USA. Provenzano and Winfield (1987) reported growth rate data for tilapia raised in a 10.7 m^3 tank covered by a polyethylene geodesic dome. Water temperatures generally remained between 24^0 and 36^0C between May and September in Virginia, USA, with an average daily fresh water make-up rate of 4% of tank volume. Diurnal fluctuations of 2-5^0C were noted. Little (1992) developed and validated a model of an insulated pond covered by a tent-shaped roof with two layers of glass at 60^0 on the south (solar) face located in Maryland, USA. On average, 9 MJ m^{-2} per day were collected over a year and it was estimated that this maintained average monthly water temperatures in the 5.7 m^2 tank at 12.9^0C above air temperatures. Wisely *et al*. (1981/2) described an alternative passive heating technique. These authors used a floating solar blanket of laminated bubble plastic to heat the seawater in a 0.11 ha coastal pond in New South Wales, Australia, containing oysters, prawns and a variety of fish. The covered pond maintained temperatures of 6-9^0C higher than two controls. However, the blanket delaminated after three weeks because pond temperatures exceeded the maximum of 30^0C recommended by the manufacturer.

Active solar systems, where a solar collector is used as the main heat generator, have also been constructed. Ayles *et al*. (1980) describe a 125 m^2 flat plate collector system designed to provide 70% of the heat requirements in a 3.5 tonne rainbow trout facility near Winnipeg, Canada. Over a six week period, collection and utilisation efficiencies of 53% and 24.9% were reported. Ray (1984) constructed a small 9.0 m^2 single layer greenhouse, which was used as a brine shrimp hatchery in North Carolina, USA. Heat collected in the greenhouse was supplemented by 3.0 m^2 of solar collector made from coiled black pipe. Water temperatures in the 0.43 m^3 system were maintained in the range 27^0-38^0C by the greenhouse alone on sunny days, while the solar panel delivered water at temperatures of 43^0-49^0C. It was estimated that heating costs were reduced by 50%. Plaia and Willis (1985) installed 7.4 m^2 of copper solar collector on a concrete block building containing a juvenile prawn nursery in Florida, USA. Average water temperatures in the 5.6 m^3 system were 8.1^0C above ambient, with the gain attributed entirely to the solar collectors. Despite significant energy losses in the system, the authors calculated that the system had a simple payback of just over five years, assuming an annual use period of 120-days. Gaigher and Leu (1985) described experiments using four 10 m^3 concrete ponds for 'wintering' of tilapia in Bloemfontein, South Africa. Two ponds were connected to 10 m^2 of solar collector and all four ponds had swimming pool blankets suspended above the water surface. Water temperatures in the solar-assisted ponds were approximately 6^0C above open pond water temperature. Fuller et al. (1998), using an earlier version of the model described in this paper, found that recirculation systems using a greenhouse and/or solar collectors could have financially attractive payback times of between 0.7 and 7.5 years, depending on location, system design and the calculation method.

Although all the systems described above report favourable results, there is little design information available to guide designers of such solar systems. This paper attempts to provide some of that information. A simulation model has been developed which enables water temperatures and energy use in small recirculation aquaculture systems using a greenhouse with and without solar collectors to be predicted. The paper begins with a description of the simulation model, together with details of the assumptions made and the general parameters used. The process used to verify the reliability of the predictions is then described. Annual thermal performance of three systems is then predicted for a hot dry inland and a cooler temperate location in southern Australia. The results of using the model to investigate the effect on thermal performance of varying solar collector area and other operational strategies are also investigated.

Model Description

The greenhouse model of Cooper and Fuller (1983) was modified to produce the simulations presented in this paper. The original greenhouse model simulates the dynamic behaviour of a horticultural greenhouse structure, predicting the temperatures of all the main system components (cover, floor mass and surface, crop, air and growing medium) on an hourly basis. This model was validated against experimental data (Fuller *et al*., 1987). The greenhouse model is based on five purpose built sub-routines compatible with the solar simulation software, TRNSYS (SEL, 2005). In order to adapt the existing greenhouse model to simulate the performance of a recirculation aquaculture system, three of the original sub-routines i.e. the cover, air space and floor were modified, and a new subroutine describing the water tanks was written.

Recirculation tanks in a polyethylene greenhouse can exchange heat and mass through various mechanisms (conduction, radiation, convection and evaporation) with the surrounding structural surfaces, floor and the enclosed air mass (Figure 1). Within the tanks, other elements (fish, pumps etc) can add heat and fresh water intake usually reduces tank temperature and heat may need to be added by an auxiliary heater. In this model, the sides of the tanks are assumed to be at the same temperature as the water. The air within the tunnel can exchange heat with the sides of the tanks and the water surface by convection. Mass transfer by evaporation from the water surface occurs to the air within the tunnel. Thermal radiation exchange between the tanks and the roof of the tunnel can also take place. Fresh water intake is defined in terms of quantity, time and temperature. The water in the tanks absorbs solar radiation directly and since the tanks are considered to be sitting on an insulated platform, any heat exchange via conduction to the floor is considered to be negligible and is ignored.

