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Analysis of energy consumption in vacuum freeze-drying of button mushroom (*Agaricus bisporus*)

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Abstract
Mathematical calculations were established for energy consumption analysis of the vacuum-freeze-drying process of button mushroom. The energy consumption and the distribution of energy in the vacuum freeze drying were evaluated. Three samples of Button Mushrooms were taken (without boiling, segment before boiling and segment after boiling) and the working pressure of 0.75 Torr or 100 Pa and temperature (-28 °C) was considered for experimental investigations. The effects of various operation conditions on the energy consumptions in the three stages *viz*: freezing, primary and secondary drying were investigated. Energy consumption during vacuum freeze drying on working pressure 0.75 Torr or 100 pa and -28 °C temperature for product and residence time of 60 min (3600s) was found to be 24578.90 W. Total heat transfer area is 5.580 m^2, Overall heat transfer coefficient is 62.68 (w/m^2 °c). Moisture content was reduced during vacuum freeze drying in all three samples but more moisture was reduced in Segment before boiling (SAB) than Segment after boiling (SAB). The moisture in whole button mushroom without boiling (WMBW) moisture was reduced less as compared to Segment before and after boiling.

Keywords: Button mushroom, vacuum-freeze drying, energy consumption, without boiling, segments before boiling and segments after boiling

Introduction
The button mushroom (*Agaricus bisporus*) is the most widely cultivated and consumed mushroom throughout the world and it contributes about 40% of the total world's production. Mushrooms are extremely perishable and the shelf-life of fresh mushroom is only about 24 h at ambient conditions. Various physiological and morphological changes occur after harvest, which make these mushrooms unacceptable for consumption. Hence, they should be consumed or processed promptly after harvest and for this reason the mushrooms are traded mostly in processed form in the world market.

Button mushroom (*Agaricus bisporus*) contributes about 90% of the total country’s production against its global share of about 40% (Chang, 1999) [3]. As a high-class food, button mushrooms do not only provide delicious taste, but also possess abundant nutritive value. It is considered as a valuable health food with high content of proteins, vitamins, minerals, polyphenols and polysaccharides.

Once the fruiting body mature, degradation process starts and it becomes inconsumable after some time. Opening of veils and browning is the first sign of deterioration and are the major factors contributing to quality loses. Therefore, application of the best post-harvest technique to enhance the shelf-life and to maintain quality of mushroom can play a vital role in commercialization of mushroom (Chang and Buswell, 1996) [3]. Amongst the various methods employed for preservation, drying is an energy-intensive operation in which the water activity of the food is reduced by removal of the water. The main objective of any drying process is to produce a dried product of desired quality at a minimum cost and minimizing enzymatic and microbial reactions. Traditionally mushrooms are dried under open sun, which results in unhygienic and poor quality products (Chua *et al*., 2001) [1].

Vacuum freeze drying is rapid, more uniform and energy efficient method compared to conventional drying. In recent years, vacuum-freeze-drying has been investigated as a potential method for obtaining high quality dried food products, included fruits, vegetable and pharmaceutical. The low temperature and fast mass transfer conferred by vacuum combined with rapid energy transfer by freeze-drying very rapid low temperature drying and thus it has the potential to improve energy efficient and product quality.

There is scanty information available either in terms of the energy analysis of drying or quality of button mushroom undergoing vacuum-freeze-drying technique (Jagadish, 2009; Liu *et al*., 2013). Despite unmatched advantages, freeze-drying has always been considered the most expensive operation for manufacturing a dehydrated product owing to the large amount of energy consumption and high costs of both operation and maintenance (Bruttini, 2001) [1]. Hence this study aimed at calculating the energy consumption incurred during vacuum freeze drying of button mushroom.

Materials and Methods

Button mushrooms (*Agaricus bisporus*) having 92-94% moisture content (W.B.) were collected from an authentic mushroom production unit and stored at 4-5 °C in a refrigerator for further use. Button mushrooms with head size of same diameter (20-25 mm) were used for conducting the experiments.

Sample preparation

White button mushrooms of uniform size were thoroughly washed under tap water to remove adhering unwanted impurities and were graded by size to eliminate the variations in respect to exposed surface area. Then, samples of button mushrooms were taken three types *viz*. whole mushrooms, segments before and after boiling mushroom vertically cut the middle with a vegetable slicer provided with adjustable cutting blade. Experiments were conducted on 0.75 Torr or 100 Pa with three type’s sample

1. Whole mushroom without boiling (WMWB),
2. Segments before boiling (SBB) and
3. Segments after boiling (SAB)

Fig. (1, 2). The whole mushrooms and segmented mushrooms were used for drying experiments and samples were frozen at −40 °C in a deep freezer methodology of the study (make: NSW—275, Mode: Lyphilizer -40 °C) for 24 hours.

