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บทความวิจัยเรื่อง Field Experiments and Economic Evaluation of Evaporative Cooling System in a Silkworm Rearing House ได้รับการตอบรับให้ตีพิมพ์ในวารสาร Biosystems Engineering มี impact factor ในปี 2004 เท่ากับ 0.496

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Field Experiments and Economic Evaluation of Evaporative Cooling System in a Silkworm Rearing House

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High ambient temperature has a negative effect on silk production. During heat stress, penalties to the efficient performance, production, reproduction, feed conversion, health and welfare of the animals can be severe. This research was aimed at investigating the feasibility of using direct evaporative cooling to improve the indoor air conditions in a silkworm rearing house. To this end, a silkworm rearing house of 32 m^2 floor area was fabricated and tested at Mahasarakham University. A cooling pad measuring 1.8m x 3.6 m was placed on the north wall and a fan on the south wall. Experiments were performed through two seasons, namely: winter (November – December 2003) and summer (March – April 2004). Various operating airflow rates were considered to assess cooling performance and energy efficiency ratio of the evaporative cooling system. The results showed indoor dry bulb temperature drops of 6 - 13°C could be achieved parallel with a 30 – 40 % rise in relative humidity. The energy efficiency ratio tends to be very high because the system consumes only fan and water pumping power. The economic analysis indicates that the payback period of the evaporative cooling system is about 2.5 years. Therefore, the direct evaporative cooling method demonstrates significant potential for silkworm rearing house cooling.

1. Introduction

Thailand is one of the countries well known for its silk fabrics and other fine silk products. During the period 1997-2001, the average annual value of the export of silk products was 1,038.8 million baht (40 Baht = 1 US$), compared to the average value of imports of 629.3 million baht, or 54% of exports (Sericulture Extension Center No.1-9, 2002). It has been shown that Thai silk production is not sufficient to meet local demands. This situation has greatly obstructed the development of Thai silk industry. Among the strategies for silk production development during the Nine National Economic and Social Development Plan (2002-2006), was a plan to increase the silk yarn about 42% by the year 2006 (Chuprayoon *et al.*, 2002).

The ability of silkworms to produce is affected by seasonal factors such as temperature and humidity. It has been well established that efficiency in silkworm production is often lower during and after the hot season. One reason for the reduction in their productive performance might be elevated ambient temperatures, which induce heat stress. This is especially true in tropical areas such as Thailand where the temperature exceeds 30°C for several months of the year (Suriyasomboon *et al.*, 2004) and, consequently, is not appropriate for rearing silkworms. Temperatures in the range of 21-27°C with relative humidity of 70-85% (Tazima, 1978) are required. Most silkworm production in Thailand is performed in conventional stables which have an open air system with no walls. In recent years, a new housing system with a direct evaporative cooling system has been introduced to improve the microclimate for livestock in Thailand such as pigs (Boonyawattana *et al.*, 2003) and poultry (Ketjoy, 1999). Various other works on evaporative cooling systems applied to greenhouses had already been published such as Willits (2003), who presented a cooling model that predicts axial gradients of temperature and humidity of a greenhouse evaporative cooling system. Kittas *et al.* (2003) reported on a large commercial greenhouse cooled with evaporative pads and partially shaded. Evaporative cooling is an adiabatic humidification process (Wiersma & Short, 1983) that does not involve heat gain or loss. Sensible heat from the air is used to evaporate the water that comes in contact with the air. This sensible heat is then converted into latent heat, resulting in a reduction of the dry bulb temperature with a complementary increase of the relative humidity and water vapour content of the air. An evaporative cooling system might be one alternative way of reducing the impact of a harsh climate on silkworm production.

This paper presents an investigation of the feasibility of using evaporative cooling in a silkworm rearing house.

2. Analysis

2.1. Cooling efficiency and enthalpy change in air

Cooling efficiency (η) is an index used to assess the performance of a direct evaporative cooler. Cooling efficiency in percentage can be defined as follows (Koca *et al.*, 1994).

$$\eta = \frac{T_d - T_c}{T_d - T_w} \times 100 \tag{1}$$

where T_d and T_w are the dry and web bulb temperatures of the ambient air and T_c is the dry bulb of the cooled air in °C.

