A Cooling System for a Mushroom House for Use in the Upper Central Region Climate of Thailand

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Received: 9 March 2018; Accepted: 28 January 2019

Abstract

This study investigated a cooling system for mushroom cultivation for both experimental and theoretical purposes. The system was used in shitake mushroom cultivation in the upper central region climate of Thailand in winter. The system consisted of a night cooling system, a cooling coil and direct evaporative pad cooling. The night cooling system was set up and tested from November to December 2017. The COP equation for the system was correlated with experimental data and then used to predict cold water tank temperature. It was found that the cold water tank temperature was 25.50 °C, while the average dry bulb day time temperature and wet bulb night time temperatures were 31 °C and 25.72 °C respectively. The outlet air temperature from the whole system was then estimated from the cold water tank temperature. The resulting outlet air temperature was cooled to 22.04 °C. Thus, the system could satisfy the criteria temperature for the air temperature inside the mushroom house which was defined at 28 °C.

Nomenclature

A	heat transfer area, m^2
C_p	specific heat, $kJ\ kg^{-1}\ K^{-1}$
COP	coefficient of performance
m	mass , kg
RH	relative humidity
T	temperature, °C
U	overall heat transfer coefficient, $W\ m^{-2}\ K^{-1}$

Subscript

ci	cold fluid inlet
db	dry bulb
hi	hot fluid inlet
w	water
wb	wet bulb

Keywords: Cooling, Mushroom, Greenhouse

Introduction

Cooling is an intensive energy consuming process especially in hot climate areas. In the agricultural sector, greenhouse cooling is essential to provide a suitable condition for plant or animal growth. A greenhouse is a viable option for sustainable crop production in regions having adverse conditions. As Thailand is located in a tropical area with a hot and humid climate, a greenhouse cooling technique can play a vital role in agricultural production.

Mushrooms have been known as a nutritious food for a long time, not only because of their flavor, but also as they are rich in minerals, vitamins and dietary fiber (Manzi, Aguzzi, & Pizzoferrato, 2001). Thailand has a warm, tropical climate and is one of the richest sources of tropical mushrooms, which are one of the economically viable crops in Thailand. Shitake mushrooms (*Lentinus Edodes*) are one of the most cultivated mushrooms in the world (Ashrafuzzaman, kamruzzaman, Razi, Shashidullah, & Fakir, 2009), having high nutritional value and several beneficial health effects including the propagation of anticancer, antidiabetic, antimicrobial, hypotensive and hypocholesterolaemic activity (Wasser, 2005). The shitake mushroom is popular in Thailand but it prefers a temperate climate, such as in northern Thailand and in the highlands of the northeast, so the yield is not adequate. The Department of Agriculture has been developed shitake strains that can be grown at a higher temperature of 28 °C, to increase shitake production (Technology Biological Research Office, 2017). The upper central region of Thailand is one of the agricultural areas with large amount of crop residues that are appropriate for mushroom cultivation. However, the types of cultivated mushrooms are limited by the weather. Environmental factors, e.g., temperature, light and humidity, have an influence on the growth of mushrooms but temperature is the most dominant factor (Chang & Miles, 1989). The average temperatures in winter, summer and the rainy season in the central region of Thailand are 26.2 °C, 29.7 °C and 28 °C respectively (Thai Meteorological Department, 2017). Types of mushroom which prefer high temperatures of 28-32 °C, such as Oyster mushroom, Sajor-caju, Jew's ear mushroom and straw mushroom etc. are mostly cultivated in this area. However, the average temperature in winter has potential for shitake production but a mushroom house equipped with a cooling system is necessary.

A fan-pad cooling system is generally applied in a mushroom house to control the inside air temperature, because of its simplicity and energy efficiency. This is direct evaporative cooling where a large amount of heat is transferred from the air to water using evaporation, and consequently the air temperature decreases with increasing humidity. This can be called an adiabatic process (Amer, Boukhnouf, & Ibrahim, 2015) A system consists of fans on one side of the greenhouse wall to induce air through the wetted porous pads on the opposite side wall. From a previous study, (Kumar, Tiwari, & Jham, 2009), this system is not as efficient in hot and humid area as it in a dry climate. However due to its advantages it can be used as a cooling process to reduce energy consumption.

