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Design of an energy efficient building equipped with air conditioning system for growing "Kladnitsa" mushrooms

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Abstract

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The purpose of the study is to create appropriate technological parameters in a building for intensive year-round cultivation of "Kladnitsa" mushroom by air-conditioning the room. To achieve this goal, an original energy efficient building was developed, consisting of a lightweight type of glasshouse with a reinforced concrete floor and a steel supporting structure. The mushrooms are grown in polyethylene bags on 4 pieces of three-storey metal racks all year-round. Based on the research, a HVAC (heating-ventilation-air-conditioning) system for year-round maintenance of the microclimate in the mushroom facility was proposed and developed. The obtained results show that the selected building materials are suitable for a year-round intensive cultivation of "Kladnitsa" mushroom. It allows successful air conditioning in the year-round. Its cooling in the summer is possible and economically feasible to be done with groundwater with t_{gw}= 10-12°C. Known deviations of 3°C from the optimum internal temperature are observed on hotter days. Higher heat and cooling loads during the cultivation are in the fruiting phase, so it is recommended that the sizing of the equipment be carried out at this phase. Evaporative cooling of the room by spraying water is successful, because it simultaneously lowers the temperature and increases the humidity. Third heat exchanger is also recommended (in the part of the general circulating air), which in the case of insufficient heat influxes from the outside, to raise the temperature of the treated air sufficiently to reach the recommended microclimatic parameters in the room.

Keywords: glasshouse; heating-ventilation-air-conditioning; microclimate; technological parameters

Introduction

Wild mushrooms, as an integral part of biocenoses, are in complex interactions with other natural sites. Global pollution has a significant impact on the species composition, quantity and quality of their production. As the demand for wild mushrooms increases that increases the need to develop more efficient technologies for their cultivation (Mirchev et al., 2009).

Today, more than 50 species of wild mushrooms are grown in artificial conditions, and one of the favorites is the "Kladnitsa" mushroom. In Bulgaria, successful attempts have been made to cultivate it by a number of mushroom growers, but the mushroom is still very rare in the markets. The reason is the insufficient information about the advanced technologies of its cultivation (intensive and extensive methods) and the lack of lasting trends in its production in our country (Mirchev et al., 2009; Michael et al., 2014).

Important factors influencing the growth and development of fungi, both during the development and dosing phase of the mycelium and during the fruiting phase, are temperature, humidity of the air and the substrate, the flow of fresh air, light (Rancheva, 1999; Mirchev et al., 2009; Denchev et al., 2013; Agro-Projects, 2020). In this aspect, the creation of favorable technological conditions for the environment for growing mushrooms depends on a careful study of the impact of these factors, on the basis of which to develop an adequate air conditioning system.

The purpose of the present study is to create appropriate technological parameters in new developed energy efficient building for intensive year-round cultivation of the mushroom "Kladnitsa" by air-conditioning the room.

Material and Methods

Object of study

To achieve this goal, an original energy-efficient building was developed, representing a lightweight type of greenhouse with a reinforced concrete floor and a steel supporting structure, consisting of columns with a 2Tshaped cross-section and arched roof trusses. In the range of the columns the fence is made of sandwich panels (thickness d=8 cm) with thermal insulation of polyurethane foam, and the roofing is made of two layers of polyethylene, between which 15 cm of compacted straw is placed. The mushrooms are grown all year round in plastic bags on 4 pieces of three-storey metal racks.

The object of study was the technological microclimatic parameters in the fungus during the periods of development and maturation of the mycelium and fruiting. The heat losses of the room in winter, its heat gains (cooling loads) in summer and the air conditioning processes are determined. Machine-free air conditioning is chosen - evaporative cooling and cooling with groundwater. Based on the conducted research, a HVAC (heating-ventilation-air-conditioning) system is developed and offered for year-round maintenance of the microclimate in the fungus.