Fig 1: Whole button mushroom (without boiling)

Fig 2: Button mushroom segment before and after boiling

A Laboratory freeze dryer was used for the drying. The dryer had the provision to fix heating platen temperature at any desired value and measure the surface temperature of food during its drying. Water of button mushrooms samples frozen first and then freeze dried. After 1 hour of drying, petri dishes were taken out of freeze-dryer, weighted and weight loss was estimated. Parameters that affect freeze drying behavior of the three materials are mentioned below along with their measured values. Fig.3 shows the flow chart of Energy consumption analysis.

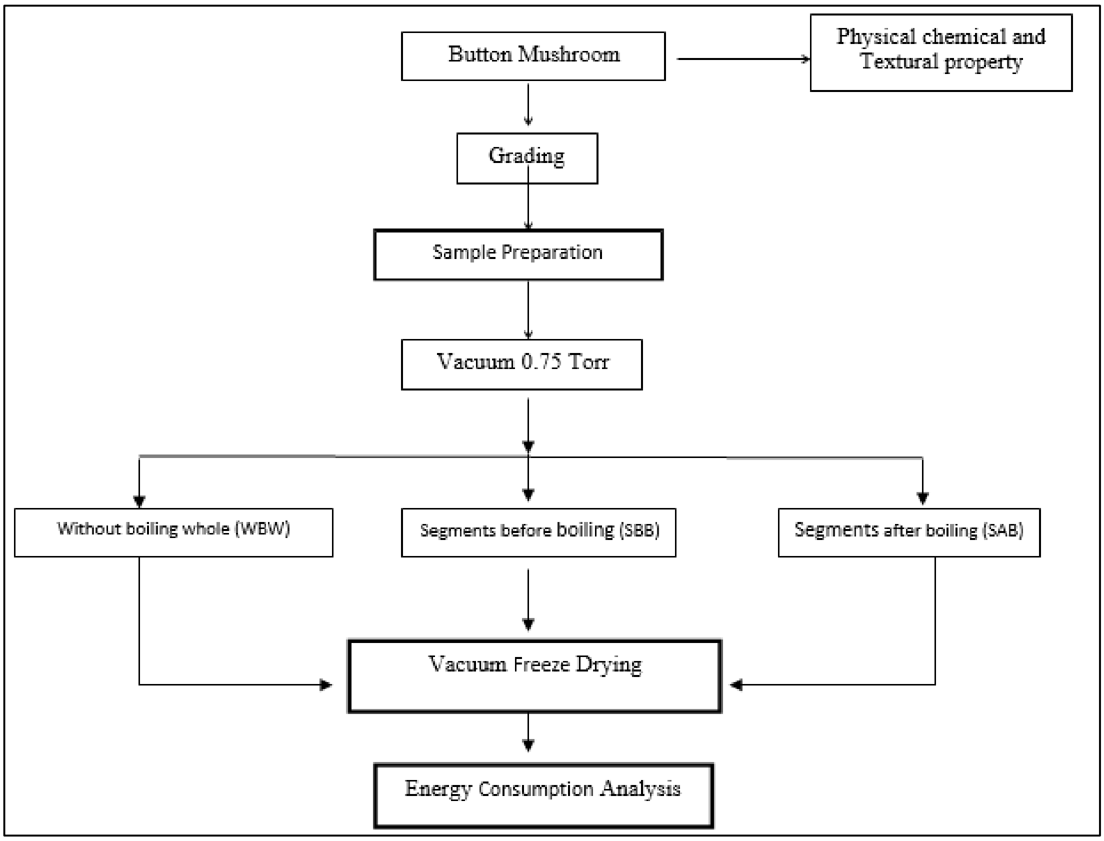

Fig 3: Flow chart of energy consumption analysis

Moisture content and drying rate

Moisture content of the food materials changes rapidly during vacuum drying due to high drying rate. Time for removal of moisture from the product is lower compared to other drying methods.

