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Development of a Ventilation Model for Mushroom House Using Adiabatic Panel

Kim, Kee Sung* · Han, Jin Hee* · Kim, Moon Ki · Nam, Sang Woon*****

Abstract

In this study, a ventilation model was developed to determine a ventilation rate for the balance of heat, moisture and CO_2 in a mushroom house. Internal and external temperature, relative humidity and CO_2 concentration were measured and used to validate the ventilation model. The effects of various environmental factors on physiological responses of mushroom were also investigated. The verified model was simulated under the observed ventilation rates with a difference of 0.001~0.065 $m^3 \cdot s^{-1}$ (relative error of 0.3~18.9%) when external temperature varied 22.5 to 24.8 ℃ and average ventilation rates was 0.35 $m^3 \cdot s^{-1}$. The optimal conditions for mushroom growth (internal temperature 22 ℃, relative humidity 80%, CO_2 concentration 1,000 ppm) were used for the model application with external temperature, relative humidity and CO_2 concentration of 27.5~33.5 ℃, 60 %, and 355 ppm, respectively. Thermal balance was a important factor for an optimum ventilation up to the external temperature of 32 ℃, while CO_2 concentration balance was more important over 32 ℃. This suggests that humidification for moisture balance is required to maintain temperature and CO_2 concentration at an optimal level by ventilation in a mushroom house.

Keywords : Mushroom house, Heat and mass balance, Ventilation model

I. Introduction

A cropping period of mushroom is relatively shorter than other crops. Mushroom is a kind of fungi that is delicate and cannot be stored for a long period. Therefore, all processes need to be done in a timely manner. Precise control of environmental factors such as temperature, humidity, and CO_2 concentration is important for the mushroom production. One of the most common methods for controlling temperature, humidity, and CO_2 concentration is ventilation (Baptista et al., 1999). An optimal design of ventilation systems can realize automatic control of environmental factors of temperature, humidity and contaminant because air flow in mush–

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* Dept. of Agricultural and Biosystems Engineering, University of Arizona
** Department of Agricultural Engineering, Seoul National University
*** Department of Bioresource Engineering, Chungnam National University
*** Corresponding author. Tel.: +82-42-821-5794
Fax: +82-42-825-5791
E-mail address: swnam@cnu.ac.kr

room house determines internal distribution of these environmental factors through ventilation (Hellickson and Walker, 1983). Mushroom houses has the type of either simple or permanent mushroom house depending on the structure and material in Korea. A simple mushroom house commonly depends on natural ventilation by farmers' experience. While a forced ventilation system is adopted in a permanent mushroom house. Although many of the forced ventilation systems have been developed, an optimum ventilation rate needs to be precisely estimated for the automatic control of the environment. Physiological responses of mushroom to the environment and the physical properties of the mushroom house such as size, location, and structure have not been incorporated into the calculation of ventilation rates. Therefore, a method that considers these factors into the calculation of ventilation rate also needs to be developed and analyses of air flow within the mushroom house should be followed to design an optimal ventilation system.

Choi (1991) developed a ventilation graph based on the assumption that an effective ventilation system can control internal temperature, humidity and contaminates. However, the use of this ventilation graph has been limited to the application to the animal house. Nam (2000) suggested a ventilation model which a shading and natural ventilation as well as evaporative cooling systems were incorporated in the greenhouse. Although an identical thermal balance equation is applied to control the environments in the animal and plant house, the modeling procedures should be different due to the difference of characteristics between animal and plant growth. Campen and Bot (2003) reported that the calculation of ventilation rate includes large uncertainty depending on plant species, the structure of house, and environmental factors. Therefore, the model should be also manipulated differently depending on the application objects.

Thepa et al. (1999) developed a ventilation model for the mushroom production using an energy balance equation. This study indicated that an evaporative cooling system with continuous ventilation can maintain temperature and humidity at proper levels for mushroom growth. Choi et al. (2000) has analyzed ventilation characteristics in a shiitake mushroom house and Son (2000) estimated ventilation rates through ventilator in a natural-ventilated shiitake mushroom house using energy balance equation and numerical methods.