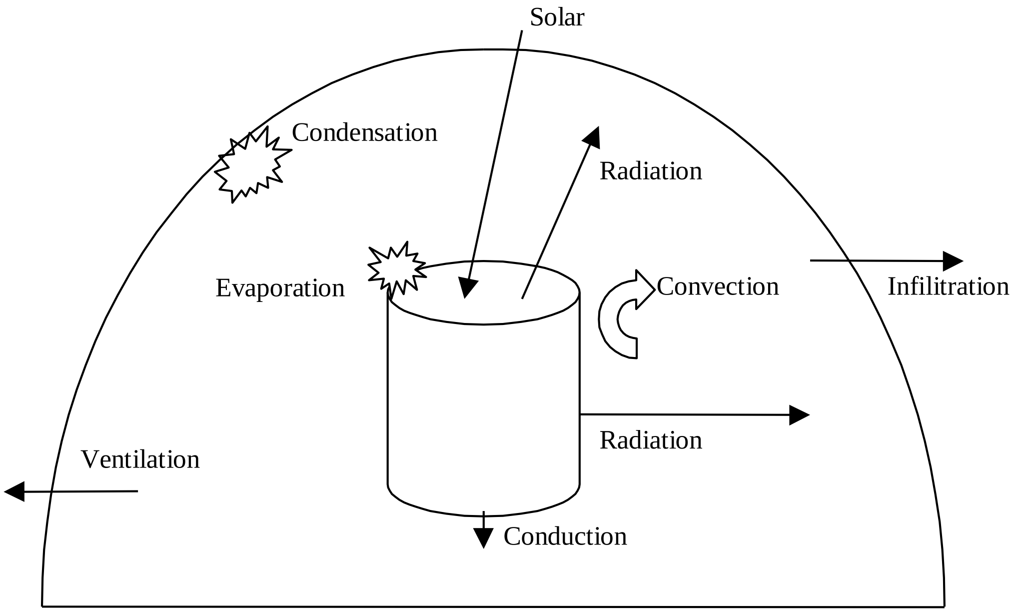

Figure 1 Heat and mass transfer mechanisms between tanks and structure

2. Model Assumptions and Parameters

In the development of the tank subroutine and the modifications to existing subroutines, certain assumptions were made. The greenhouse is covered with a double glazing layer because this is the simplest and most effective way to reduce heat losses. Walker and Walton (1971) showed that even heavy condensation only covered 68% of the glazing surface. Therefore, if condensation is predicted to occur on the inner cover, the long wave transmittance of the material is reduced to 30% of its original value. Various researchers have investigated the impact of condensation on the solar transmittance of plastic films. Geoola *et al*. (1994) and Pearson *et al*. (1995) determined average reductions of 9.9% and 13% respectively. Pollet and Pieters (2000) measured decreases of 11% on low-density polyethylene film. In this model, condensation has been assumed to reduce the solar radiation penetrating the structure by 12%. Of the solar radiation entering the structure, the percentage striking the water is defined by the ratio of the water surface to total floor surface area. The remaining solar radiation is assumed to strike the floor. Eighty five percent of the radiation incident on the water surface is absorbed and the remainder is reflected back into the greenhouse. Of this reflected solar radiation, 90% is absorbed by the inner glazing material, 5% by the outer glazing and the remaining 5% is transmitted back through to the outside. Only 10% of the solar radiation reflected from the floor to the tank walls is absorbed and effectively used to heat the water. The remainder is absorbed by or transmitted through the glazing materials in the same proportions as other reflected solar radiation.

As in the original greenhouse model, the mass transfer effect of evaporation from the inner cover surface is ignored, as it is assumed that there is insufficient water on this cover to sustain this mechanism for a significant period of time. The floor area used for convective and radiative heat transfer is the area which is not covered by the tanks. The whole floor surface is assumed to be at the same temperature and conduction takes place between this surface and the floor mass, which in turn exchanges energy with a theoretical 'sink' assumed to be at the long-term average ambient air temperature. For radiative transfer between the floor and tank surfaces and the inner cover, the area-weighted mean of the first two surface temperatures is used. The infiltration rate is determined using a wind-dependent expression derived from measurements in a tunnel greenhouse (Fuller *et al*., 1987). In calculating the external convective heat transfer coefficient, it is important that the radiation component has not been included in the expression used, as this is calculated separately by the model. The expression proposed by Watmuff *et al*. (1977) has therefore been used. Although not specifically derived for tunnel greenhouses, the heat transfer coefficient at a wind velocity of 1.0 m s^{-1} will be 5.8 W m^{-2} K^{-1}, which is close to the value of 6.1 m^{-2} K^{-1} determined experimentally by Seginer *et al*. (1988).

The fresh water inlet temperature is assumed to be equal to the annual average air temperature for the particular location, and the supplementary heater is set to maintain the water in the tanks at 22.5^{0}C. The heat input from pumps and fish have also been included in the present model. The pump size used for the 10.6 m^3 system used in this study is 1 kW with a pumping efficiency of 70%. Half of the electrical energy not used for moving water is assumed converted to heat and transferred to the water, while the remainder is lost to ambient. A standing biomass rate of 50 kg of fish per m^3 of water has been assumed with a heat input of 550 kJ h^{-1} of heat to the tank water calculated using the equations suggested by Cho and Bureau (1998). Apart from the above assumptions, other influences on predictions are defined as parameters in the TRNSYS input file. The sources of these parameters are as used in Cooper and Fuller (1983) or Fuller et al. (1987), except where otherwise noted. The values used in the simulations (unless specified in later sections) are shown in Table 1.

