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Improving indoor conditions of a Thai-style mushroom house by means of an evaporative cooler and continuous ventilation

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Abstract

The paper discusses the effect of an evaporative cooling process and continuous ventilation for improving the indoor conditions of a conventional Thai-style mushroom house. A numerical model describing the behaviour of the Thai-style mushroom house model was developed. It was validated by comparing its output with that of the experiment of a small model of a mushroom house. It was found that the combination of evaporative cooling and continuous ventilation reduced the temperature and increased the relative humidity of air inside a mushroom house that is suitable for growing Lentinus. © 1999 Elsevier Science Ltd. All rights reserved.

Keywords: Lentinus edodes; Evaporative cooling; Continuous ventilation

1. Introduction

The potential for *Lentinus edodes* growing in Thailand is rather high. The mushroom is already a popular food in the country and is, at present, imported from other countries (about 40 million baht per year, 40 baht = 1 US$). This is also expected to increase every year.

As Thailand is located in a tropical zone, the outdoor temperature is quite high varying, depending on season, between 27 and 40°C and, consequently, not appropriate for growing *L. edodes* as it requires temperatures in the range of 22–26°C with

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Fig. 1. Traditional mushroom house.

relative humidity of 80–90 % [1]. However, *L. edodes* can grow in the north of Thailand for about 4 months during winter (October to February) because the temperature then is suitable [2].

The shape of the conventional mushroom house in Thailand is like a cottage, made with cogon grass, Fig. 1. Inside there is a shelf on which to lay the sawdust bags for fruiting body. The sawdust substrates are soaked three times in 24 h. The resulting temperature and humidity inside a mushroom house are about 28–35°C, 60–70 % RH, which differ from those required. To overcome this, simple techniques are used such as opening doors and spraying water several times a day.

This paper presents a method to reduce the temperature inside a mushroom house by means of continuous ventilation and evaporative cooling.

2. Experimental setup

The experimental mushroom house was a two post type, Fig. 2, 0.7 m high in the middle with four shorter side posts, each 0.4 m high with a 1×1.7 m rectangular base. The roof was an attic type, at 54° from the horizontal. The house was made of a bamboo skeleton covered with cogon lalong (dry grass) of 25.4 mm thickness. The house was oriented by setting its long side along the north–south direction so the sides of the roof were facing east and west. The house was set on ground. Seventy-two sawdust bags were installed inside the mushroom house with water saturated surfaces.

A simple Evaporative Cooler (EC) was made using vertical cloth sheets; each was separated by a distance of 10 mm. The lateral surface was set equal to the surface

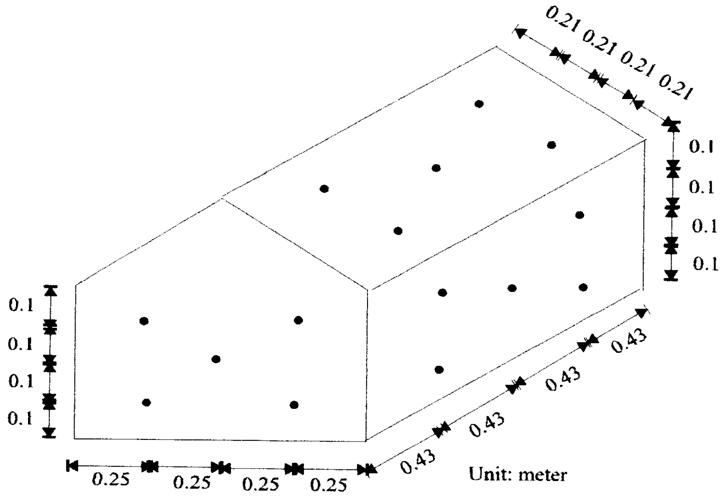

Fig. 2. Schematic representation of the experimental mushroom house without EC. (● Location of temperature measurement on roof and wall.)

area of the northern side of the mushroom house (0.4 m^2). A basin of water was placed on top. This water flows down the cloth sheets by gravitational force. The right and left walls of EC were insulated by polypropylene.