Investigations of cooling pads coupled to condensers in vapor compression systems have been conducted in studies. The ambient air flowing to the condenser was pre-cooled by the pad to improve system energy efficiency. The results showed that the pad can reduce the system's power consumption and the COP was improved (Martinez et al., 2016; Hajidayaloo & Eghtedari, 2010). Water cooled at night by a cellulose-pad system has been investigated (Hou, Hsieh, Lin, Chuang, & Huang, 2016). When compared to a conventional cooling tower, the pad consumed much less power. In the study, cooled water was stored and used as a heat transfer medium in a cooling system during daytime. The air wet bulb temperature at night influenced the cooled water temperature. A study of a cooling pad system for a hybrid system has also been conducted, (Heidarinejad, Farahani, & Delfani, 2010). The system consisted of nocturnal radiative cooling, an indirect cooling coil unit and an evaporative cooling pad system. The evaporative pad complemented the system as it consumed less energy, but the cooling pad alone could fulfill the required temperature. The study showed that this system could be used as a replacement for a vapor compression system.

In this paper, an air cooled system for a mushroom house was investigated for both experimental and theoretical work. A night air cooling system was set up and tested in winter for its potential to produce cooled water. This was done at Kasetsart University, Kamphaengsaen campus in Nakhonpathom province. The results from the experiment were then used to predict the output air temperature from the whole system. This system consisted of a night cooling pad, a cooling coil and evaporative cooling. The system application was for a mushroom house for shitake cultivation in winter, in the upper central region of Thailand. The defined maximum air temperature inside the house was 28 °C.

Methods and Materials

Figure1 and figure 2 show the schematic diagram and the test rig of the night cooling system which consisted of a cellulose pad, an electrical fan, two water pumps and an insulated water tank. The equipment specifications are summarized in Table 1.

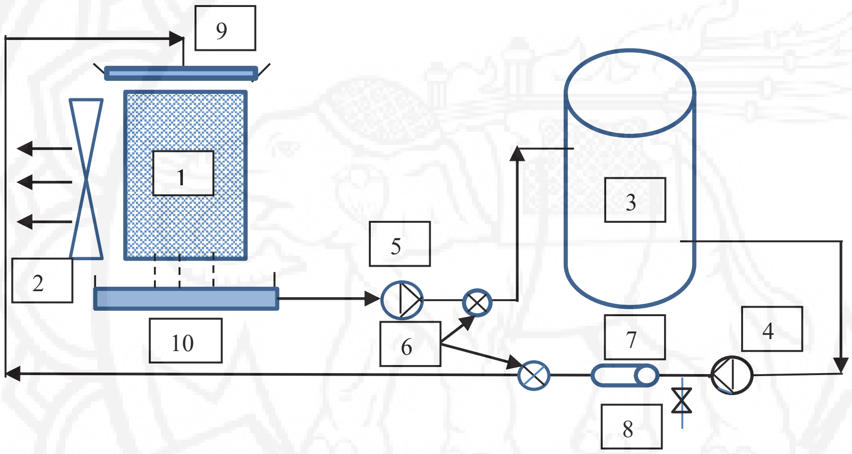

Figure 1 Schematic diagram of the night cooling system

1-Cooling pad 2- Fan 3-Water storage tank /insulation 4-Pump 1 5-Pump 2 6-Gate valve 7-Flow meter 8-Bypass valve 9-Water distribution panel 10-Water basin

Figure 2 Experimental set up of the night cooling system

Table 1 Equipment specifications for the cooling system

Cellulose pad	0.3 m (width)× 0.9 m (height) × 0.20 m (thickness)
Electrical fan power	0.5 kW
Water pump	25 W (each)
Water tank / insulation	85 Litre/ Fiberglass with 1 inch thickness

The system operated automatically at night when the air was not saturated at100 % relative humidity. When the system was turned on, pump no. 1 discharged water from the tank to the pad and pump no.2 circulated water back to the tank again. Ambient air was flowed through the pad by the fan and exchanged heat with the water. The measured variables were ambient air dry bulb temperature and relative humidity, inlet and outlet air temperature and humidity at the cooling pad and water temperature in the tank. The water evaporation rate was also measured by the difference between the water volume at the initial and final times of operation. Temperature and humidity probes were used to measure the temperature and relative humidity with an accuracy of ± 0.3 °C and ± 2% RH respectively. Cold water flow rate was measured by a rotameter with ± 3 % accuracy. The temperature and humidity data was automatic recorded every 5 minutes. The control systems uses Arduino, an open- source hardware and software platform, for the microcontroller to automatic collect data from the system. This is from its relative low-cost, larger user community, and adaptability. It will also be used in the future research as the control environmental system in a mushroom house. The Arduino model in the experiment here is Mega 2560, and the temperature humidity sensor brand is ASAIR, AM3202 model, which is compatible with this Arduino type.