Methods for determining heat loss in winter

Total heat losses of the room *(Stamov et al., 1990):*

They are determined by the formula:

$$Q_T = \sum Q_{T,int} + Q_{inf}, W \quad (1)$$

where: $\sum Q_{T,int}$ is the sum of the losses from heat transfer through the various enclosing elements of the room

$$(\sum Q_{T,int} = Q_{T,r} + Q_{T,w} + Q_{T,f}).$$

Heat losses through the roof (Q $(Q_{T,r})$ (Stamov et al., 1990):

They are calculated by the formula:

$$Q_{T,r} = F_r\, q_r, W \quad (2)$$

where: F_r is the roof area, m^2; q_r - heat losses in 1 m² area of the roof

Heat losses through the walls $(Q_{T,w})$ (Stamov et al., 1990):

They are calculated for each wall of the room and summed according to the following formula:

$$Q_{T,w} = \sum F_{T,w,i}\, q_{w,i}, W \quad (3)$$

where: $F_{w,i}$ is the area of the wall, m^2; $q_{w,i}$ - heat losses through 1 m^2 wall area.

Heat losses through the floor $(Q_{T,f})$ (Ordinance 15/28.07.2005 on technical rules and regulations for design, construction and operation of sites and facilities for production, transmission and distribution of heat):

Heat losses through the mushroom floor can be calculated by the simplified method. The calculated stationary heat loss coefficient through the floor ($H_{T,ig}$) from the heated space (i) to the ground (g) is determined as follows:

$$H_{T,ig} = f_{g1}\, f_{g2}\, (\sum A_к\, U_{equiv,k})\, G_w, W/K \quad (4)$$

where: f_{g1} is a correction factor depending on the average annual change in outdoor temperature; f_{g2} - temperature factor, taking into account the difference between the average annual temperature and the calculated outdoor temperature; $A_к$ is the area of an element of the building in contact with the soil (denoted by index k), m²; $U_{equiv,k}$ - the coefficient of equivalent heat transfer through an element of the building (denoted by index k), W/m²K; G_w - correction factor taking into account the impact of groundwater.

Heat losses through the floor are determined by the formula:

$$Q_{T,f} = H_{T,ig}\, (t_{int} - t_e), W \quad (5)$$

where: t_{int} is indoor room air temperature, °C, t_e - the calculated outdoor temperature, based on the average outdoor temperature for the heating season ($t_{e,av}$), according to Ordinance № RD-16-1058 of 10.12.2009, °C

Heat losses from infiltration (Q_{inf}) (Stamov et al., 1990):

They are taken into account only for the phase of dosing and development of the mycelium, when there is no ventilation. In the fruiting phase, instead of heat losses from infiltration (Q_{inf}), heat losses from ventilation are reported (Q_v).

$$Q_{inf} = \sum(a_i\, l_i)\, R\, B\, K_o\, (t_{int} - t_e), W \quad (6)$$

where: a_i is the coefficient of air permeability of a joint of an air-permeable element with a length of 1 m; l_i - the length of the joint of the air-permeable element; R - characteristics of the room; B - characteristics of the building; K_o - total weighting.

Ventilation losses (Q_v) (Stamov et al., 1990):

They are determined by the formula:

$$Q_v = V_a\, \rho\, c_p\, (t_{int,i} - t_e), W \quad (7)$$

where: V_a is the air flow rate for the heated space (i), m³/s; ρ - air density at $t_{int,i}$, kg/m³; c_p - the specific heat capacity of the air at $t_{int,i}$, J/kgK, $t_{int,i}$ - the internal design temperature of the heated space, °C;

Method for determining heat gains (cooling loads) in summer

Cooling loads are determined in accordance with "Ordinance 15/28.07.2005 on technical rules and regulations for design, construction and operation of sites and facilities for production, transmission and distribution of heat."

Cooling load from external influences:

Heat transfer through dense building structures and elements illuminated by the sun ($\Phi_{dT,i}$):

It is calculated for each hour of the day according to the formula:

$$\Phi_{dT,i} = U.\, F\, \Delta t_{CL}, W \quad (8)$$

where:

U is the heat transfer coefficient, W/m²K;

F - the surface of the corresponding element, m²;

Δt_{CL} - the temperature difference for the cooling load, °C.

Cooling load from internal sources:

People ($\Phi_{d,p}$) - calculated for each hour of the day by the formula:

$$\Phi_{d,p} = n\, \Phi_{s,p}\, F_{CL}, W \quad (9)$$

where:

n is the number of people;

$\Phi_{s,p}$ – the apparent heat released by one person, W.

F_{CL} – the factor of the cooling load (chosen depending on the length of stay of people in the air- conditioned room);

Illumination (**$\Phi_{d,L,i}$**) - calculated for each hour of the day and separately for the different types of luminaires:

$$\Phi_{d,L,i} = P\ \Psi_{use}\ \Psi_{sa}\ F_{CL}\ ,\ W \quad (10)$$

where: P is the total power of all the same type of radiators, W; Ψ_{use} - utilization factor (the ratio of the power to be used to the total power); Ψ_{sa} - coefficient for the type of luminaire; F_{CL} - cooling load factor.