Table 1 Parameters and their values used in simulations

Parameter	Value	Units
Solar absorptance of floor material	0.72	n.a
Emittance of floor material	0.91	n.a.
Conductivity of floor material	6.23[a]	kJ m^{-2} K^{-1}
Specific heat of floor material	0.84 [a]	kJ kg^{-1} $^{0}C^{-1}$
Long term ground sink temperature (Melbourne) Long term ground sink temperature (Mildura)	14.8[b] 16.8[b]	^{0}C ^{0}C
Emittance of water	0.96[c]	n.a.
Specific heat of water	4.18 [a]	kJ kg^{-1} K^{-1}
Convective heat transfer coefficient between air and floor	14.1	kJ m^{-2} K^{-1}
Convective heat transfer coefficient between air and tank surfaces	12.6	kJ m^{-2} K^{-1}
Convective heat transfer coefficient between air and inner cover	10.1	kJ m^{-2} K^{-1}
Overall heat transfer coefficient between inner and outer glazing	8.4	kJ m^{-2} K^{-1}
Longwave transmittance of glazing material	0.57	n.a.
Emittance of glazing material	0.35	n.a.
Refractive index of glazing material	1.41	n.a.
Thickness-extinction coefficient product of glazing material	0.05	n.a.
View factor between tank sides and floor - calculated	0.40	n.a.
View factor between tunnel and sky	0.69	n.a.

sources: [a]Duffie and Beckman (1991); [b]calculated from TMY data file; [c]Kreith and Bohn (1986).

Other system characteristics were as follows:

- greenhouse orientation: long axis in north-south direction
- greenhouse floor dimensions: 4.3 m x 6.1 m
- tank volume: 10,584 litres
- water surface area: 8.84 m^2
- fresh water intake: 10% of tank volume per day between 10am and 3pm

3. Climatic Data

The performance of various system configurations (see Section 5) was predicted for two locations within Victoria. These are Melbourne, the capital, and Mildura, an inland city 600 km to the north of Melbourne and a major horticultural production area. Table 2 summarises the main climatic variables of these two locations. Simulations were performed using Typical Mean Year (TMY) data files for the two locations generated by Morrison (1990).

Table 2 Summary of Melbourne and Mildura climates

(source: BOM, 2004, except [1]Roy and Miller, 1981)

Climatic Variable	Melbourne	Mildura
Mean daily maximum temperature (^{0}C)	19.8	24.5
Highest recorded maximum temperature (^{0}C)	45.6	50.7
Mean daily minimum temperature (^{0}C)	10.1	10.4
Lowest recorded maximum temperature (^{0}C)	-2.8	-5.0
Mean relative humidity at 9am (%)	69	64
Mean relative humidity at 3pm (%)	54	43
[1]Mean total global horizontal solar radiation ($MJ^{-2}d^{-1}$)	15.9	18.8
Mean wind speed at 9am (ms^{-1})	3.0	2.1
Mean wind speed at 3pm (ms^{-1})	4.2	2.6
Mean annual rainfall (mm)	653	268

4. Model Verification

Full validation of the model, i.e. comparing hourly predictions with known forcing functions against measured data, was not possible because of the lack of such experimental data. A number of cross checks were therefore conducted to verify that the predictions made by various aspects of the model were credible. These include the overall heating load, the heating effect of a greenhouse alone and the heat delivered by the swimming pool collectors.

4.1 Heating Load

Using the methodology described in the Australian Standard (AS, 1989) for the calculation of swimming pool heating loads, a daily energy demand was calculated for a 8.84 m^2 indoor pool, assuming the conditions expected in a RAS in winter. Unpublished data collected from an unheated commercial RAS system in southern Victoria between November and March showed that tank and water temperatures were similar, internal relative humidity levels were approximately 75% and air movement was very low i.e. less than 0.1 m s^{-1}. Assuming that internal air temperatures would be lower and relative humidity levels would be higher in winter, the heating load calculation used water and air temperatures of 22.5^0 and 20^{0}C respectively, an air speed of 0.1 ms^{-1} and 80% relative humidity within the building. A daily heating load of 55 MJ was calculated. Various assumptions and parameters of the greenhouse model were changed to approximate a tank (or pool) within a conventional building. The structure was effectively made opaque to solar and thermal radiation by changing the relevant parameters. Since the method described in the Australian Standard does not include conduction losses from the floor, the ground sink temperature in the model was made equivalent to the water temperature, so that there would effectively be no heat losses through the floor. The overall heat transfer coefficient between the polyethylene covers was reduced to a level similar to a conventional building with metal roof and 50 mm of polystyrene insulation i.e. 2.7 kJ h^{-1} m^{-2} K^{-1}. With these changes, the model predicted a daily heat load of 74 MJ i.e. 35% more than the figure calculated using the method described in AS 3634.

4.2 Greenhouse Effect

The only measured data located for verifying the passive heating effect of a greenhouse on a recirculation aquaculture system is that published by Braley *et al*. (1992). From their research with a 9,000-litre recirculation system for rearing giant clams, the authors measured mean tank water temperatures 5-7^{0}C warmer in the tanks in the greenhouse compared to those located outside. The measurements were made between July and September in Townsville, a coastal town in northern Queensland. Unfortunately, no typical meteorological year (TMY) climatic data file for Townsville is available. The predictions were therefore made using July climatic data for the coastal city of Rockhampton, which is approximately 650 km south of Townsville. Since the long term mean solar radiation and ambient temperatures in July in Rockhampton are 21% and 14% lower than in Townsville, the hourly values of these two climatic variables were increased by these factors. A small number of additional changes were made to the greenhouse model so that it was more comparable to Braley's system. The initial water temperature was set at 20.5^{0}C, the average temperature of the water entering the uncovered tanks. The water volume was reduced to 9000 litres. No other aspects of the model were changed. The mean water temperature predicted over July was 31.5^{0}C. The average tank-water temperature for July estimated from Braley's Figure 5 was 27.5 ^{0}C, indicating that the model's prediction was 15% higher than the measured value.