However, ventilation in most mushroom production facilities have been commonly practiced on the basis of farmers' experiences. Therefore, precise calculation of ventilation rate by analyses of air distribution within mushroom houses is necessary for the mushroom production. This study was conducted to develop a ventilation model including the physiological responses of mushroom to the environmental differences by structural characteristics of the mushroom house. The developed model was validated using experimental data and applied to estimate an optimum ventilation rate for the mushroom production. Basic information to design a ventilation system was also provided.

Ⅱ. Materials and Methods

1. Developing ventilation model in mushroom house

1) Ventilation model for thermal balance

Thermal energy balance is defined by interactive relationship among input, generated, loss of heat and consumed thermal energy in single control volume. Following equation is based on steady state

$$Q_s + Q_m + Q_{so} + Q_h + Q_{vi} = Q_w + Q_f + Q_e + Q_{vo} \quad \cdots\cdots (1)$$

where Q_s is the heat generated from mushroom [W], Q_m is the input heat by machinery device [W], Q_{so} is the input heat from sun [W], Q_h is the input heat from a heater [W], Q_{vi} is the input heat from input air flow [W], Q_w is the heat loss through wall and roof [W], Q_f is the heat loss through perimeter of floor [W], Q_e is the heat loss by conversion from sensible heat to latent heat [W] and Q_{vo} is the heat loss by discharged air.

As a result of concerning characteristics of the mushroom house, Q_{so} was ignored because of no direct radiation transmitting due to no windows in mushroom house and small rate of radiation absorption. Q_m was ignored because machinery devices for the ventilation were installed in external. In case of Q_e, evaporation from the floor was negligible because the floor was made of concrete material assuming that latent heat generated by mushroom is combined into Q_s. However, Q_e could be considered when evaporation is generated due to artificial water adding. Heat loss was negligible due to insulating concrete floor and heat loss of perimeter of floor was considered.

$$Q_s + Q_h + Q_{vi} = Q_w + Q_f + Q_{vo} \quad \cdots\cdots (2)$$

$$Q_w = UA(t_i - t_o) \quad \cdots\cdots (3)$$

$$Q_{vo} - Q_{vi} = \rho C_p V_{temp}(t_i - t_o) \quad \cdots\cdots (4)$$

$$Q_f = FP(t_i - t_o) \quad \cdots\cdots (5)$$

Substituting equation (3), (4), (5) to equation (2), the following equation is gained.

$$V_{temp} = \frac{Q_s + Q_h - (UA + FP)(t_i - t_o)}{\rho C_p(t_i - t_o)} \quad \cdots\cdots (6)$$

where V_{temp} is the ventilation rate for thermal balance [$m^3 \cdot s^{-1}$], F is the coefficient of perimeter heat loss [$W \cdot m^{-1} \cdot K^{-1}$], U is the convective heat transfer coefficient [$W \cdot m^{-2} \cdot K^{-1}$], A is the area of the wall and roof [m^2], P is perimeter of mushroom house [m], ρ is the air density [$kg \cdot m^{-3}$] and C_p is the heat capacity [$J \cdot kg^{-1} \cdot K^{-1}$].

2) Ventilation model for moisture balance

Air flow in the mushroom house contains moisture. This moisture has mass and mass conservation law can be applied using following equation (Albright, 1990).

$$M_s + M_{vi} = M_{vo} \quad \cdots\cdots (7)$$

where M_s is the moisture generated in mushroom house [$kg \cdot s^{-1}$], M_{vi} is the moisture content of input airflow [$kg \cdot s^{-1}$] and M_{vo} is the moisture content of discharged air [$kg \cdot s^{-1}$].

$$M_{vo} - M_{vi} = \rho V_{moist}(W_i - W_o) \quad \cdots\cdots (8)$$

substituting equation (8) to equation (7), the following equation for controlling moisture is gained.

$$V_{moist} = \frac{M_s}{\rho(W_i - W_o)} \cdots\cdots (9)$$

where V_{moist} is the ventilation rate for moisture balance $[m^3 \cdot s^{-1}]$, W_i is the internal humidity ratio $[kg \cdot kg^{-1}-da]$ and W_o is the external humidity ratio $[kg \cdot kg^{-1}-da]$

Most moisture in the animal house is generated by respiration of animal and evaporation from floor and in case of the greenhouses it is generated by evapotranspiration of crops. In this study moistures generated by transpiration of mushroom and evaporation of water supplied to mushroom house artificially are applied.