The enthalpy change in air ΔH, which can be calculated as follows:

$$\Delta H = MC_{pa}\left(T_d - T_c\right) \tag{2}$$

where C_{pa} is the specific heat of moist air in kJ kg^{-1} K^{-1}; and M is the air mass flow rate in kg s^{-1}

2.2. Energy efficiency ratio

Energy efficiency ratio (EER) was developed by the industry to evaluate the rate of energy consumption for air conditioning units (El-Dessouky *et al.*, 2000). The EER represents a measure for rating air conditioning units. The energy efficiency ratio is defined as the net thermal energy removed from air for cooling purposes per watt of energy expended. That is

$$E_{ER} = \frac{\Delta H}{P} \tag{3}$$

where P is input electrical power in kW of the exhaust fan and water pump

The value of EER is calculated by determining the difference in the enthalpy of the inlet and outlet air streams through the cooling pad and the input power.

3. Experimental silk worm rearing house and measurements

3.1. Silk worm rearing house

A roof type even span house with an effective floor area of 8 m x 4 m and a height of 2.5 m, with one access door and no windows has been considered for experimental purposes as shown in Figure 1. The walls are made of asbestos-cement flat sheet. The roof gable, tilted at a 20°, is covered by Roman tiles. The horizontal ceiling is made of gypsum with 36 cm attic height. A cooling pad sized of 1.8 m x 3.6 m is located on the north wall and a 746 W exhaust fan is fitted at the south wall. The cooling pad is made of corrugated cellulose of 15 cm thickness has been impregnated with wetting agents. It was used to provide maximum surface area for evaporation. A water inlet is fitted on the top of the cooling pad. Several small holes of different diameters are made in the top solid part of the cooling pad to insure uniform distribution of the water throughout the cooling pad. A 373 W pump with water tank was attached to cooling pad for continuous water trickling.

3.2. Measurements

The silkworm rearing house temperature and humidity were measured at nine positions using nine calibrated temperature and humidity sensors [Testo model 175-H2, Germany, accuracy ±0.5°C and ± 3% relative humility (RH)] as shown in Figure 2. The ambient temperature and humidity were also measured by Testo model 175-H2. A hot wire anemometer (Testo model 445, Germany, accuracy ± 0.03 m s^{-1}) was used to measure air velocity (average of nine points as shown in Figure 2). A variable voltage was used to drive the exhuast fan. A clamp on power meter [Hioki model 3286, Japan, accuracy ± 2.3% reading (rdg.) ± 5 digit (dgt.)] was used to measure the power consumption of the exhaust fan and water pump. The experiment started at 10 am and ended at 5 pm with data recording at 15 minute intervals.