4.3 Solar Collector Model

Data from the report by Guthrie (1984) was used to verify the predictions of the solar collector model in TRNSYS. The flow rate used was 0.071 l s^{-1} per m^2. The collector parameters used were $F_R\tau\alpha$ = 0.98 and F_RU_L = 39.6 Wm^{-2} K^{-1}. The latter figure is based on a wind speed of 2.5 ms^{-1}. This characteristic is for a typical strip solar collector mounted on roof decking. The standard TRNSYS collector subroutine predicted that a collector inclined at 38.8^0 with a fixed inlet water temperature of 20^{0}C would have a heat output of 35.7 MJ m^{-2} for the month of June in Melbourne i.e. 1.19 MJ m^{-2} per day. This figure compares with the prediction of 1.2 MJ m^{-2} per day calculated using the Heat Table method used by Guthrie (1984).

5. System Configurations

The verified model was used to determine the performance of the following system configurations:

- non-solar system i.e. an opaque structure with no solar input
- greenhouse only
- greenhouse and solar collectors (Figure 2)

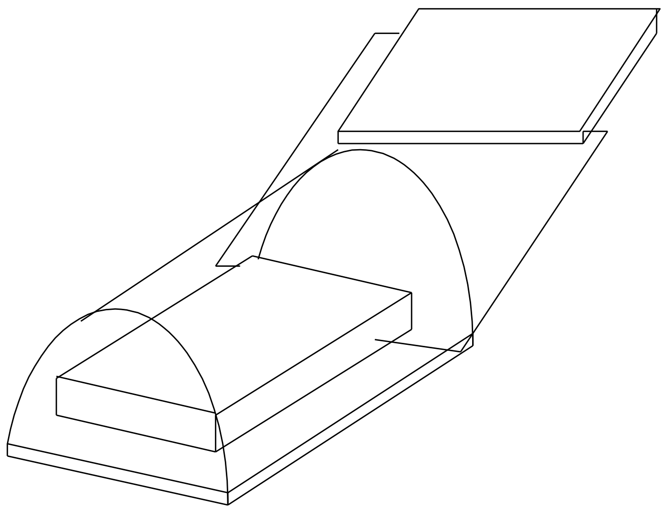

Figure 2 Schematic diagram of greenhouse, tank and solar collector

Two collector area-inclination angle scenarios were initially investigated. The first scenario represents a system with a collector inclined at an angle to optimise solar energy gain in winter. A ground-mounted free-standing structure to support the collector is envisaged. The second scenario represents a collector located on a typical roof and hence is inclined at a shallower angle. Collector areas were initially chosen based on typical 'rules of thumb' used by swimming pool collector installers in Victoria. A greenhouse-collector ratio of 1:1 was selected if the collector was inclined to optimise winter energy collection. To compensate for the lower output in winter of a roof-mounted collector, the area was increased by 50%. The collector system characteristics were as therefore as follows:

- ground-mounted collector optimally inclined for winter energy collection
  - 58^0 and 26 m^2 north facing for Melbourne
  - 51^0 and 26 m^2 north facing for Mildura
- roof-mounted collector, non-optimal inclination for winter energy collection
  - 25^0 and 39 m^2 north facing for both Melbourne and Mildura

6. Results and Discussion

6.1 Energy Use

Predictions were made of the supplementary energy required to maintain the tank water temperature at 22.5^0C for each system in the two locations. Predictions were made on an hourly basis, integrated for each month (Figures 3 & 4) and summed for the year (Table 3).

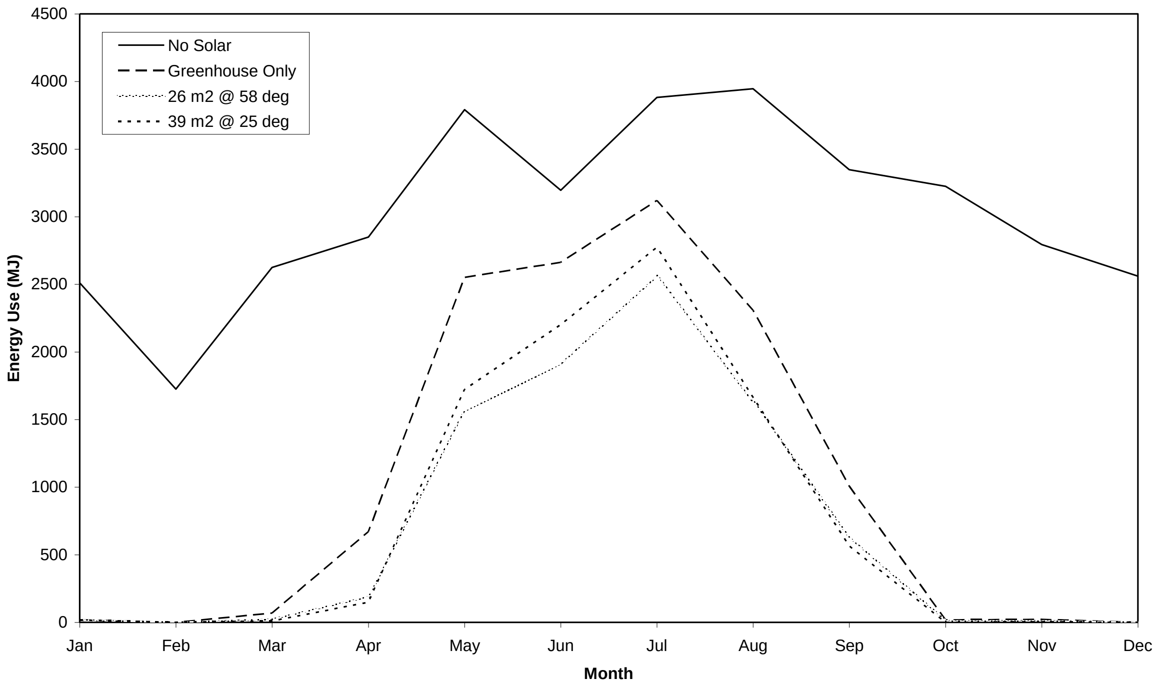

Figure 3 Predicted supplementary energy demand of solar and non-solar systems in Melbourne