Data Reduction

The pad efficiency (η_{pad}) was calculated from the following equation,

$$\eta_{pad} = \frac{(T_o - T_{pad})}{(T_o - T_{wb})} \quad (1)$$

where T_o and T_{wb} were the ambient air dry bub and wet bulb temperature in °C respectively, and T_{pad} was the cooled air temperature from the pad. Wet bulb temperature was estimated from the relationship between the measured dry bulb temperature and relative humidity (Stull, 2011).

The COP of the system was defined as,

$$COP = \frac{Q_{tank}}{P_{in}} \quad (2)$$

where, Q_{tank} was the tank energy storage in kJ, and P_{in} was the power input to the system in kWh.

$$Q_{tank} = (m_w c_{pw} \Delta T)/3600 \quad (3)$$

where, ΔT was the temperature difference between the initial anf final temperature of water in the tank. The uncertainties of the variables were calculated from the following equation (Taylor,1982).

$$\frac{\delta X}{X} = \sqrt{\left(\frac{\delta Y_1}{Y_1}\right)^2 + \left(\frac{\delta Y_2}{Y_2}\right)^2 + .. + \left(\frac{\delta Y_n}{Y_n}\right)^2} \quad (4)$$

From Eq.(4), The uncertainty of the variable X, $\frac{\delta X}{X}$, is estimatted from the uncertainties of the related variables, Y_1....Y_n. The results are presented in Table 2.

Table 2 The uncertainties in calculated variables

Variables	**Uncertainty**
T_{wb}	4.81%
η_{pad}	0.6%
Q_{tank}	3%
COP	3%

Results and discussions

-Night cooling system experiment

The cooling pad system was tested at night in winter from 5/11/2017 to 13/12/2017. The weather in this season was more variable compared to several previous years especially in December when it was rainy, had high relative humidity and low temperatures. The average day dry bulb and wet bulb temperatures and relative humidity at night for some of the test days are shown in Figure 3

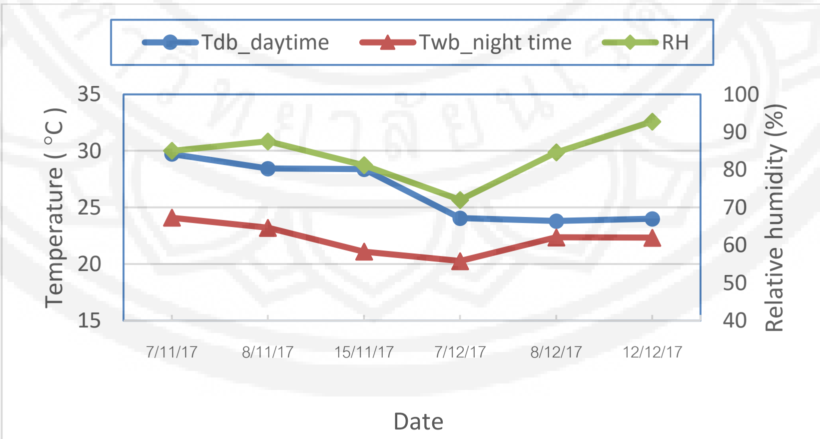

Figure 3 Average day and night ambient data

To save water, the cold water flow rate during the test was adjusted via a regulating valve to be at a minimum rate while maintaining a completely wetted pad and this rate was 4.55 kg/min. From the pad manufacturer's data, efficiency is increased with pad thickness and at low air speed. However, the pad thickness in this experiment was 0.20 m which not defined in the data sheet. Thus, the pad was first tested for its efficiency during the day time by measuring inlet and outlet air temperature and inlet air relative humidity, and recorded every 5 minutes. The pad efficiency was calculated according to Eq. (1) at each day during the test period and then averaged. It was found that the pad efficiency was 0.85 at 0.5 m/s air velocity.