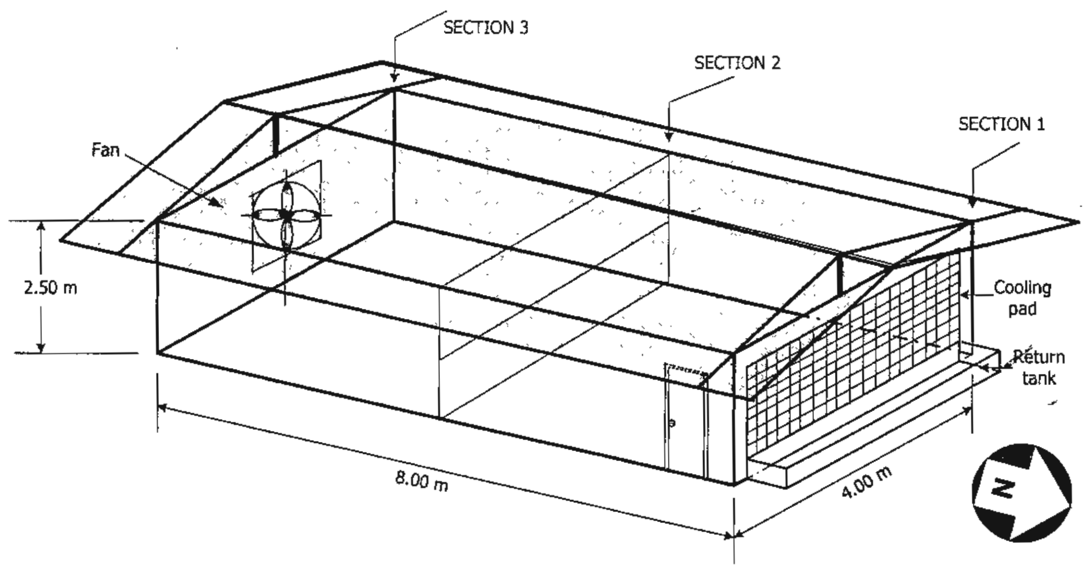

Fig. 1. Isometric view of silkworm rearing house

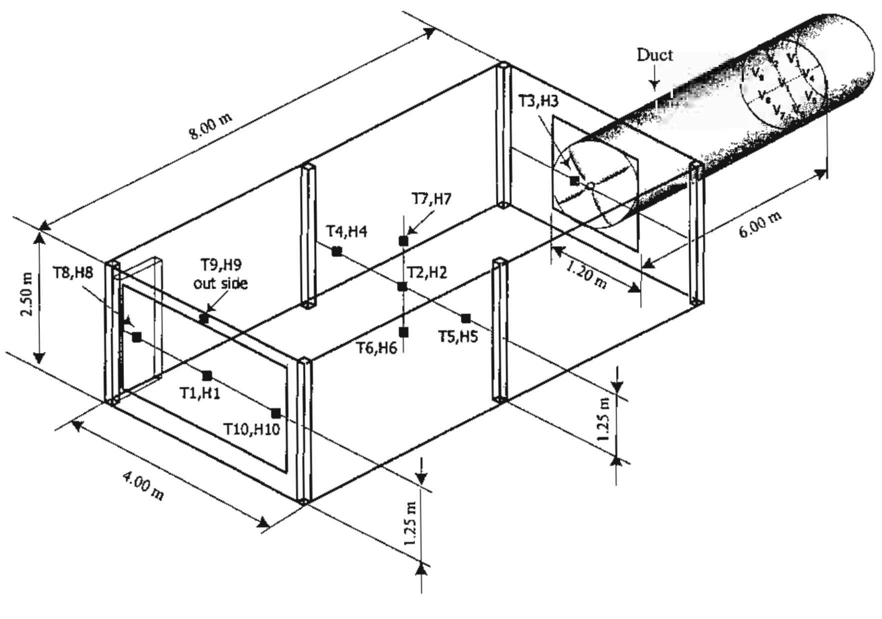

Fig. 2. Locations of temperature (T), humidity (H) and velocity (V) sensors in the experimental house

4. Results and discussion

4.1. Indoor temperature and humidity fluctuation

Figure 3 shows that when the evaporative cooling system was not operating, the room temperature (average of nine points) was nearly the same as the ambient (before 14:00 h) because outdoor air infiltrates through the channels of the cooling pad. After 14:00 h, the room temperature was higher than ambient. This was due to the heat accumulated in the room. The maximum indoor temperature was about 33.1°C. When the evaporative cooling system was turned on, the room temperature decreased from 32 to 22°C while relative humidity increased from 33 to 82% RH, which is appropriate for rearing the silkworm (suggest temperature in the range of 21-27°C with relative humidity of 70-85% (Tazima, 1978)) as shown in Figure 4. The results in this study indicate that silkworms in the conventional system were exposed to higher temperatures than silkworms in the evaporative cooling system.