The inner and outer surface temperatures of the cogon grass of the roof and walls were measured at 5 points on each surface as shown in Fig. 2 [3]. The air temperature inside and outside the house was measured by a set of *K*-type thermocouples. The relative humidity of air was measured at two positions: outdoors and in the middle of the mushroom house. The global radiation and diffuse radiation was measured by Kipp and Zonen pyranometers with sensitivity of ± 0.5 % at 20°C and 500 W m^{-2}. The wind speed was measured by 'Anemomaster' anemometer with an accuracy of ± 0.1 m s^{-1}. All the data were recorded for 24 h, at 15 min intervals.

3. Mathematical model

The mass and thermal modeling of the mushroom house was based on the following assumptions:

(a) The walls made of cogon grass were assumed to be flat plates.
(b) The cogon grass was homogeneous with constant thermal properties.
(c) The thermal capacity of cogon grass and wood were negligible.
(d) There was no stratification in the air temperature of the mushroom house.
(e) Internal surface to surface radiation is ignored.
(f) The sawdust is a wetted surface.
(g) Latent heat from respiration of the mushroom is negligible.

The basic mass and energy analysis for each component of the mushroom house could be written as shown below:

3.1. Energy balance of the walls

$$Q_{\mathrm{wall}} = \rho_{\mathrm{w}} C_{\mathrm{w}} V_{\mathrm{w}} \frac{\mathrm{d}T_{\mathrm{w}}}{\mathrm{d}t} = Q_{\mathrm{su}} - Q_{\mathrm{sk}} + A_{\mathrm{w}} h_{\mathrm{wo}} (T_{\mathrm{o}} - T_{\mathrm{w}}) + A_{\mathrm{w}} h_{\mathrm{wi}} (T_{\mathrm{a}} - T_{\mathrm{w}}) \tag{1}$$

where

Q_{wall} = variations of internal energy of wall [kW]
ρ_{w} = density of wall (cogon grass) [kg m^{-3}]
C_{w} = specific heat of wall (cogon grass) [kJ kg^{-1} K^{-1}]
V_{w} = volume of wall [m^3]
T_{w} = mean wall temperature [°C]
t = time [s]
Q_{su} = the solar energy incident on the wall [kW]
Q_{sk} = the energy loss to sky [kW]
A_{w} = the wall surface area [m^2]
h_{wo} = the outer convection heat transfer coefficient [kW m^{-2} K^{-1}]
h_{wi} = the inner convection heat transfer coefficient [kW m^{-2} K^{-1}]
T_{o} = ambient temperature [°C]
T_{a} = inside mushroom house temperature [°C]

3.2. Energy balance of the roof

$$Q_{\mathrm{roof}} = \rho_{\mathrm{r}} C_{\mathrm{r}} V_{\mathrm{r}} \frac{\mathrm{d}T_{\mathrm{r}}}{\mathrm{d}t} = Q_{\mathrm{su}} - Q_{\mathrm{sk}} + A_{\mathrm{r}} h_{\mathrm{ro}} (T_{\mathrm{o}} - T_{\mathrm{r}}) + A_{\mathrm{r}} h_{\mathrm{ri}} (T_{\mathrm{a}} - T_{\mathrm{r}}) \tag{2}$$

where

Q_{roof} = variations of internal energy of roof [kW]
ρ_{r} = density of roof ($\rho_{\mathrm{r}} = \rho_{\mathrm{w}}$)[kg m^{-3}]
C_{r} = specific heat capacity of roof ($C_{\mathrm{r}} = C_{\mathrm{w}}$) [kJ kg^{-1} K^{-1}]
V_{r} = volume of roof [m^3]
T_{r} = mean roof temperature [°C]
A_{r} = the roof surface area [m^2]
h_{ro} = the outer convection heat transfer coefficient [kW m^{-2} K^{-1}]
h_{ri} = the inner convection heat transfer coefficient [kW m^{-2} K^{-1}]

3.3. Energy balance of sawdust substrate

$$Q_{\mathrm{s}} = \rho_{\mathrm{s}} C_{\mathrm{s}} V_{\mathrm{s}} \frac{\mathrm{d}T_{\mathrm{s}}}{\mathrm{d}t} = A_{\mathrm{s}} h_{\mathrm{s}} (T_{\mathrm{a}} - T_{\mathrm{s}}) - m_{\mathrm{ws}} h_{\mathrm{fg}} \tag{3}$$

where

Q_{s} = variations of internal energy of sawdust substrate [kW]