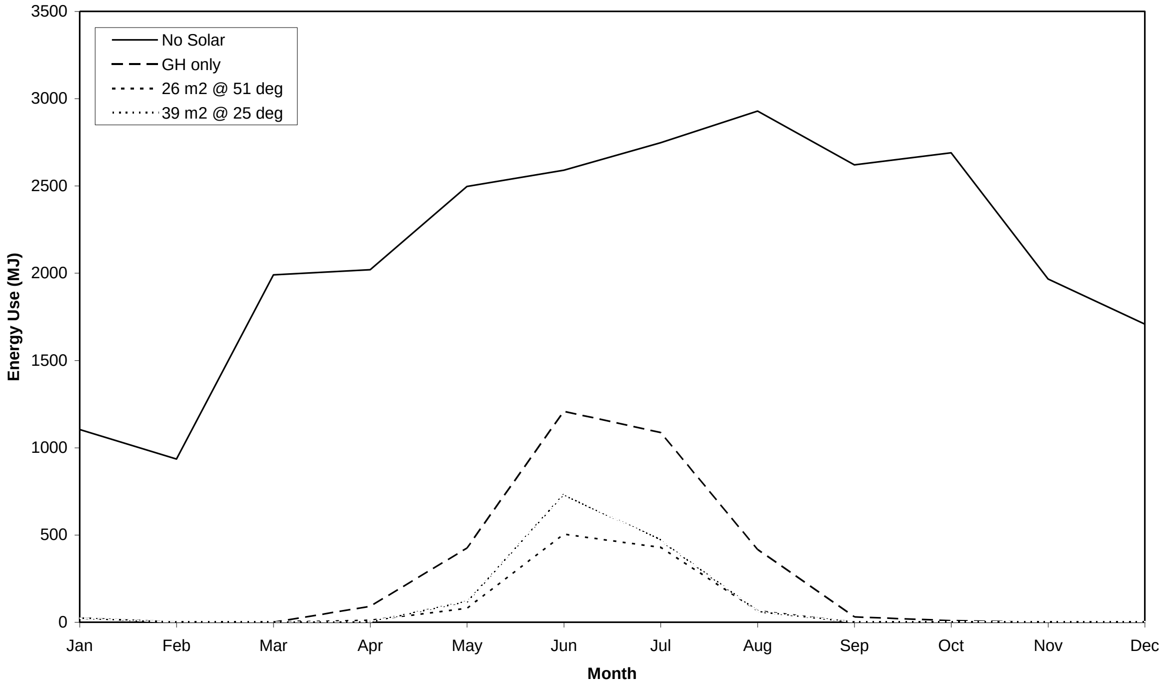

Figure 4 Predicted supplementary energy demand of solar and non-solar systems in Mildura

Table 3 Annual supplementary energy consumption of solar and non-solar systems

Location	Non-solar (GJ)	Greenhouse Only (GJ)	Greenhouse + 26 m^2 at 58^0 or 51^0 (GJ)	Greenhouse + 39 m^2 at 25^0 (GJ)
Melbourne	36.5	12.4	8.5	9.1
Mildura	25.8	3.3	1.1	1.4

Differences in energy requirements for the non-solar system in the two locations are due to the differences in fresh water inlet and ambient air temperatures. The fresh water inlet and the average mean daily temperatures are 2^0C and 2.5^0C warmer in Mildura respectively, compared to Melbourne. In each location, the greenhouse alone can reduce energy requirements significantly. The reductions, compared to the non-solar building are 66% and 87% respectively for the temperate and hot climates respectively. As expected, the collector systems optimised for winter energy collection are superior to those systems inclined at the shallower angle, although the percentage increases in energy collection are only small i.e. 1-2%. However, this increased energy saving is achieved with a 50% smaller collector area. The costs incurred to optimise the solar collector angle for winter heat collection must therefore be compared against greater collector array costs plus the additional energy use.

The predictions of conventional energy use for the greenhouse-only scenario are much lower than those predicted by Zhu *et al*. (1998) for a greenhouse-covered tank. Over a 7-month period, these authors predicted an energy use of 1.4 GJ m^{-2} compared to 0.13 and 0.47 GJ m^{-2} for Mildura and Melbourne respectively. Several important variations explain the difference. The greenhouse simulated by Zhu *et al*. (1998) has a single glazing layer and ambient temperatures are significantly lower, with -7.7^0C being the minimum, compared to 2.1 and 0.2^0C in the Melbourne and Mildura TMY data respectively. No average solar radiation figures over the seven months were provided but three days of data (averaging 4.4 MJ m^{-2}) quoted in their study indicate that solar radiation levels are much lower compared to those used in this study. Water temperatures were, however, lower (20^0C) compared to 22.5^0C in this study.

6.2 Water Temperatures

No upper limit on water temperature was set within the model. Therefore the tank water temperatures in the solar heating systems were higher than the minimum set temperature of 22.5^0C of the non-solar case. Mean annual water temperatures in the solar systems range from 25.7^0 to 27.8^0C for the solar systems in Melbourne, and from 28.4^0 to 31.3^0C for Mildura. To achieve the higher water temperatures in the non-solar case would require greater energy consumption. For example, the energy required to maintain an annual mean water temperature of 25.7^0C in the non-solar case in Melbourne would require nearly 56.4 GJ or 54% more conventional energy to achieve the same mean water temperature.