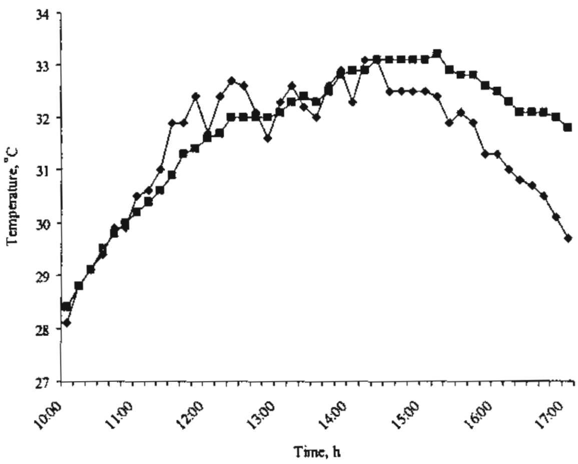

Fig.3. Hourly variation of ambient and room temperatures when the evaporative cooling system was not operating (23/11/2003); —◆—, ambient temperature; —■— room temperature

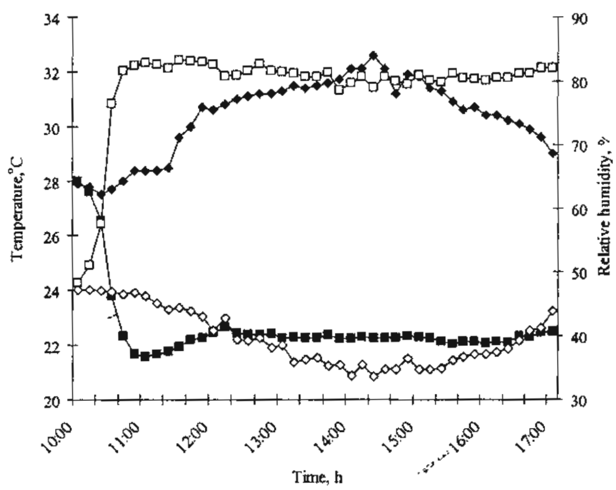

Fig. 4. Hourly variation of ambient and room temperatures and humidities of the open evaporative cooling system (4/12/ 2003); —◆—, ambient temperature; —■— room temperature; —◇—, ambient relative humidity; —□—, room relative humidity

4.2. Effect of seasonal variation

In general, three different seasons in Thailand can be recognized as follows: the summer season is about three months long: from mid-February to mid-May. The Rainy season occurs from mid-May to mid-October, and the winter season occurs from mid-October to mid-February (Khedari *et al.*, 2002). A comparison of ambient air inlet/outlet temperatures and humidity during different seasons of the year was undertaken during the winter season (4/12/2003) and the summer season (25/3/2004). It was seen that a lower outlet temperature of the processed air can be realized if the temperature and relative humidity of the air is lower at the inlet. In the summer, the maximum outside air temperature was 39.2°C at 14:00 h. The system reduced the air temperature by 13°C and increased the relative humidity by about 51.2%. In the winter the air temperature drops by about 10°C as shown in Figures 5 and 6. This drop is because the ambient humidity in summer is lower than in the winter. In summer there is a greater potential to absorb the moisture of the evaporative water. It is clear that evaporative cooling systems are efficient for dry conditions, but not as effective for humid conditions.

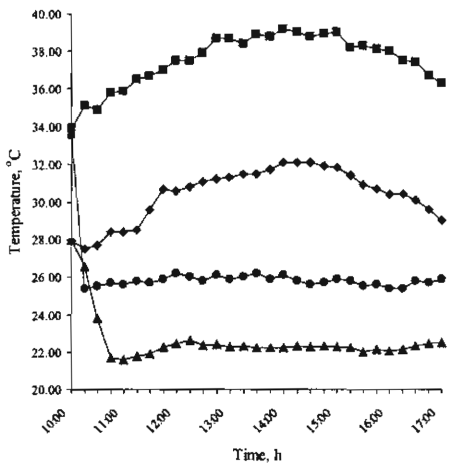

Fig. 5. Effect of seasons on room temperature (air mass flow rate = 6.3 kg s^{-1}); —◆—, outside temperature (4/12/2003); —■— outside temperature (25/3/2004); —▲—, room temperature (4/12/2003); —●—, room temperature (25/3/2004)