Ventilation load:

Perceptible ventilation cooling load - calculated by the formula:

$$\Phi_{v,s,CL,i} = 1000\ \rho_s\ c_{p,a}\ V_e\ (t_e - t_{int,i}) \approx 1230\ V_e\ (t_e - t_{int,i})\ ,\ W \quad (11)$$

where: ρ_s is the density of the compressed air, kg/m³; V_e - the outside air flow, m³/s; $c_{p,a}$ - the specific heat capacity of dry air; kJ/kg.

Latent ventilation load:

$$\Phi_{v,l,CL,i} = 1000\ \rho_s\ V_e\ h_w\ (x_e - x_{int,i}) \approx 3.01\ .\ 106\ V_e\ (x_e - x_{int,i})\ ,\ W \quad (12)$$

where: h_w is the enthalpy of water vapor in the air, kJ/kg; x_e - the calculated moisture content of the outside air, kg/kg; $x_{int,i}$ - the moisture content of the air in the room, kg/kg.

Humid cooling load for a room ($\Phi_{h,CL,i}$) (if such is found):

Moisture is a source of latent (latent) heat in the room, which is its humidity cooling load. It is calculated for each hour of the day according to the formula:

$$\Phi_{h,CL,i} = 1000 \sum m_{w,j}\ h_{w,j},\ W \quad (13)$$

where: $m_{w,j}$ are the moisture releases from one source, kg/s; $h_{w,j}$ - enthalpy of water vapor at the temperature of the source of moisture release, kJ/kg.

The expectations for maximum cooling load are in the period from 12:00 to 18:00 h.

Air conditioning method (Stamov, 1993) - machine-free air conditioning is accepted.

Evaporative cooling.

Evaporative cooling systems are autonomous devices that cool the air using its ability to absorb water vapor. The heat exchange takes place when an air flow passes through a humidified filter element.

Cooling with groundwater.

The groundwater cooling method is suitable for maintaining in summer in an air-conditioned room at a temperature above 20°C. Surface heat exchangers (water heaters) are used, through which groundwater passes, and the treated air enters through their facade section. During the heating season, hot water can pass through them, i.e. they can perform the function of air heaters.

The results obtained in the study are presented in tabular and graphical form.

Results and Discussion

Figure 1 shows the drawings of the building developed by us - aboveground mushroom, greenhouse type. The results of the study of its energy efficiency are the basis for developing a system for air conditioning.

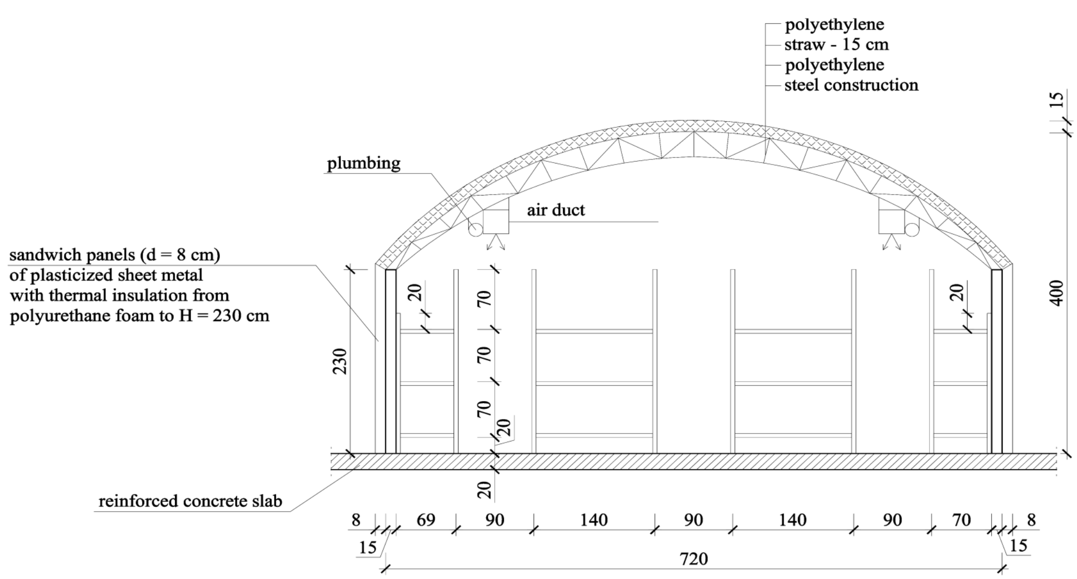

Fig. 1. Cross-section of a mushroom growing facility for growing "Kladnitsa" mushroom