ρ_s = density of sawdust substrate [kg m^{-3}]
C_s = specific heat capacity of sawdust substrate [kJ kg^{-1} K^{-1}]
T_s = mean sawdust temperature [°C]
A_s = the surface area of sawdust [m^2]
h_s = the convective heat transfer coefficient [kW m^{-2} K^{-1}]
m_{ws} = the mass flux of water from the sawdust's surface [kg m^{-2} s^{-1}]
h_{fg} = the latent heat of evaporation of water [kJ kg^{-1}]

3.4. Heat transfer due to infiltration and ventilation

$$Q_{vent} = \frac{ACH(V)}{3600V_o}[C_{pa}(T_a - T_o) + (W_a - W_o)h_{fg}] \tag{4}$$

where

Q_{vent} = heat transfer by infiltration [kW]
ACH = air change rate [h^{-1}]
V = gross volume of space [m^3]
V_o = specific volume of air [m^3 kg^{-1}]
C_{pa} = specific heat capacity of moist air [kJ kg^{-1} K^{-1}]
W_a = humidity ratio inside mushroom house [kg kg^{-1}]
W_o = humidity ratio outside mushroom house [kg kg^{-1}]

The ACH in the experimental mushroom house depended on the temperature difference $\Delta T = T_a - T_o$ and the wind speed V_{ws} (m s^{-1}). It could be estimated by the following correlationship [3]: $ACH = 0.464 + 0.069\Delta T + 0.963V_{ws}$.

3.5. Heat transfer from the ground surface

$$Q_g = U_{bg}A(T_a - T_g) \tag{5}$$

where

u_{bg} = the overall heat transfer coefficient for the ground [0.51 kW m^{-2} K^{-1}]
T_g = the ground temperature at 1 m deep [°C]
(Preliminary measurements allowed us to determine this depth at which the ground temperature is constant year round in Bangkok.)
A = floor area [m^2]

3.6. Energy balance for the conventional mushroom house

$$\rho_a C_{pa} V_a \frac{dT_a}{dt} = \Sigma Q_{wall} + \Sigma Q_{roof} + Q_{vent} + Q_g + Q_s \tag{6}$$

where

C_{pa} = the specific heat capacity of moist air inside house [kJ kg^{-1} °C^{-1}]
ρ_a = the density of moisture air [kg m^{-3}]
V_a = the volume of enclosure [m^3]

3.7. Water mass balance of the conventional mushroom house

$$\frac{dm}{dt} = m_{w,in} + m_{w,g} - m_{w,out} \tag{7}$$

where

m = mass of water in the air of mushroom house [kg]
$m_{w,in}$ = rate of water entering mushroom house [kg s^{-1}]
$m_{w,g}$ = rate of water generated in mushroom house ($m_{w,g} = m_{ws}$) [kg s^{-1}]
$m_{w,out}$ = rate of water leaving mushroom house [kg s^{-1}]

3.8. Energy balance at wetted surface of a sawdust

$$(h_{ao} + W_{op}h_{go}) = (W_{op} - W_i)h_f + (h_{ai} + W_ih_{gi}) + Q_{cv} \tag{8}$$

where

h_{ao} = specific enthalpy of dry air after the wet surface [kJ kg^{-1}]
h_{ai} = specific enthalpy of dry air before the wet surface [kJ kg^{-1}]
h_{go} = specific enthalpy of water vapour after the wet surface [kJ kg^{-1}]
h_{gi} = specific enthalpy of water vapour before the wet surface [kJ kg^{-1}]
h_f = specific enthalpy of water at the wet surface [kJ kg^{-1}]
W_{op} = the specific humidity of air [kg kg^{-1}]
W_i = the specific humidity of moist air before the wet surface [kg kg^{-1}]
Q_{cv} = the heat absorbed by the air in the mushroom house
$= \Sigma Q_{wall} + \Sigma Q_{roof} + Q_g + Q_{vent}$.