3) Ventilation model for CO_2 balance

In addition to temperature and humidity, contaminants, and chemical factors were also taken into account to determine ventilation rate (Hellickson and Wallker, 1983). Chemical factors have various components such as dust, ammonias, hydrogen sulfide and carbon dioxide. Carbon dioxide gas is easy to quantify, so it was used for this model as a representative of the chemical factor (Choi et al., 1991). In the case of the mushroom house, CO_2 gas generated from media on which mushroom were grown can't be ignored (Loeffen, 1995). Mass conservation law was applied equally to a model.

$$G_s + G_{vi} = G_{vo} \cdots\cdots (10)$$

where G_s is the CO_2 gas generated in mushroom house $[m^3 \cdot s^{-1}]$, G_{vi} is the CO_2 gas of input airflow $[m^3 \cdot s^{-1}]$, and G_{vo} is the CO_2 gas of discharged airflow $[m^3 \cdot s^{-1}]$.

$$G_{vo} - G_{vi} = V_{CO_2}((CO_2)_i - (CO_2)_o) \cdots\cdots (11)$$

where the $(CO_2)_i$ and $(CO_2)_o$ are for internal and external CO_2 concentration $[m^3 \cdot m^{-3}]$, respectively.

Substituting equation (11) to equation (10), the following equation is gained.

$$V_{CO_2} = \frac{G_s}{(CO_2)_i - (CO_2)_o} \cdots\cdots (12)$$

where V_{CO2} is the ventilation rate for CO_2 concentration balance $[m^3 \cdot s^{-1}]$.

4) Computational programing for calculating ventilation rate

Variables of properties of mushroom house, heat loss by refrigerator, internal moisture and CO_2 gas generation, aimed value of internal temperature, relative humidity and CO_2 concentration and internal air density according to the changes of environmental conditions can be input data for the model application. The program (Visual C++ 6.0) which can calculate a ventilation rate for controlling temperature, humidity and CO_2 concentration was developed through input data file of external values of temperature, relative humidity and CO_2 concentration. User can input properties of mushroom house, cooling load, aimed internal value of temperature, relative humidity and CO_2 concentration freely. Fig. 1 shows flow chart of program.