Determination of heat losses in winter

Figure 2 presents the results for the determined total heat losses of the fungus during the two phases: dosing and development of the mycelium and fruiting. The total heat losses during the phase of dosing and development of the mycelium are obtained by adding the heat losses from infiltration to those from heat transfer through the enclosing elements of the room, and during the fruiting phase - the losses from ventilation.

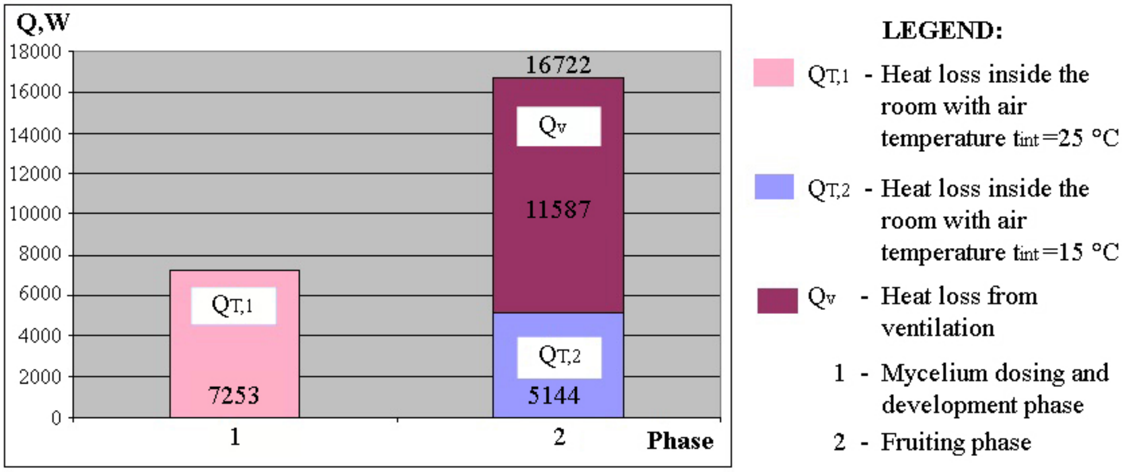

Fig. 2. Heat losses during phases dosing and development of mycelium and fruiting

Heat gains (cooling loads)

The cooling loads from external and internal influences are calculated at air temperatures in the fungus respectively: t_{int}= 25°C (for the dosing and micelle development phase) and t_{int}= 23°C (for the mushroom fruiting phase). The results obtained are shown in Figures 3 and 4.