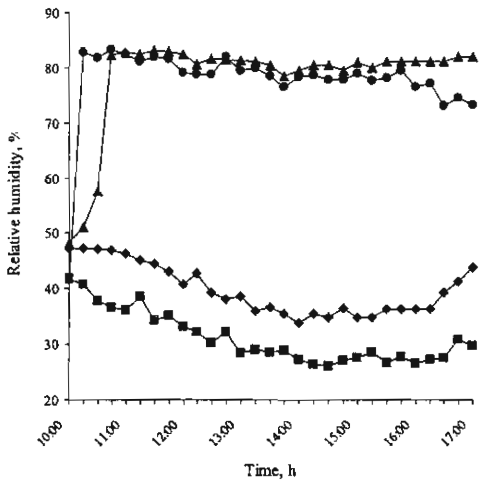

Fig. 6. Effect of seasons on room humidity (air mass flow rate = 6.3 kg s^{-1}); —◆—, outside relative humidity (4/12/2003); —■— outside relative humidity (25/3/2004); —▲—, room relative humidity (4/12/2003); —●—, room relative humidity (25/3/2004)

4.3. Effect of air mass flow rate

Testing of the effects of air mass flow rate on room temperature and humidity was undertaken on different days. Thus, it was not easy to draw a comparison amongst the results because of the various climatic conditions as presented in the above section. Nevertheless, general and subjective conclusions could be formulated. Tests were conducted at three different air mass flow rates: 4.4 kg s^{-1} (8/12/2003), 6.3 kg s^{-1} (4/12/2003) and 9.2 kg s^{-1} (3/12/2003). There is a little variation of relative humidity with increase of air mass flow rate from 4.4 to 9.2 kg s^{-1} as shown in Figure 7, whereas the temperatures are reduced with increase of air mass flow rate as shown in Figure 8. The cooling efficiency is affected by several factors, such as pad design, thickness of pad, airflow rates and outside air temperature and relative humidity. Using a fixed 15 cm thickness of pad, the cooling efficiency varies between 66 and 80.2%. This result agreed well with that presented in (Watt, 1986).

The power consumption in kWh and EER for the three air mass flow rates is shown in Table 1. The EER range of 24.4 to 59.9 at air mass flow rates increased from 4.4 to 9.2 kg s^{-1}. This is due to the cooling effect, which prevails over power consumption. However, in order to reduce the power consumption of the fan, an alternative scenario could be proposed by varying the airflow rate between summer and winter seasons. An example of temperature and humidity of the system are also shown in Figures 5 and 6. Where two airflow rates were considered, the air mass flow rate of 6.3 kg s^{-1} for summer and 4.4 kg s^{-1} for winter are shown.

Table 1
Input power and energy efficiency ratio at different airflow rate

Air flow rate, kg s^{-1}	Input power, kW	Energy efficiency ratio
4.4	1.14	24.4
6.3	1.15	51.2
9.2	1.23	59.9

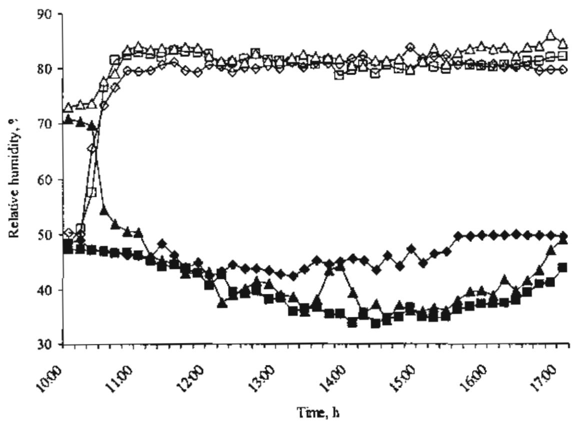

Fig. 7. Effect of ambient relative humidity and air mass flow rates on room humidity; —◆—, ambient relative humidity (4.4 kg s^{-1}); —■— ambient relative humidity (6.3 kg s^{-1}); —▲—, ambient relative humidity (9.2 kg s^{-1}); —◇—, room relative humidity (4.4 kg s^{-1}); —□—, room relative humidity (6.3 kg s^{-1}); —△—, room relative humidity (9.2 kg s^{-1})