The temperature of the water in the tanks is, however, predicted to exceed 30^0C for a considerable number of hours. Excess temperatures are undesirable because of the stress they place on the fish, and the solar systems should not be credited with supplying heat that creates unfavourable conditions for fish growth. Assuming that 30^0C is the desired upper water temperature limit, the percentages of time when the tank temperature exceeds this value are shown in Table 4. Tank overheating occurs in all of the systems, but particularly those using a solar collector. When the solar collector is inclined at 25^0 this effect is more serious than for the collector inclined at 51^0 or 58^0. Depending on location, a collector inclined at the optimum angle for winter collection can thus be beneficial not only in terms of energy collection in the coldest part of the year, but also reduces the danger of overheating the tank in summer, particularly in Melbourne.

Table 4 Percentage of the year when tank temperatures exceed 30^0C

System	Melbourne	Mildura
greenhouse alone	16	39
greenhouse + 26 m^2 @ 58^0 or 51^0	27	54
greenhouse + 39 m^2 @ 25^0	33	56

6.3 Solar Fraction

The solar fraction, *f*, is defined as the ratio of useful energy contribution of each of the solar system configurations to the total energy that would be required to heat the water in the fish tanks if there was no solar system (Eqn 1).

$$f = \frac{(energy\,use\;by\;non\text{–}solar\;system) - (auxiliary\,energy\,use\;by\;solar\;system)}{(energy\,use\;by\;non\text{–}solar\;system)} \quad ......(Eqn1)$$

As noted, the water temperature is often significantly higher than 22.5 ^{0}C because the solar collector system collects more energy than is required to maintain this minimum. Up to a certain temperature, which will be species dependent, the warmer water in the tanks will be beneficial for fish growth. The energy from the collection system can therefore be described as 'useful'. Above a certain temperature, the heated water is no longer useful as it may cause stress to the fish and some action will be required by the grower to minimise overheating.

The optimum collector area can be defined as that which maximizes both solar fraction and the utilization of collected energy. To determine this optimum collector area for a typical system, simulations were performed at various collector areas. The resulting tank temperatures at the end of each hour were analysed and the energy collected by the solar system in any particular hour was discounted if the tank temperature rose above 30^0C. Figure 5 shows the relationship between collector area, annual solar fraction and percentage of collected energy used for Melbourne, while Figure 6 shows the similar relationships for Mildura.

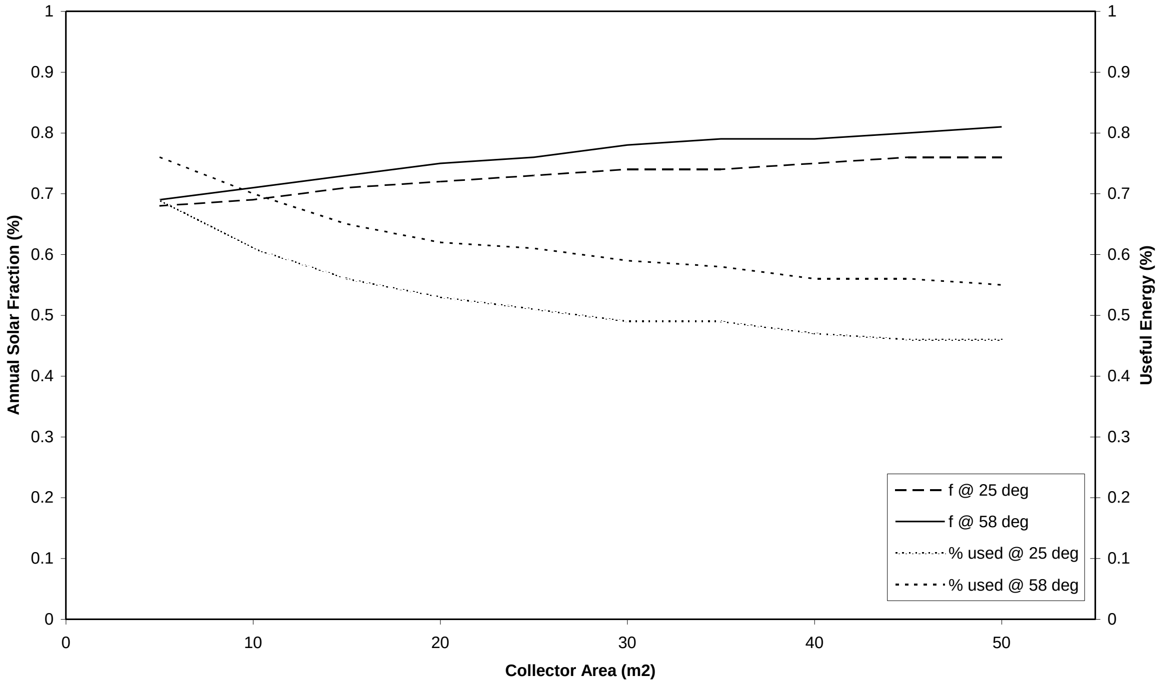

Figure 5 Collector area versus annual solar fraction and useful energy @ 25^0 and 58^0 for Melbourne

Figure 5 shows the annual solar fraction increases from approximately 66% when no collector is used to 76-81% with a solar collector area of 50 m^2. As the collector area increases, the water in the tank exceeds 30^0C on a greater number of occasions and therefore less of the solar energy collected is productively used. The point of intersection in each case represents the compromise between solar fraction and percentage of collected heat actually used. For the optimally inclined solar collector, this is approximately 10 m^2, while the intersection point for the solar collector inclined at 25^0 it is approximately 6 m^2. The solar panel inclined at the lower angle collects more heat in spring and autumn, but more of this collected energy is rejected. Figure 5 indicates that the initial estimate (26 m^2) of solar collector area was an overestimate for the optimally inclined solar panel.