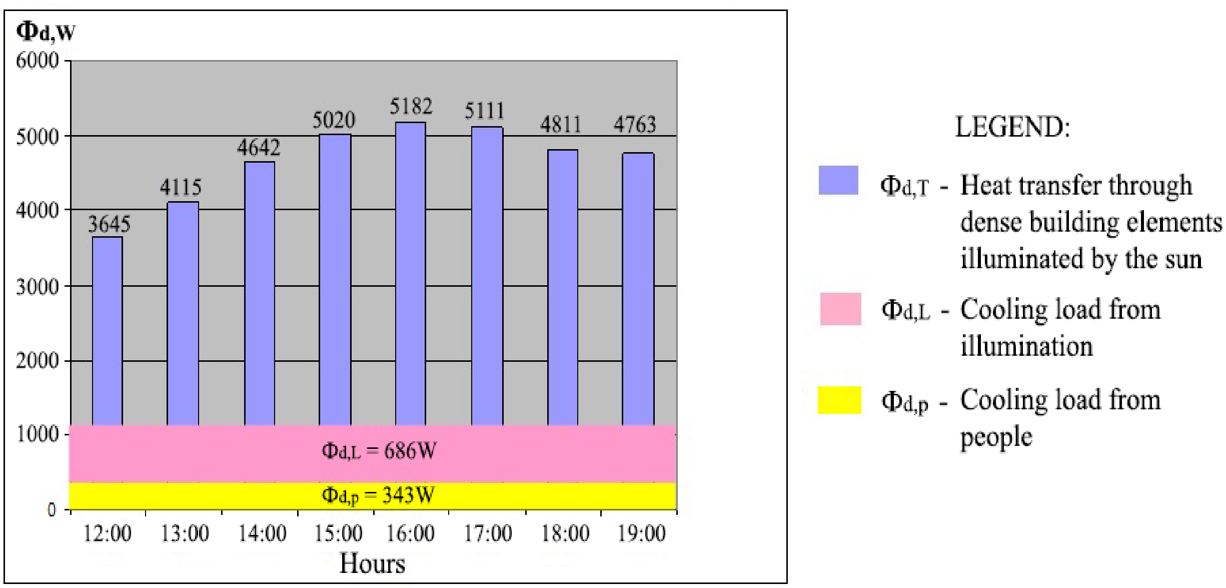

Fig. 3. Heat inflows (cooling loads) for the room during the phase of dosing and development of the mycelium

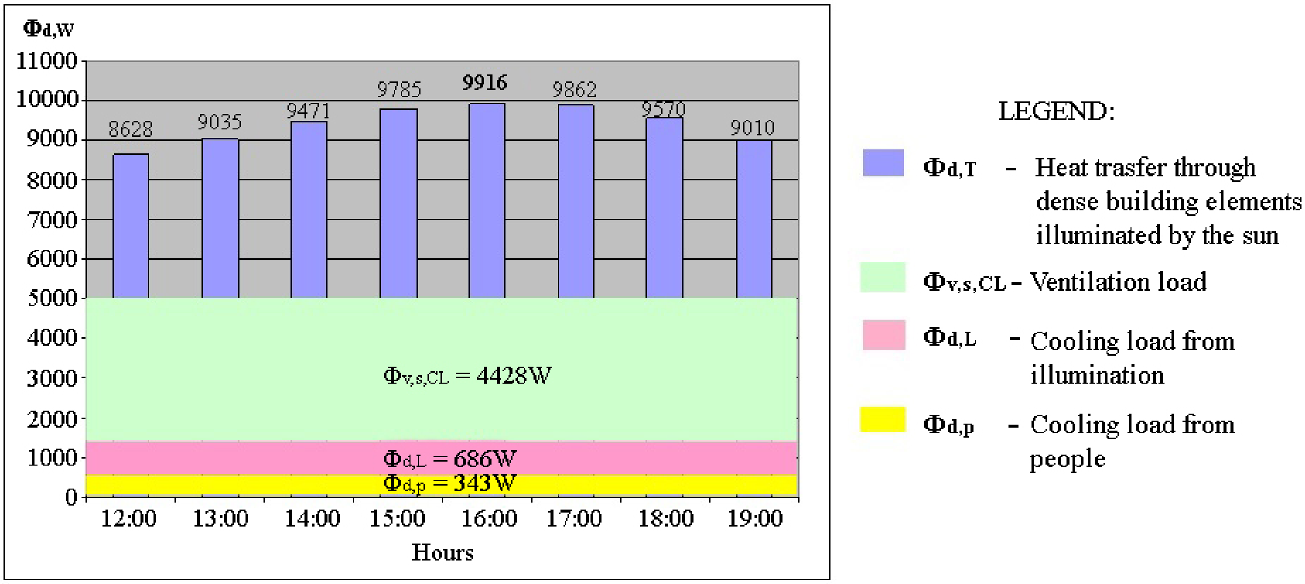

Fig. 4. Heat inflows (cooling loads) for the room during the fruiting phase

The data show the highest values of the studied indicators, reported at 16:00 h.

Processes of air conditioning in winter

No outside air is needed during the mycelium development phase. Only recirculated air with temperature t_{int} = 25ºC and humidity φ_{int} = 90% is used. The temperature in the room is achieved by ventilation air heated by a water heater. When the humidity changes, it can be corrected by spraying water with nozzles in the room itself.

Figure 5 shows the H-x diagram describing the processes of air conditioning in winter during the phase of dosing and development of the mycelium.