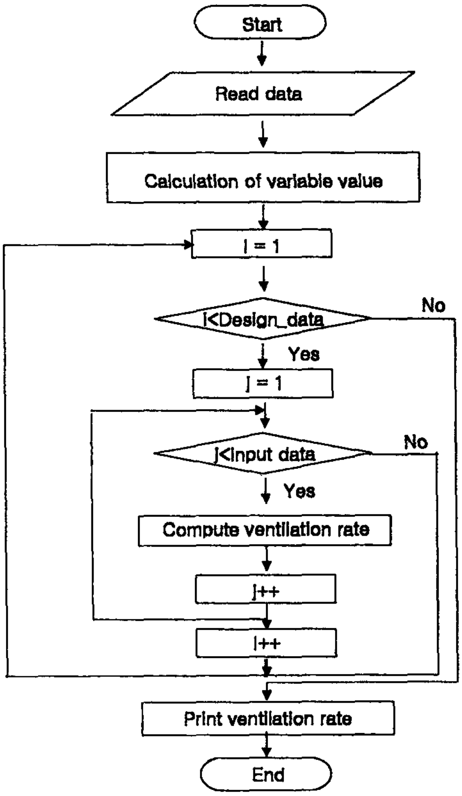


Fig. 1 Flow chart of calculating ventilation rate

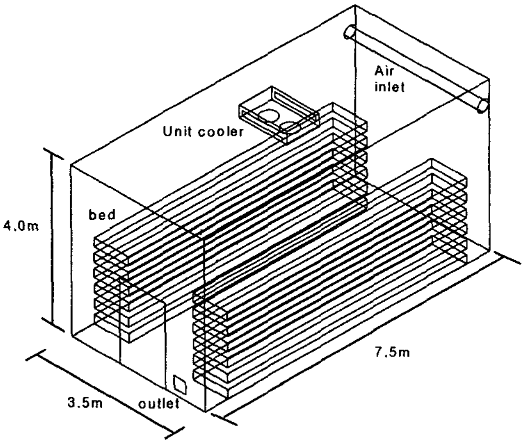


Fig. 2 3D view of experimental mushroom house

2. Field experiment for validation

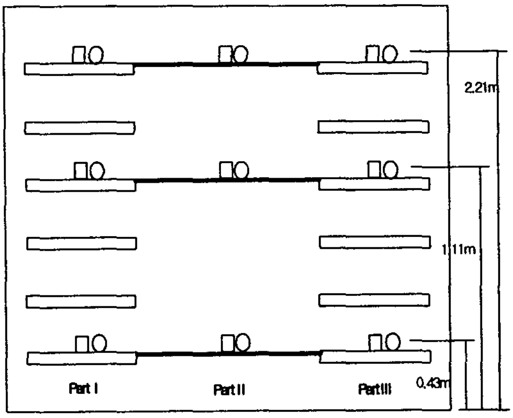
Field experiment for validating the ventilation model was performed from June, 2003 to September, 2003 in the mushroom house located at Hwaseong, Gyeonggi-do. Main factors affecting on growth of mushroom are temperature, humidity, CO_2 gas. In this study, the inducing generation state, the first mushroom growth stage and the harvest stage which are considered most important period for ventilation were applied to this experiment. The oyster mushroom was used for the experiment and cropping method was bottle cropping in multiple stacks. Fig. 2 shows the schematics of the mushroom house which is made of adiabatic panel (3.5 m wide, 7.5 m long and 4.0 m high). Air was supplied through Siroco fan (0.5 hp) for internal ventilation. Water was supplied at floor in mushroom house for manipulating moisture.

Measurement devices were installed at 0.43, 1.11 and 2.21 m away from floor in each left, right bed and middle pathway for measuring temperature, relative humidity and air current speed as shown in Fig. 3(a). CO_2 measured from the sensor (GMW-22) installed at 1.65 m away from floor in entrance, middle pathway and rear as shown in Fig. 3(b). Air current speed of an outlet in front of entrance was measured by anemometer (series 640) to calculate ventilation rate. Table 1 shows various sensors used for the measurements.

Internal temperature and relative humidity were maintained at 15~17℃ and 80~100% respectively. CO_2 concentration was controlled at 1,500 ppm during the inducing generation stage and was 600~700 ppm during first mushroom growth stage as well as harvest stage. Air current speed and CO_2 concentration were stored

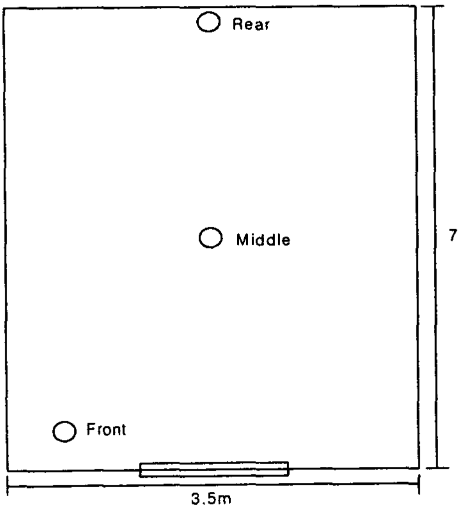
Table 1 Specification of measurement sensors

Parameter	Model	Range	Sensitivity
Temperature & relative humidity	H08-032-08	0~95%	±5%
CO_2	GMW-22	0~2000 ppm	±100 ppm
Air current speed	Series640	0~5m · sec^{-1}	±2%



□ : Anemometer (Series 640)
○ : Temperature and humidity sensor (H08-032-08)

(a) Sensors for measuring temperature and relative humidity



(b) Sensors for measuring CO_2

Fig. 3 Layout of measuring sensors

every 5 seconds to the data logger (DC 100, Yokogawa). While temperature and relative humidity were measured every 10 minutes using temperature and relative humidity sensor (H08-032-08, Onset Computer Corp).