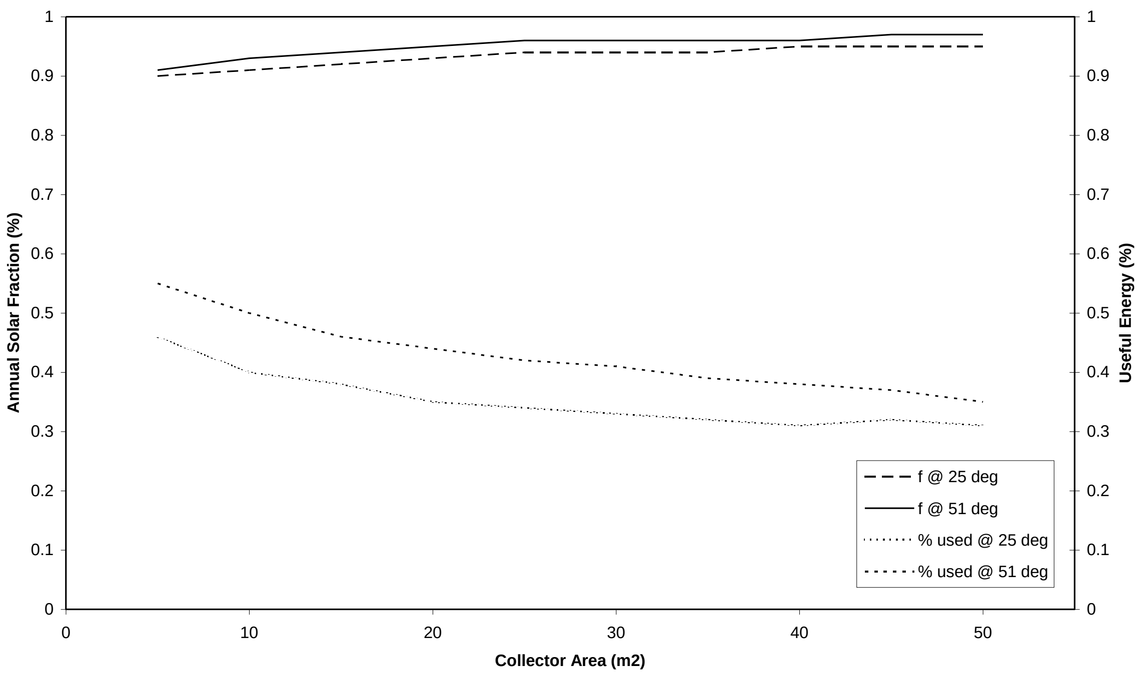

Figure 6 Collector area versus annual solar fraction and useful energy @ 25^0 and 51^0 for Mildura

Figure 6 indicates a quite different relationship between the annual solar fraction and the percentage of collected solar energy used in a hot climate. There is no intersection point between the respective curves for either the optimally inclined or roof-mounted collector arrays. This is because the greenhouse alone is so effective in raising the water temperature that even with small collector array areas, solar heat rejection is common. Even with a smallest collector area (5 m^2), 45-54% of the collected solar energy is rejected.

6.4 Condensation

Condensation is significant in buildings containing recirculation aquaculture systems. As Zhou (1998) reported, condensation on the inner surface of the polyethylene glazing occurs frequently. For many producers, excess condensation may be perceived to be a nuisance and they may take action to reduce it. The traditional strategy to overcome condensation is to increase ventilation but this will also increase energy consumption because the potential for evaporation also increases when the dewpoint temperature of the greenhouse air is lowered. Since evaporation is the largest cause of energy loss from the water in a RAS, the energy required to maintain a given water temperature will increase. In determining the thermal performance of the previous systems it was assumed that the greenhouse was unventilated and any fresh air exchange was solely the result of infiltration. The infiltration rates were wind dependent and ranged from 0.7 to 10.5 for wind speeds from zero to 14.9 m s^{-1}. The model was therefore modified to introduce additional fresh air into the greenhouse at various rates. Fresh air exchange was now due to the combined effect of positive ventilation and infiltration. Figure 7 shows the predicted relationship between ventilation rates, expressed as changes in greenhouse volume per hour (ach^{-1}), annual energy use and the hours of condensation.