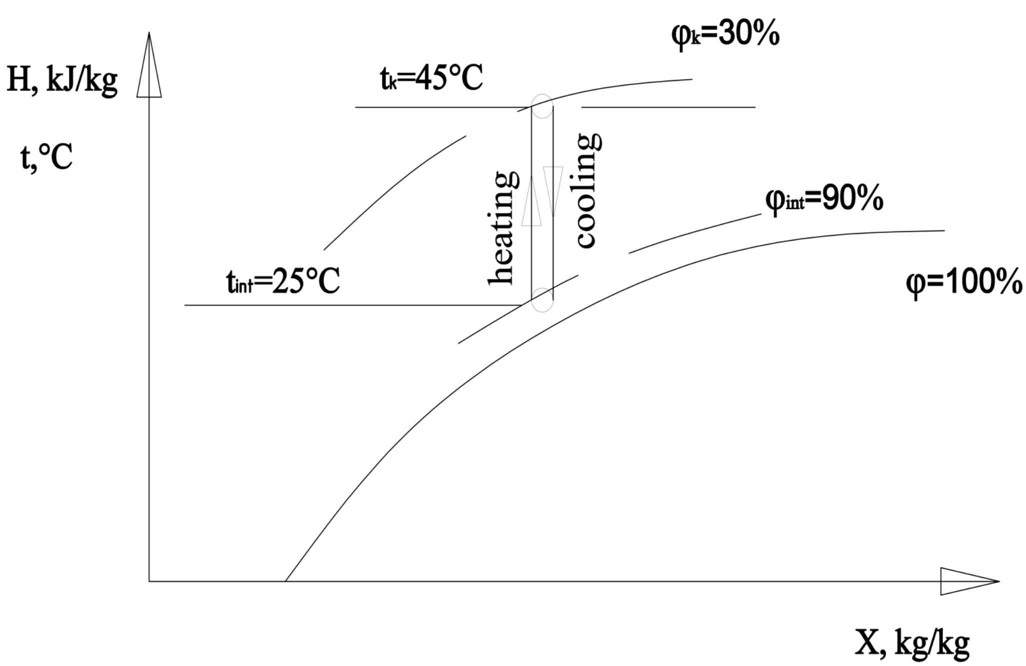

Fig. 5. Processes of air conditioning in winter during the phase of dosing and development of the mycelium

For technological reasons, we assume t_k= 45°C - a temperature that can be easily reached by a heater supplied with hot water from a boiler. The heat output of the water heater (Q_h) is defined as a function of the total heat loss (Q_T) in the fungus:

$$Qh = QT \{QT,r ; QT,w; QT,f\}, W$$

$$Qh = Vrc\ \rho en\ cen\ \Delta tk, W$$

We find the flow rate of the air heated by the heater (V_{rc}):

$$V_{rc} = \Sigma Q_T / [\rho_{en}\, c_{en}\, (t_k - t_{int})] = 7253 / 1.18 \,.\, 1005 \,.\, 20 = 0.3\ m^3/s$$

where: ρ_{en} is the density of the intake air, kg/m³; c_{en} - the specific heat capacity of the intake air, J/kgK.

Figure 6 shows the H-x diagram describing the processes of air conditioning in winter during the mushroom fruiting phase.

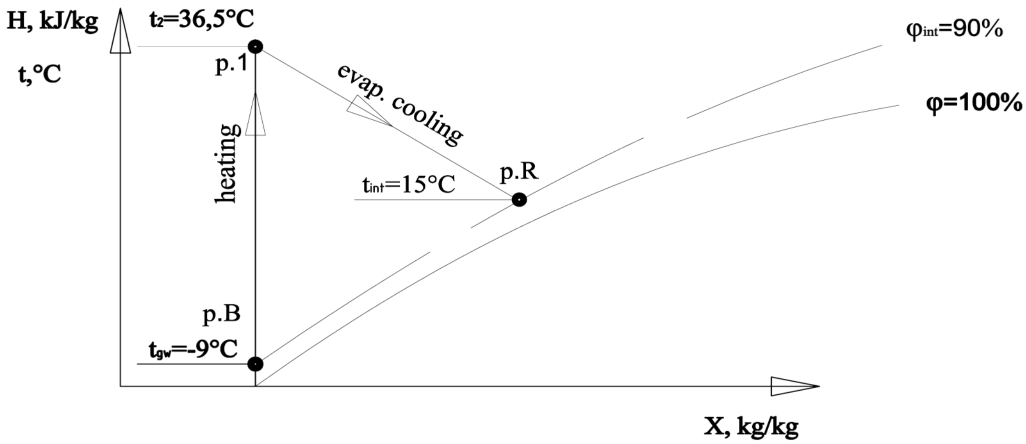

Fig. 6. Processes of air conditioning in winter for the fruiting phase of mushrooms