Procedure for moisture content and drying rate determination

1. Taken a fresh button mushroom sample for drying.
2. Taken the weight of the sample to be dried.
3. Kept the sample inside the chamber.
4. Closed the door of the chamber and the valves.
5. Switched on the heater or inside the chamber and the vacuum pump.
6. Note the time in which drying started by using a stopwatch.
7. Controlled the temperature and pressure inside the vacuum chamber by adjusting the pressure and temperature indicator.
8. After a fixed time, released the pressure inside the chamber by opening the released valve.
9. Taken out the sample from the chamber and taken the weight immediately.
10. Note down the weight of the sample after the fixed time.
11. Continue the procedure for a fixed time and taken the weight of the sample accordingly.
12. Determine the moisture reduction and drying rate.

Moisture content determination

Moisture content was calculated as per equ. (1) and equ. (2).

$$\text{Moisture content (WB \%)} = \frac{\text{Weight of moisture}}{\text{Weight of sample}} \text{x100} \qquad (1)$$

$$\text{Moisture of content (WB \%)} = \frac{\text{initial weight of sample - bone dry weight}}{\text{initial weight of sample}} \text{x 100} \qquad (2)$$

Drying rate

Drying rate is high for vacuum freeze drying because food materials are dried under vacuum and has a high vapor pressure gradient exist in food materials. Drying rate in a vacuum dryer is influenced mainly by temperature and pressure.

Drying rate in gram of water per minute per 100 gram of bone dry weight of material was calculated using equ.(3).

$$R = \frac{\text{Amount of moisture removed (g)}}{(\text{Time taken (g)})\left\{\dfrac{\text{Total bone dry weight of sample in gram}}{100}\right\}} \qquad (3)$$

Calculation of Energy consumption

Energy consumption during vacuum-freeze-drying at 0.75 Torr or 100 Pa

Analysis of vacuum-freeze-drying process has solved using (1) ice made from distilled water and (2) frozen mushroom as the model foods.

Maximum rate of freeze drying of Ice (R_C)

Operating parameters

1. Temperature of heating platen during freeze-drying, T_p= 0 °C
2. Absolute pressure maintained inside freeze-drying chamber during operation, P_s= 0.75 Torr or 100 Pa .
3. Condenser temperature, T_{cn} = -50 °C
4. Inner diameter of aluminium Petri Dish, d_p=.053m
5. Thickness of Petri dish, t_a =.0008m
6. Duration of freeze drying, θ =3600s
7. Weight of distilled water kept in Petri dish before freezing and freeze drying, W_{ci} =0.006051Kg
8. Weight of Button Mushroom before freeze drying, W_{ai} =0.0152 Kg
9. Initial moisture content of Button mushroom, M_w= 0.80kg water/kg Button mushroom (Xi=3.926kg water /kg dry solid (Reddy and Das, 1993).

Performance Parameters

- Weight of ice after partial freeze drying, W_{co} = 0.000125 Kg
- Weight of Button Mushroom after partial freezing drying, W_{ao} = 0.0076 Kg
- Density of unfrozen Button Mushroom, ρ_{am} =1072 kg/m^3

Surface temperature of Button Mushroom and ice freeze drying, t_{1m} = -28 °C

Freeze Drying Rate of Ice

Saturation temperature Ts (°C) of ice at present at pressure P_s (Pa) prevailing inside freeze- drying chamber can be expressed by the equ.(4).

$$T_s= 11.281*\log_e (53.6193*10^6 Ps) -273 \quad (4)$$

Eqn. (4) has been developed from equilibrium pressure and temperature data available for ice. Ts (°C) is also the sublimation ice front temperature, at pressure Ps (Pa), during freeze drying of ice made from distilled water. Assuming that the lower surface of ice is maintained at temperature close at heating platen temperature Tp (°C), average temperature Tic (°C) of ice existing between heating platen and sublimation ice front will be as per equ. (5) to (7).

$$T_{ic} =0.5 (Tp +Ts) \quad (5)$$

Density of ice ρic (kg/m^3) can be expressed as function of temperature Tic (°C) as,

$$\rho_{ic} =1022.73 - 1.374 (Tic + 273) + 0.0066 (Tic +273)^2 - 1.098*10^{-5}(Tic +273)^3 \quad (6)$$

Eqn (6) has been developed from the density data available for ice at different temperatures.

Rate of freeze-drying Rc (m/s) of ice made from distilled water can be obtained from the following.

$$R_c = \frac{(Wci - Wco)}{\rho ic(\frac{\pi}{4}dp^2)\theta} \quad (7)$$

Where, W_{ci} (Kg) and W_{co} (Kg) are the initial and final weight of ice respectively. θ (s) is the freeze –drying time and d_p (m) is the inner diameter of cylindrical shaped Petri dish.