A similar equation could be written for the Evaporative Cooler (EC) by assuming adiabatic saturation (no heat is added $Q_{cv} = 0$). This means that the addition of water vapour increases the latent heat of the air–vapour mixture. As the overall process is adiabatic, this increase is offset by a sensible heat reduction and a consequent lowering of the dry-bulb temperature of the air. During the cooling process the wet bulb temperature of the air remains constant. Thus, the performance of EC is rather defined by the saturation efficiency as follows.

$$\varepsilon_{evap} = \frac{T_{d,i} - T_{d,o}}{T_{d,i} - T_{w,i}} \tag{9}$$

where

$T_{d,i}$ = dry bulb temperature of moist air entering the evaporative cooler [°C]
$T_{d,o}$ = dry bulb temperature of moist air leaving the evaporative cooler [°C]
$T_{w,i}$ = wet bulb temperature of moist air entering the evaporative cooler [°C]

From this equation it can be seen that a saturation efficiency of 1 indicates maximum possible cooling of the air flow.

The estimation of the coefficients of heat exchange, which depend on the type of mushroom house, is based on usual correlationships available in the literature [4–7]. They are listed here below:

- Natural convection

$$h_{wo} = h_{ro} = 2.8 + 3V_{ws},$$

$$h_{wi} = \frac{Nu.\lambda}{L}; \quad Nu = \left\{0.825 + \frac{0.387 R_a L^{1/6}}{[1+(0.492/Pr)^{9/16}]^{8/27}}\right\}^2,$$

$$\text{for} \quad 10^{-1} < Ra_L < 10^{12}$$

$$h_{ri} = \frac{Nu.\lambda}{L}; \quad Nu = \left\{0.825 + \frac{0.387 R_a L^{1/6}}{[1+(0.492/Pr)^{9/16}]^{8/27}}\right\}^2,$$

$$\text{for} \quad 10^{-1} < Ra_L < 10^{12} \quad (g\cos\beta)$$

where the gravitational constant in the Grashof number is $g\cos\beta$, (β is the tilt angle of the roof).

$$h_s = \frac{Nu.\lambda}{L}; \quad Nu = 0.27 {R_a}^{1/4}, \quad \text{for } 10^5 < Ra_L < 10^{11}$$

$$m_{ws} = \frac{h_s}{C_{pm}}(W_i - W_a),$$

where C_{pm} is the humid specific heat of the air defined by $C_{pm} = (1+W_i)C_p$.

- Forced convection

laminar $Nu = 0.664\mathrm{Re}^{1/2}\mathrm{Pr}^{1/3}$; turbulent $Nu = 0.037\mathrm{Re}^{4/5}\mathrm{Pr}^{1/3}$

4. Results and discussion

4.1. Validation of model: the traditional mushroom house

The experiments were carried out between March and May 1996. An example of the intensity of incident solar energy on the roof and walls of the mushroom house is given in Fig. 3.

As mentioned in the introduction, Fig. 4 shows that, the indoor conditions are not suitable for growing *L. edodes*. The temperature is higher than needed, whereas the relative humidity is lower than that required.

Figure 5 indicates that the calculated mushroom temperature agrees well with that of the measurements. Therefore, the model developed is valid and can be used to simulate the behaviour of a mushroom house under different operating conditions.

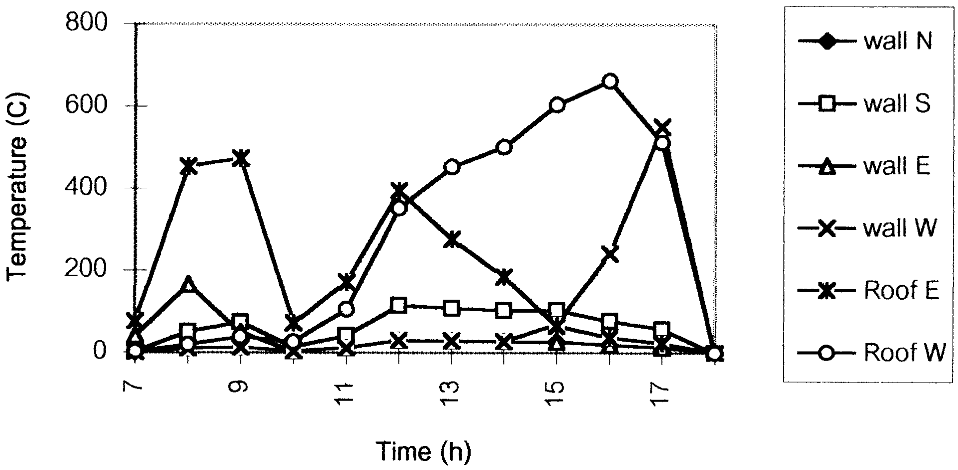

Fig. 3. Solar radiation on the walls and the roof. (Calculated from measurements on a horizontal plane; 25 March 1996.)