Figure 2 shows that the total heat loss in the fruiting phase is 16 722 W. To compensate for heat loss from heat transfer and ventilation, the incoming outside air in point B is heated until it reaches point 1 (up to 36.5°C) from a heater. The heated air is subjected to evaporative cooling and reaches the point R (at 15ºC and φ = 90%) without the need for additional processes. The indicated temperature values are calculated as follows:

$$Q_{m,2} + Q_v = V_{en}\,\rho_{en}\,c_{en}\ (\ t_1 - t_2) \rightarrow t_1 = t_e + (Q_{m,2} + Q_v) / V_{en}\,\rho_{en}\,c_{en}$$

$$t_1 = -9 + 16\,722 / 0.3 \,.\, 1.20 \,.\, 1005 = 36.5\ ºC$$

Air conditioning processes in summer

In the mycelium development and dosing phase, there is only recirculation of the indoor air, without an inflow of outside air. It is customary to extract heat in the summer by using groundwater circulating in a heat exchanger. Groundwater temperature (t_{gw}) is in the range of 10-12° C (Stamov, 1990). The calculations were performed at t_{gw} = 11 °C.

The H-x diagrams describing the air conditioning processes during the summer are shown in Figures 7 and 8.

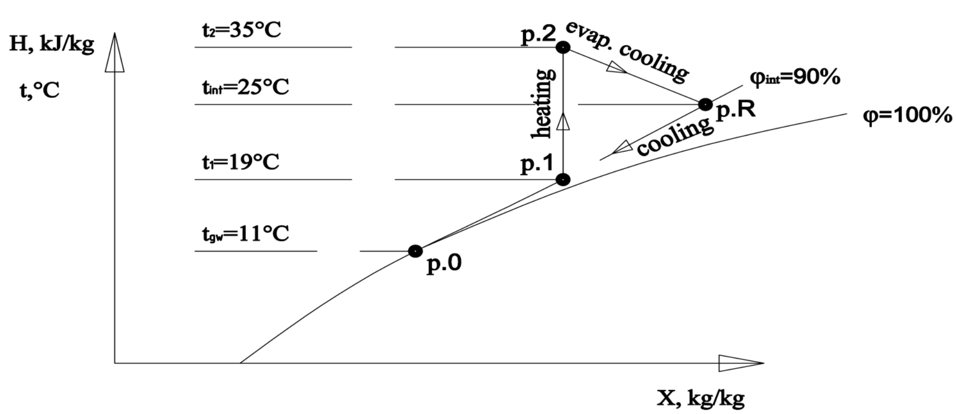

Fig. 7. Processes of air conditioning in the summer for the dosing phase and mycelium development

The diagram shows that in the heat exchanger the recirculated air is cooled to point 0 ($t_0 = t_{gw} + \Delta t$), where the temperature difference is Δt = 6 - 10ºC (Stamov, 1993). In point 1 the temperature is determined by the formula:

$$t_1 = t_{gw} + 8 = 11 + 8 = 19\ ºC$$

From point 1 to point 2 the air is heated by the heat sources, which are the cooling load for the room.

The recirculation air flow rate is as follows:

$$V_{rc} = Q_{T,1} / \rho_{en}\, c_{en}\, (t_{int} - t_1) = 4153 / 1.2.\ 1005.\ (25 - 19) = 0.6\ m^3/s$$

In case of insufficient heat supply to point 2 in the scheme of the air-conditioning installation an additional heat exchanger Tсм is provided, heating the recirculated air.