The inlet cold water temperature ($T_{cw,i}$) and air wet bulb temperature at night ($T_{wb,n}$) affect the tank energy storage (Q_{tank}). This calculated using Eq. (3) and presented in Figure 4. The Q_{tank} on any day was estimated by summation of the tank energy every 5 minutes from the initial to the final operating time. The difference between the initial and final water volume in the tank was the evaporation rate, which was then averaged at the same operating time as Q_{tank}. The mass of cold water in the tank (m_w) at any calculated time was the mass of cold water at the previous time minus the average water evaporation rate. The COP of the cooling system was then evaluated from Eq. (2) and shown in Fig.5 which was related by $T_{cw,i}-T_{wb,n}$.

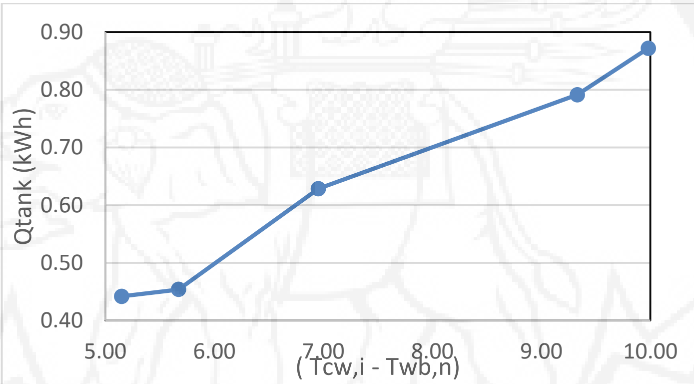

Figure 4 Tank energy storage

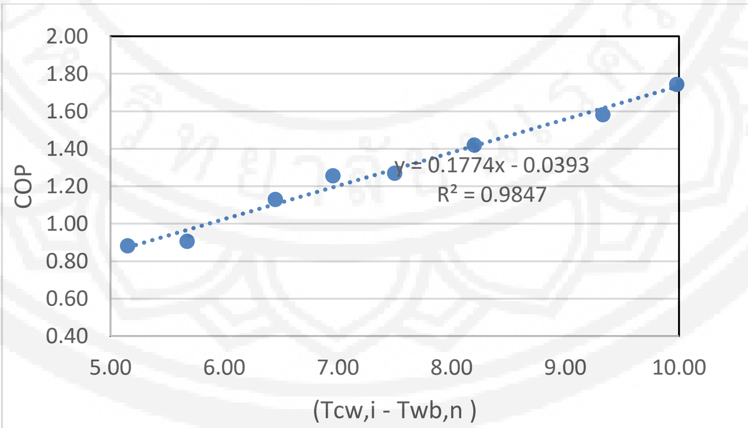

Figure 5 COP of the system

From Figure 5, the COP empirical correlation can be expressed as

$$y = 0.1774x - 0.0393 \quad (5)$$

where, y and x are COP and ($T_{cw,i}$-$T_{wb,n}$) respectively, and the residual graph of the estimated COP is also shown in Figure 6. The obtained formula was then used to estimate the cold water tank temperature at the average temperature in winter. The average air dry bulb temperature during the day and air wet bulb at night were substituted as $T_{cw,i}$ and $T_{wb,n}$ respectively. The temperature data was from the Meteorological Department located in Kasetsart University, Kampaengsaen campus as averaged for 3 years. The calculated cold water tank temperature was 25.50 °C where $T_{cw,i}$ and $T_{wb,n}$ were at 31 °C and 25.72 °C respectively.

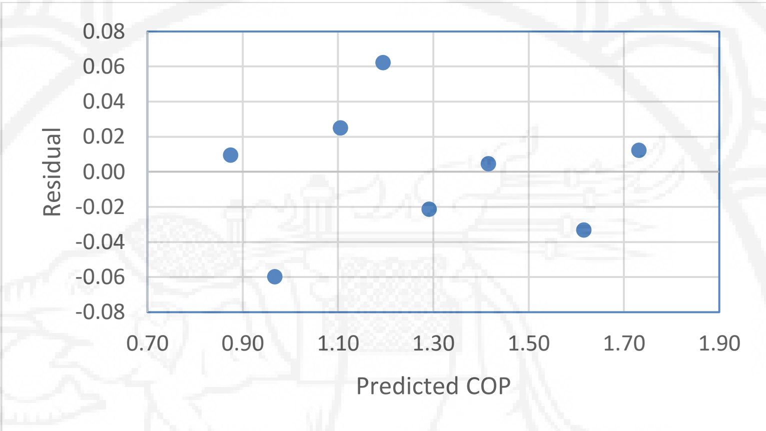

Figure 6 The residual of the estimated COP

-Estimated cooled air temperature from the cooling system

The system design consisted of a night water cooling system, a cooling coil and a direct evaporative cooling pad. Cooled water from night cooling system was used to pre-cool the air in a cooling coil. Then air was cooled and humidified in a direct evaporative cooling pad. The objective of the cooling system was to supply cold air to an experimental mushroom house measuring 2m × 3m × 2.5 m.