Ⅲ. Result and Discussion

1. Correcting parameters of ventilation model

Vital heats of mushroom with temperature change (Trevor, 2002) and CO_2 generations of mushroom by respiration(Loffen, 1994) were used for this study.

When cultivation temperature was maintained at 30℃, the media in the bottle was increased until 33~34℃. For this reason, growth of spawns is depressed and generation rate of pathogen is increased (Cha et al., 1989). Therefore, vital heat of mushroom is very important in calculating ventilation rate for the temperature control. In addition, accurate calculation of vital heat is required to determine ventilation rate because vital heat changes with surrounding temperature. Concerning these aspects, a functional relationship between internal temperature and vital heat of mushroom was applied for this ventilation model.

Vital heats are 1708~2684, 4270, 6100, 16104 ~19276 kcal/ton · day when internal temperature is 0, 5, 10, 20℃, respectively (Trevor, 2002). In case of 0℃ and 20℃, a mean value was used. Fig. 4 shows resulting curve fitting relationship of these data and then R^2 value was 0.9953. There are data of vital heat of animal according to species of animal and surrounding temperature in animal house applying ventilation

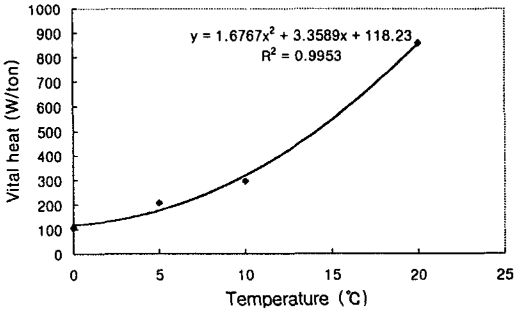


Fig. 4 Relationship between vital heat of mushroom and temperature

model (Esmay and Dixon, 1986). However, such data are insufficient in case of mushroom and mathematical function which can calculate vital heat concerning relationship between vital heat and surrounding temperature is not also enough. Therefore, a functional relationship between internal temperature and vital heat of mushroom was derived and applied for calculation of ventilation rate.

$$Y = 1.6767t_i^2 + 3.3589t_i + 118.23 \cdots\cdots\cdots\cdots\cdots\cdots (13)$$

where Y is the vital heat(W/ton), and t_i is the internal temperature (℃).

Heat loss by refrigerator(unit cooler, M-type Diameter 40 cm, flow rate 81 CMM) should be also applied to correcting model for thermal balance. Refrigerator was consist of two fans of which each cooling capacity was 4896.9, 6711, 10538 W when differences between external and internal temperature were 5 ℃, 7 ℃ and 10 ℃, respectively.

Differences between external and internal humidity ratio determined by using psychrometric property base on data such as internal temperature and internal relative humidity, external temperature and external relative humidity were used to determine moisture contents generated in mushroom house (Albright, 1990).

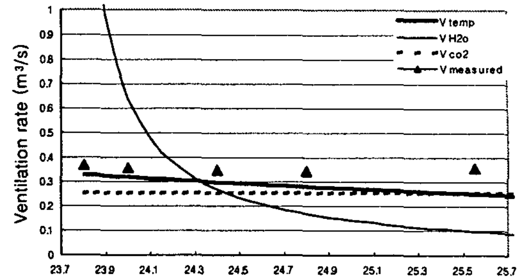
It is important that internal humidity is maintained properly for growth of mushroom. In case of oyster mushroom, relative humidity ought to be maintained at 80~90% from the period of mushroom development to the formation of cap, and at 80~85% in harvesting periods. To prevent cap of mushroom from being dried, prudent operation of ventilation is required(Cha et al., 1989). Therefore, it is important keeping relative humidity high continuously in mushroom house through sufficient water supply. To keep internal relative humidity proper, both evaporation from floor and moisture content generated by physiological respondence of mushroom were used to calculate total generated moisture contents. As the result of calculation by equation(8) using measured ventilation rate, internal and external humidity ratio, mean value of generated moisture contents in mushroom house was 0.13307 $g \cdot s^{-1}$ when internal temperature was 15~17℃ and relative humidity was 84~88%. At this time, total weights of mushroom were 2.688 ton and generated moisture contents per weight can be 178.2 g/ton · h.