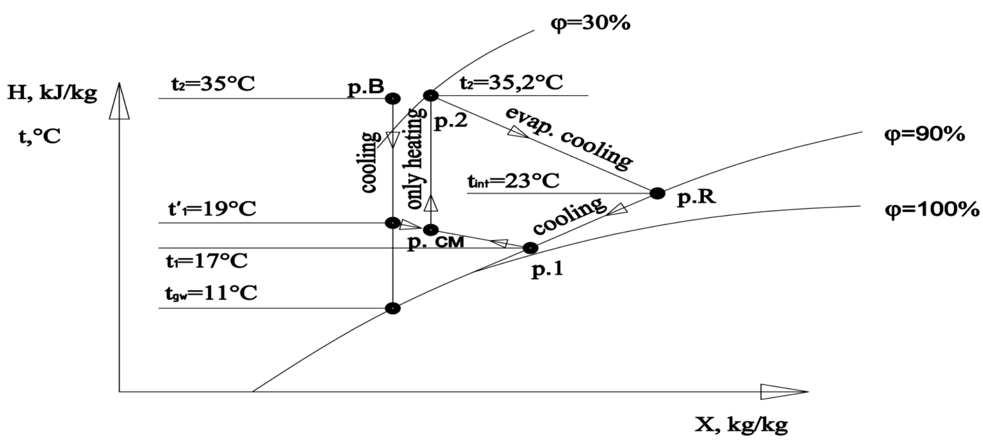

Fig. 8. Processes of air conditioning in the summer for the fruiting phase

According to literature data (Mirchev, 2009), summer strains of mushrooms bear fruit at a temperature of about 17-20ºC. The temperature difference (Δt_h) by which the air is heated by heat in summer is determined as follows:

$$\Delta t_h = (\Phi_{d,T} + \Phi_{d,L} + \Phi_{d,p} + \Phi_{v,s,CL}) / V_{rc}\, \rho_{en}\, c_{en} = (4459 + 686 + 343 + 7011) / 0{,}3.1{,}2.1005 = 34.5 \approx 35°C$$

The results show that when the ventilation system is used twice for one hour (average of the values recommended by scientific research), the heating of the air in the room (Δt_h) from the heat inflows is unacceptably high (35°C). In order to reduce it in the summer during the fruiting phase, it is necessary to double the air circulating through the installation. We assume V_{rc} = 0.6 m³/s, where Δt_h is obtained 17.2°C.

Technological scheme for air conditioning in a room for growing mushrooms "Kladnitsa"

Based on the conducted research, a technological scheme for HVAC (heating-ventilation-air- conditioning) system for year-round maintenance of the microclimate in the fungus has been developed (Figure 9). In summer, both air streams (ventilation and recirculation) are cooled with heat exchangers Te and Tint, respectively to 19°C and 17°C. The two streams are then mixed and fed into the room. The air in the mushroom house is heated by the heat inflows and reaches point 2, and through evaporation it reaches point R (of the room).

In case of insufficient heat inflows, the Tсм heat exchanger can be used for reheating.

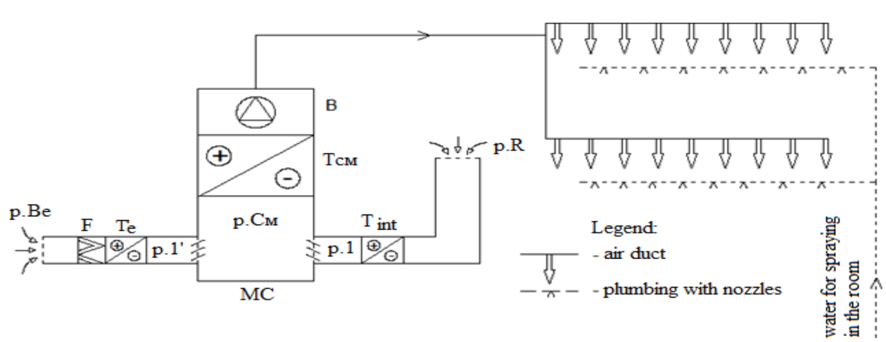

Fig. 9. Technological scheme for air conditioning in a room for growing mushrooms "Kladnitsa": F - filter; MC - mixing chamber; T_e - heat exchanger for outdoor air treatment; T_{int} - heat exchanger for indoor air treatment; B - fan, Tсм - heat exchanger for mixed air treatment

Conclusion

The selected construction materials are suitable for a building for year-round intensive cultivation of Kladnitsa mushroom. It allows successful air conditioning throughout the year. The cooling of the building in the summer is possible and economically advantageous to do with groundwater with t_{gw}= 10-12°C. Some deviations of 3°C from the optimum internal temperature are observed on hotter days. Larger heat and cooling loads during the cultivation of the mushroom "Kladnitsa" are in the fruiting phase, so it is recommended that the sizing of the equipment to be done in this phase. Evaporative cooling of the room by spraying water is successful because it simultaneously lowers the temperature and increases the humidity. It is also recommended a third heat exchanger (in the part of the general circulating air), which in case of insufficient heat inflows from the outside should sufficiently increase the temperature level of the treated air in order to reach the recommended microclimatic parameters in the room.

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