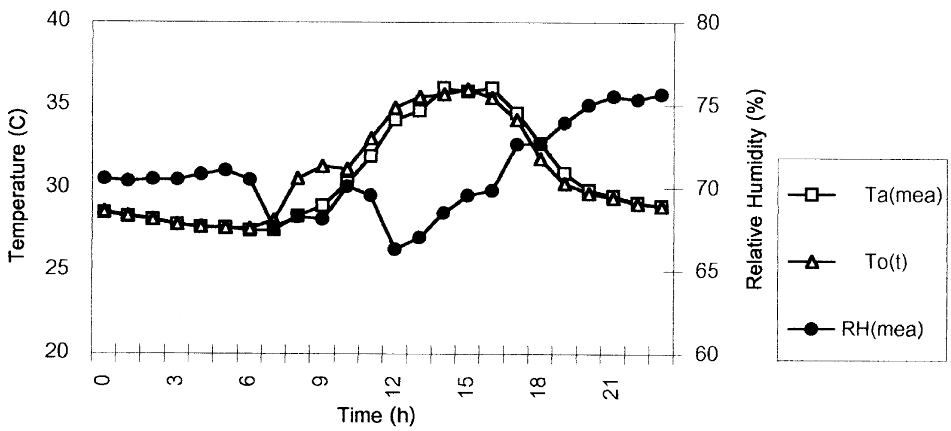

Fig. 4. Hourly variations of indoor conditions of the mushroom house and ambient temperature (measured on 25 March 1996.)

4.2. The proposed configuration

To improve the indoor conditions of the mushroom house, the configuration presented in Fig. 6 [8–9] is proposed here. A simple evaporative cooler (EC) is installed at the northern side of mushroom house and a fan circulates the air through the EC and controls the air change rate. To investigate the saturation efficiency defined by eqn (9), preliminary tests of the simple Evaporative cooler were made. Figure 7 indicates that the highest efficiency is obtained with 50 cm pad. Also even though

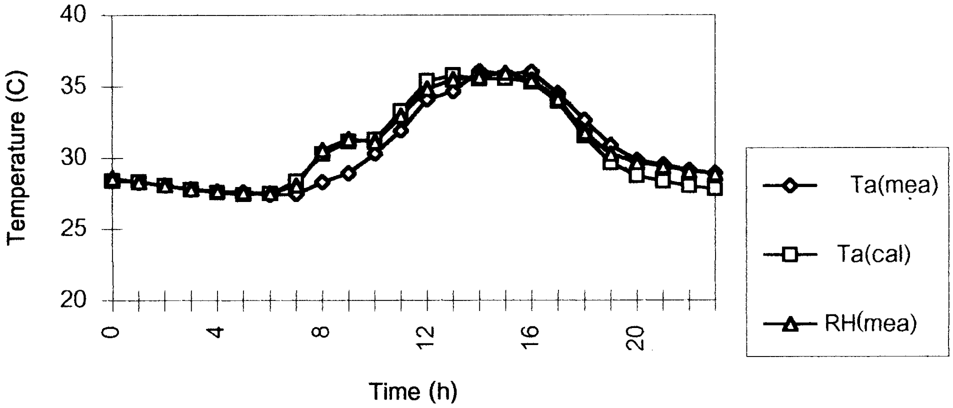

Fig. 5. Simulated and measured temperature of the mushroom house.