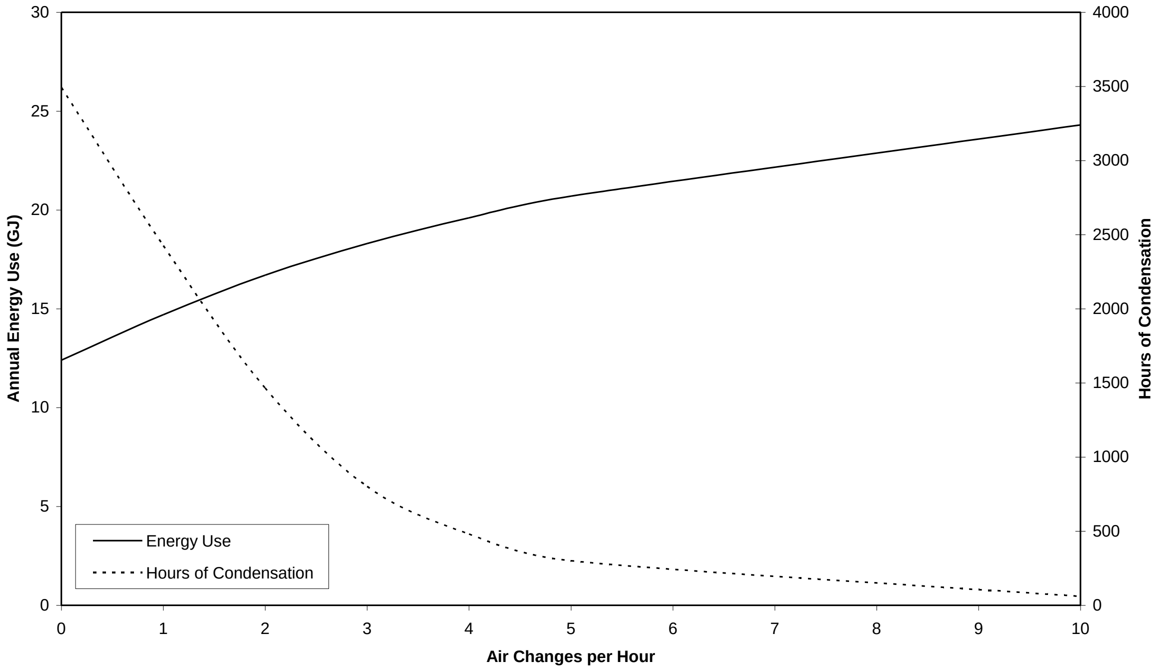

Figure 7 Effect of ventilation rate on annual energy use and hours of condensation

By ventilating the greenhouse at 10 ach^{-1}, the annual hours of condensation may be reduced from nearly 3500 hours or 40% of the time to just 60 hours, which is less than one percent of the year. However in adopting this ventilation solution to reduce condensation, the energy use to heat the water in the tanks almost doubles from 12.4 GJ to 24.3 GJ per annum. This is clearly an undesirable outcome. One alternative strategy to reduce condensation is to place covers on the tanks at night. The effect of covering the exposed water surface to varying degrees in a tunnel greenhouse located in Melbourne without forced ventilation is shown in Figure 8.

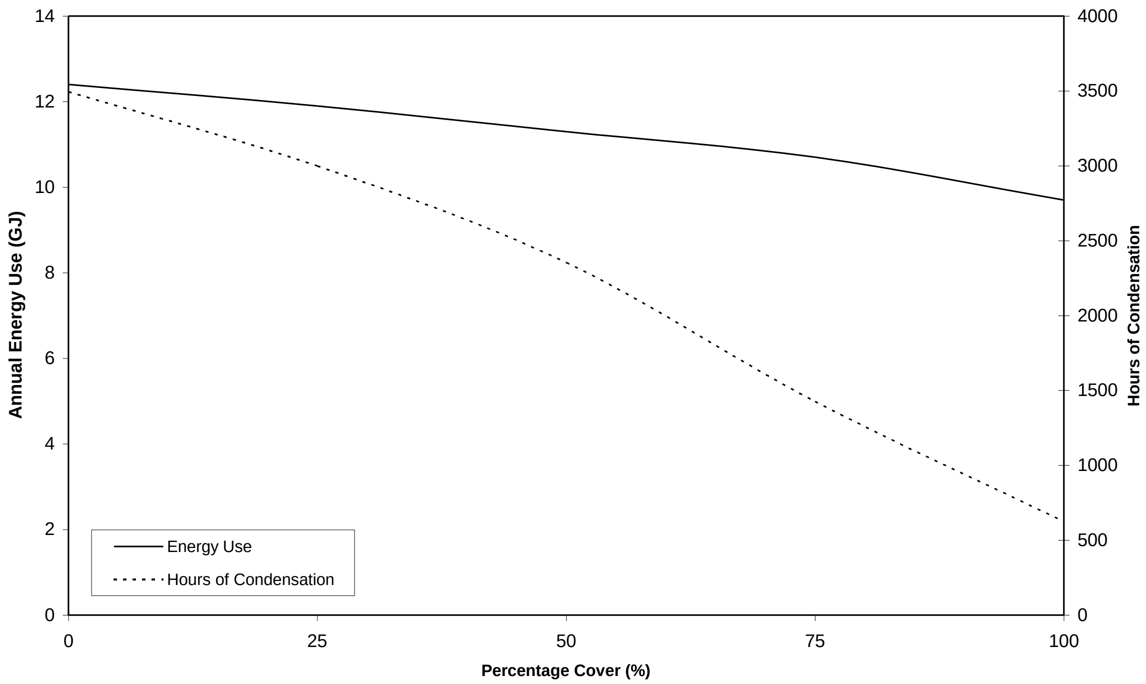

Figure 8 Effect of tank covers on annual energy use and hours of condensation

Four levels of cover between zero and 100% cover were simulated. The model indicates that a maximum 22% reduction in annual energy use combined with an 82% reduction in the number of hours of condensation can be achieved by covers preventing all night-time evaporation. Although covers are not as effective as ventilation in reducing condensation, they have the simultaneous and additional benefit of reducing energy use.

7. Conclusions

The literature suggests that passive and active solar technologies can reduce conventional energy requirements for water heating in recirculation aquaculture systems. However, no studies are available to indicate the potential annual energy savings for different configurations in different climates. The systems investigated in this study indicate that in a hot sunny climate a double skin greenhouse alone can provide significant savings, when relatively small rises (5-6^{0}C) in water temperature are required. In a temperate climate, moderate areas of unglazed swimming pool collectors, inclined at the optimum angle for winter heat collection, can reduce conventional energy by a further 11%. Ventilation is the most effective strategy to reduce the occurrence of condensation on the inner glazing surface but this strategy will also increase energy requirements. The placement of covers on the RAS tanks at nights will simultaneously reduce energy requirements and the occurrence of condensation.

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