CO_2 concentration as other important factor is changed according to cropping period, media temperature and surrounding environmental factors (Loeffen, 1994: 1995). Loeffen (1994) reported that CO_2 concentrations were 51.5~86 g/ton · h when spawns are growing, and maximum 238 g/ton · h after the casing. Also they were 57.2~105.9 g/ton · h and maximum 222 g/ton · h at the first generating. In this study, maximum value of 222 g/ton · h (82.878×10^{-6} m^3/s) was used to develop ventilation model.

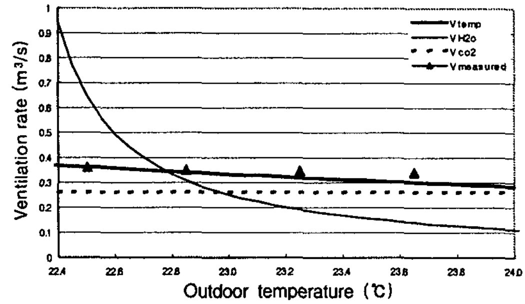
2. Validating of ventilation model

Validating of model was performed concerning that internal temperature of 16.8 ℃ and 15.6 ℃, internal relative humidity of 88.0% and 84.0%, and CO_2 concentration of 674 ppm were used as design values of mushroom house. External temperature, relative humidity and CO_2 concentration obtained by field experiment were used as input data of the corrected ventilation model. In addition, ventilation rates calculated by using experimental data of air current speed in an outlet of mushroom house were used as validation data as shown in Table 2.

Fig. 5(a) and (b) show results of simulated value by applying corrected model and observed data in Case I and Case II. Although ventilation rate should be determined according to curve for moisture balance before an intersection of ventilation rate curve for moisture balance and curve for thermal balance, curve for thermal balance can be applied to calculate ventilation rate because relative humidity ought to be high in mushroom house. After an intersection, curve



(a) Case I



(b) Case II

(a) : internal design value of temperature 16.8℃, humidity 88.0%, CO_2 674ppm

(b) : internal design value of temperature 15.6℃, humidity 84.0%, CO_2 674ppm

Fig. 5 Predicted and measured ventilation rates

Table 2 Data for validating ventilation rate model

Case	Internal design temperature (℃) /RH (%)/CO_2 (ppm)	External temperature (℃)	External RH (%)/ CO_2 (ppm)	Observed ventilation rate ($m^3 \cdot s^{-1}$)	Simulated ventilation rate ($m^3 \cdot s^{-1}$)	Error ($m^3 \cdot s^{-1}$ (%))
I	16.8/88.0/674	23.6 24.0 24.4 24.8	57.3/ 347	0.367 0.358 0.348 0.344	0.329 0.318 0.297 0.279	0.038(10.4) 0.040(11.2) 0.051(14.7) 0.065(18.9)
II	15.6/84.0/674	22.5 22.9 23.2 23.6	55.9/ 355	0.361 0.350 0.348 0.338	0.362 0.341 0.319 0.299	0.001(0.3) 0.009(2.6) 0.029(8.3) 0.039(11.5)

for thermal balance is optimum ventilation rate curve. Therefore, curve for thermal balance was used applying observed data from field experiment for validating model. However, curve for CO_2 balance was used for optimum ventilation curve after an intersection, 25.3 ℃ of curve for CO_2 balance and curve for thermal balance and in Case Ⅰ. As the result of using optimum ventilation curve, in case of Case Ⅰ, maximum simulated ventilation rate was about 0.3 $m^3 \cdot s^{-1}$ and differences between observed and simulated data were 0.038 $m^3 \cdot s^{-1}$ (10.8%)~0.065 $m^3 \cdot s^{-1}$ (18.9%). In case of Case Ⅱ, differences were 0.001 $m^3 \cdot s^{-1}$ (0.3%)~0.039 $m^3 \cdot s^{-1}$ (11.5%).