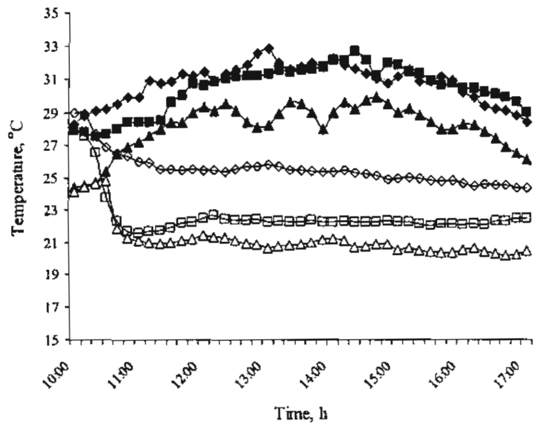

Fig. 8. Effect of ambient temperature and air mass flow rates on room temperature; —◆—, ambient temperature (4.4 kg s^{-1}); —■— ambient temperature (6.3 kg s^{-1}); —▲—, ambient temperature (9.2 kg s^{-1}); —◇—, room temperature (4.4 kg s^{-1}); —□—, room temperature (6.3 kg s^{-1}); —△—, room temperature (9.2 kg s^{-1})

4.4. Rearing of silkworms – a demonstrative application

The general question of the feasibility of a given application is not being addressed in this study. Instead, an experiment performed on the evaporative cooling system for rearing silkworms is used to illustrate a possible application. At this stage, two generations of Multivoltine Thai silkworm 'Nanglai' (Bombyx mori) with 5,000 larvae per generation were reared in the evaporative cooling house. The first and second generations were reared during November to December 2003 and March to April 2004, respectively. An interesting observation here is that, the percentage of survival of silkworms was 91% for the first generation and 93% for the second generation. Comparable conventional system percentage survival rates of silkworms were separated by season as follows: 46.5% for summer, 82.4% for rainy and 83% for winter (Attathom et al., 2002). Obviously, the percentage of survival of the silkworms reared in the evaporative cooling system was higher than that obtained with the conventional rearing system, especially in summer. It could be concluded that the evaporative cooling system application could be an alternative in the silkworm rearing process.

4.5. Economic evaluation

In this section, a cost analysis of the evaporative cooling is evaluated. A payback period is employed to determine the period of time required for a profit that could be attributed to using the evaporative cooling. The payback period is defined as the investment of time required for the profit of an investment to equal the cost of the investment (Newnan, 1980). The life cycle of the Thai silkworm is approximately 25 days. Thus, twelve generations of silkworm can be raised per year with 44,000 larvae per generation. Assuming the percentage survival of silkworms was 90%, silkworm survival would be 39,600 larvae per generation. The average weight of a Thai silkworm cocoon was 1.3 g per larvae. The total weight for a survival of 39,600 larvae would be 51.48 kg per generation. During 2003, the purchase price of cocoon in the local market was 80 Baht per kg. The resulting annual income would have been 49,420.8 Baht. Fixed costs for the evaporative cooling house, including those for construction cost, suction fan, pump, piping and cooling pad, were 70,000 Baht. Variable costs, mainly the power cost, silkworm eggs and feed, were 22,000 Baht. These costs divided by the annual income of 49,420.8 Baht give a payback period of approximately 2.5 years. The summary of economic evaluation is given in Table 2. Therefore, the evaporative cooling system in a silkworm rearing house should be promoted as an alternative technology for the household farmer. Additional cost savings could be recognized in larger scale operations.

Table 2
Summary of economic evaluation of evaporative cooling system

Item	Value, Baht
Fixed cost	70,000
Variable cost	22,000
Income	49,420.8

5. Conclusions

The feasibility of improving the indoor condition of a silkworm rearing house by using direct evaporative cooling was investigated experimentally. An experimental silkworm rearing house was built. The study was conducted during the summer and winter seasons in Mahasarakham, Thailand. It was found that the evaporative cooling system was capable of reducing the temperature and increasing the relative humidity as required for rearing the silkworm. An alternative scenario was also proposed that involved varying the air mass flow rate between summer and winter seasons to reduce operating costs. Consequently, as the experiment revealed, the evaporative cooling system should be recommended.

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