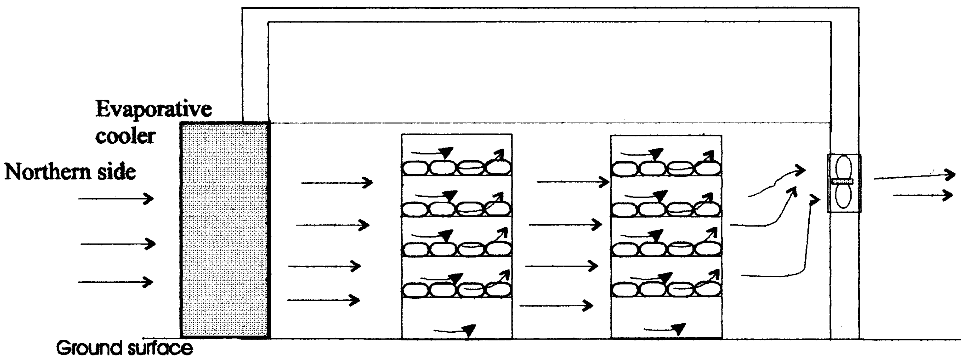

Fig. 6. Schematic representation of the proposed configuration of a mushroom house.

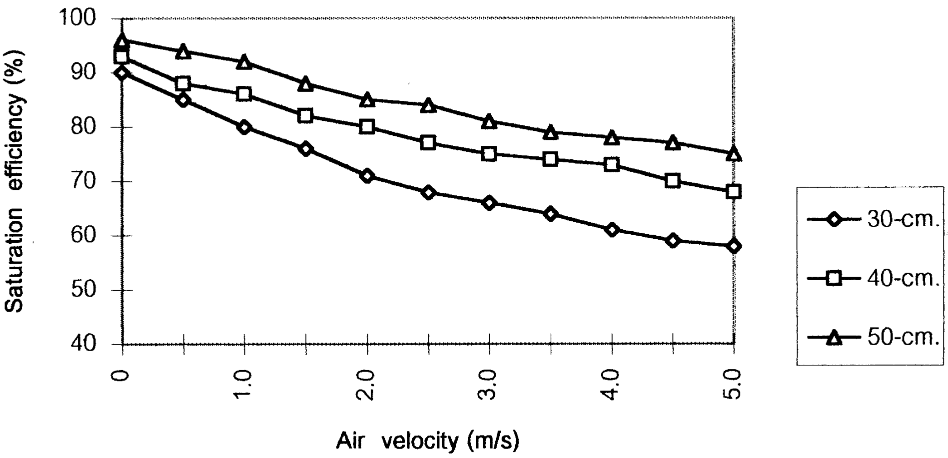

Fig. 7. Evaporative cooler effectiveness for various pad thickness and air flow.

higher pad thickness would obviously increase the saturation efficiency, practical constraints such as availability of surface area, power consumption, etc. limit it.

Figures 8 and 9 show the expected performance of the proposed mushroom house. It can be seen that increasing the number of ACH decreased the indoor temperature and increased the relative hymidity. It is obvious that this effect is more important during daytime. Also, number of ACH higher than 10 does not give any significant improvement.

Consequently, in order to reduce the electricity consumption of the fan, an alternative scenario could be proposed by varying the ACH between daytime and night-

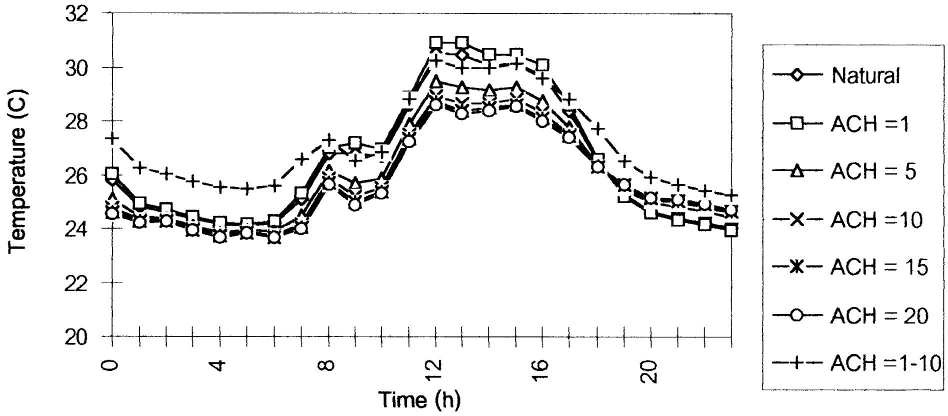

Fig. 8. Hourly variation of indoor temperature of the proposed mushroom house for different values of *ACH* compared with the traditional house.