3. Application of the model

In case of summer oyster, concerning that optimum range of each temperature, relative humidity and CO_2 concentration for generating mushroom is 18~24 ℃, 75~85% and 600~4,900 ppm, internal design value of temperature 22 ℃, relative humidity 80% and CO_2 concentration 1,000 ppm were applied to developed ventilation model base on external value of temperature of 27.5~33.5 ℃, relative humidity of 60% and CO_2 concentration of 355 ppm. Fig. 6 shows ventilation rate applying above mentioned values.

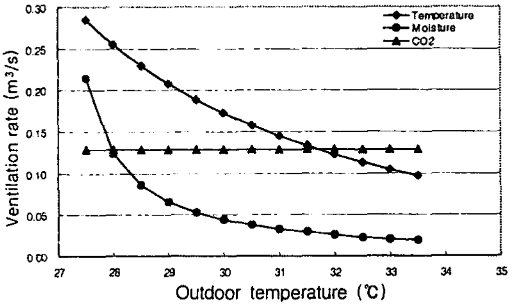


Fig. 6 Ventilation graph calculated by ventilation model

As shown in Fig. 6, curve for thermal balance was used for optimum ventilation curve before 32 ℃ and after then, it was converted to curve for CO_2 balance. In this optimum ventilation curve, supply of water must be required to control moisture contents. By following equation, required moisture contents for adding can be calculated.

$$H_s = \rho \Delta V (W_i - W_o) \cdots\cdots\cdots\cdots (14)$$

where Hs is required moisture contents (kg $\cdot$ s^{-1}), and ΔV is the ventilation rate for moisture balance ($m^3 \cdot s^{-1}$).

As the result of applying ventilation model, when external temperature was 30~32 ℃, required ventilation rate was 0.15~0.18 $m^3 \cdot s^{-1}$ and adding moisture contents of 1.95~3.66 kg $\cdot$ h^{-1} was needed.

Using this developed ventilation model is able to control ventilation system optimally in mushroom because maximum ventilation rate is critical in designing ventilation system and temperature, relative humidity and CO_2 concentration is needed in controlling ventilation system.

Ⅳ. Conclusion

In this study, ventilation model for calculating optimum ventilation rate was developed based on energy conservation equation and mass conservation equation concerning relationship between physiological characteristics of mushroom and environmental factors in mushroom house using adiabatic panel with forced ventilation system. Developed model was validated through comparing observed data with simulated ones. In addition, ventilation rate was determined for controlling temperature, relative humidity and CO_2 concentration during summer through applying this model and suitability was assessed.

In conclusion, difference between observed and simulated data was 0.038~0.065 $m^3 \cdot s^{-1}$ (10.4~18.9%) when external temperature was 23.6~24.8 ℃ and mean ventilation rate was 0.354 $m^3 \cdot s^{-1}$ and 0.001~0.039 $m^3 \cdot s^{-1}$ (0.3~11.5%) when external temperature was 22.5~23.6℃ and mean ventilation rate was 0.349 $m^3 \cdot s^{-1}$.

Ventilation graph was determined by using internal design value of temperature 22 ℃, relative humidity 80% and CO_2 concentration 1,000 ppm based on external values of temperature 27.5~33.5 ℃, relative humidity 60% and CO_2 concentration 355 ppm for application of developed ventilation model. As the result of application, optimum ventilation curve was determined by curve for thermal balance up to external temperature 32 ℃ and after then, controlled by curve for CO_2 balance. In addition, humidification was required for moisture balance.

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