The cooling coil unit was a fin type cooling coil and its operating parameters are listed in Table3.

Table 3 Cooling coil parameters

Fin Type	Corrugate/3 -Row coil
Fins per inch	18
Cooling Capacity	12,000 Btu/h
Water pipe size	5/8 inch

The Ɛ-NTU method was used to calculate the cooling coil effectiveness from the manufacturer's data. The effectiveness of the cooling coil (Ɛ) is defined as

$$\varepsilon = \frac{Q_{actual}}{Q_{max}} \tag{6}$$

where, Q_{max} was the maximum possible heat transfer rate

$$Q_{max} = C_{min}(T_{hi} - T_{ci}) \tag{7}$$

C_{min} was the minimum heat capacity rate from a comparison between the hot and cold fluid. The effectiveness of a finned coil with a counter flow arrangement is nearly the same as that of a crossflow arrangement as reported by (Wang, 1993)

$$\varepsilon = \frac{1-\exp[-NTU(1-C)]}{1-C\exp[-NTU(1-C)]} \tag{8}$$

The number of transfer units (NTU) can be calculated as

$$NTU = \frac{UA}{C_{min}} \tag{9}$$

and, C is the heat capacity ratio

$$C = \frac{C_{min}}{C_{max}} \tag{10}$$

The calculated result for ε was 0.81. The outlet air temperature from the cooling coil was then estimated from this ε value. When the air dry bulb temperature was at 31 °C and 1200 CFM was the flow rate, the pre-cooled air temperature from the cooling coil was 26.53 °C. Finally, the air was then cooled and humidified by the direct evaporative cooling pad. The outlet air temperature was estimated from Eq. (5) at 0.85 pad efficiency and the air dry bulb and wet bulb temperature were the average temperature during day time in winter. It was found that the outlet air temperature from the evaporative cooling pad was 22.04 °C which satisfied the criteria temperature in a mushroom house. For validation the result, the model was then used to predict the outlet air temperature from the cooling unit in day time which was successfully set up in November 2018. On 27 November 2018 at 33.47°C average air dry bulb day temperature and 53.37 % relative humidity, the outlet air temperature predicted from the model was 24.0 °C which was deviated from the measured value, 23.48 °C, by 2.2%. This cooling system can fulfill the demand for a small scale mushroom house with the maximum capacity of 35 m^3.

Conclusion

The cooling system for this mushroom house was studied for both experimental and theoretical purposes. The objective of the system was to supply cooled air for shitake mushroom cultivation in winter in the upper central region climate of Thailand. The system design consisted of a night water cooling system, a cooling coil and a direct evaporative cooling system. The night cooling system produced cooled water by circulating water through the cooling pad and transferred heat to the ambient air at night. The cooled water was stored in the tank and used during the day by pre-cooling the air at the cooling coil. Then the precooled air was cooled again and humidified in the direct evaporative cooling pad before flowing to the mushroom house. The system was designed to overcome the problem of evaporative cooling pad applications where the temperature of the outlet air depends on the ambient day time conditions. The night water cooling system was set up and test for its capability to produce cooled water in winter. The COP empirical equation of the system was correlated to the experimental data. The set up correlation was used to predict the cooled water tank temperature in winter. It was found that the system could produce cooled water in the tank at 25.50 °C, when the day air dry bulb and night air wet bulb temperatures were 31 °C and 25.72 °C respectively. It was found that the estimated outlet cooled air temperature was 22.04 °C. Thus, the system satisfied the temperature criteria as the air temperature inside the mushroom house was 28 °C. To validate the result the model was used to predict the outlet cooled air temperature from the recently set up day time cooling system and compared with the measured value. It was found that the error was 2.2 %. In future work the automatic control cooling mushroom house will be set up and tested.

Acknowledgement

This study was supported by Faculty of Engineering at Kampaeng Saen, Kasetsart University and edited by Mr. Thomas Elliott at the Graduate School at Naresuan University, Phitsanulok.

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