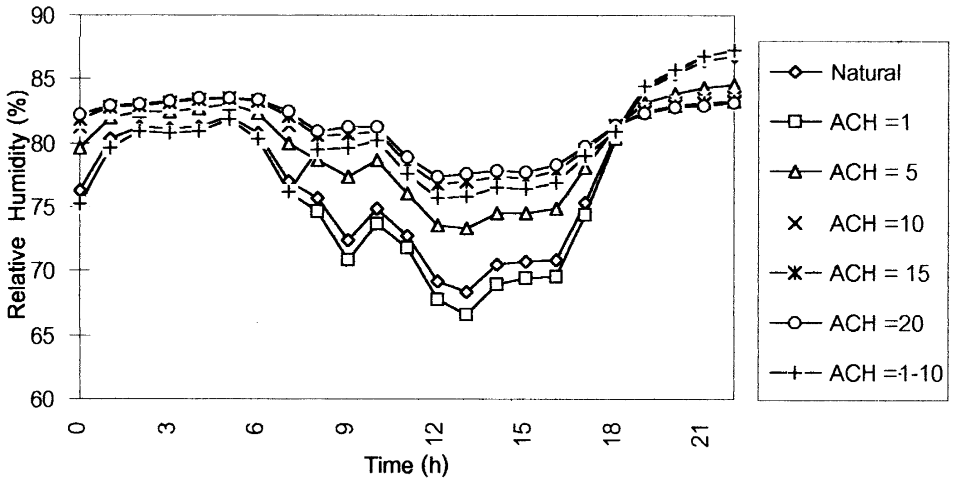

Fig. 9. Hourly variation of indoor relative humidity of the proposed mushroom house for different values of *ACH* compared with the traditional house.

time. An example of performance is also shown in Figs. 6 and 7 where two air changes were considered: ACH = 1 between 6 p.m. to 8 a.m. and ACH = 10 between 8 a.m. to 6 p.m.

5. Conclusion

The feasibility of improving the indoor condition of a traditional Thai-style mushroom house by combining evaporative cooling process with continuous ventilation is investigated experimentally and numerically. A small scale mode of mushroom house was built. The study was conducted during the hottest season in Bangkok.

It was found that the proposed combination can reduce the temperature and increase the relative humidity as required for growing *L. edodes*.

An alternative scenario was also proposed by varying the number of ACH between daytime and nighttime that could reduce operating cost.

An economical study and a full-scale testing have to be made in order to assess the viability of such mushroom house.

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References

[1] Han YH, Veng WT, Chin LC, Cheng S. Psysiology and Ecology of Lentinus Edodes (Berk.) Sing, Mushroom Science XI, Proceedings of the Eleventh International Scientific Congress on the Cultivation of Edible Fungi, Australia, pp. 621–658, 1981.
[2] Nutalaya S, Pataragetvit. Shiitake Mushroom Cultivation in Thailand, Mushroom Science XI, Proceedings of the Eleventh International Scientific Congress on the Cultivation of Edible Fungi, Australia, pp. 723–736, 1981.
[3] Thepa S, Hirunlabh J, Kirtikara K., Khedari J, Kiatsiriroat T. A Study of Infiltration–Exfiltration from Mushroom House and Reducing the Temperature Inside, The 35th Kasetsart University Annual Conference, 3–5 February 1997.
[4] Thepa S. Feasibility of Evaporative Cooling Applications for a Lentinus Edodes (Berk.) Sing House, Doctorate Thesis, King Mongkut's Institute of Technology, Thonburi, Bangkok, 1997.
[5] McQuiston Faye C, Parker D. Heating, Ventilating and Air Conditioning Analysis and Design, 4th ed, John Wiley & Sons Inc., 1992.
[6] Holman JP. Heat Transfer, 7th ed., McGraw-Hill International Edition, 1992.
[7[Duffie John A, William A. Beckman, Solar Engineering of Thermal Processes, John Wiley & Sons, 1980.
[8] Zaki GM, AL-turki A, Al-Lhayyib AS. A study of reducing heat loads on tents due to solar insolation. Energy and Building 1991;17:13–19.
[9] Chandra S, Chandra S. Temperature control in a building with evaporative cooling and variable ventilation. Solar Energy 1983;30(4):381–387.