Freeze Dried material Thickness and Freeze drying Rate

Sublimation temperature T_1 (°C) of ice present in mushroom at pressure Ps(Pa) prevailing inside freeze drying chamber can be obtained from consideration that water, minerals and sugars will from dilute solution with water present in mushroom and Raoults law will be applicable for this solution. Considering that the minerals are sodium chloride and the reducing sugars are glucose. Sublimation temperature was calculated using equ. (8). Density (mushroom), Initial thickness, porosity, Avg. temp, density (freeze dried layer) were calculated using equ. (9) to (13).

$$\log_e\left[\frac{\frac{Mw-X*(1-Mw)}{18}}{\frac{Mw-X*(1-Mw)}{18}+\frac{M1(1-Mw)}{58.5}+\frac{M2(1-Mw)}{180}}\right]=\frac{18\lambda}{R}\left[\frac{1}{Ts+273}-\frac{1}{T1+273}\right] \quad (8)$$

Eqn. (8) represents natural logarithm of mole fraction of water that is present in the solution containing water and dissolved solids.

Density ρ_{ai} (Kg / m^3) of button mushroom before freezing or freeze drying can be expressed as,

$$P_{ai} = \left[\frac{Mw}{\rho w}+\frac{1-Mw}{\rho s}\right]^{-1} \quad (9)$$

Initial thickness a (m) of button mushroom sample kept inside Petri dish can be obtained from the value of ρ_{ai} eqn (9).

$$a = \frac{4Wai}{\pi dp^2 \rho ai} \quad (10)$$

Porosity ε of this layer can be expressed as

$$\varepsilon = \frac{(Wai - Wao)/\rho c}{(\pi/4)dp^2 \rho aibm} \quad (11)$$

Average temperature T_{av} (°C) of ice existing between sublimation ice fronts and heating platen will be.

$$T_{av} = 0.5(Tp + T1) \quad (12)$$

Density ρ_{ao}(Kg/m^3) of freeze-dried layer of button mushroom can be expressed as,

$$\rho_{ao} = A = \left[\frac{X^*/(1+X^*)}{\rho w} + \frac{1/(1+X^*)}{\rho s}\right]^{-1} (1-\varepsilon) \quad (13)$$

Since, it has been assumed that

1. Volume of button mushroom does not change during freezing or freeze drying.
2. Moisture content of frozen layer of button mushroom does not change during freeze drying weight loss of freeze-dried layer of button mushroom can be expressed in terms of its bulk density before and after and freeze drying i.e. get bm (m) of freeze-dried layer of Button mushroom as,

$$bm = \frac{4(Wai - Wao)(1 - A/\rho c)}{\pi dp^2 (pai - A)} \quad (14)$$

Average rate of freeze-drying (m/s) of Button mushroom can be expressed as,

$$R_a = \frac{b\,m}{\theta} \quad (15)$$

Where, θ (s) is the duration of freeze-drying.

Overall heat transfer coefficient during freeze drying

Amount of heat λT1 (J/kg) required for sublimation of ice at temperature T1 (°C) is given by

$$\lambda_{T1} = \lambda_f + \lambda_c + c_{vp}T_1 - c_{pc}T_1 \quad (16)$$

Thermal conductivity of ice k_c (W/m°C) at its average temperature Tav can be estimated from the following regression equation.

$$k_c = 1.258*10^{-7}(T_{av}+273)^3 - 4.431*10^{-5}(T_{av}+273)^2 - 0.01197(T_{av}+273)+6.227 \quad (17)$$

Since frozen Button mushroom contains three components, *viz* starch, bound water, and ice.

Thermal conductivity k_f (w/m°c) of the Button mushroom can be computed from the consideration that the components of button mushroom exist parallel to direction of heat flow (Lewis 1987) i.e.

$$k_f = V_c k_c + V_w k_w + V_s k_s \quad (18)$$

Overall heat transfer coefficient U (w/m^{-2} °C) at the lower surface of frozen mushroom can now be obtained from the equations (2.21).

$$U = \left[\frac{\theta(T_p - T_1)(1+X_i)}{bm\,\rho ai(X_i - X^*)\lambda_{T1}} + \frac{bm}{2k_f} + \frac{a}{k_f}\right]^{-1} \quad (19)$$

Results and Discussion

Moisture Content 0.75 Torr or 100 p_a (Freezing after drying)

Moisture content is reduced during vacuum freeze drying. There was a reduction in all 3 types of samples. 1 Whole Button mushroom without boiling (WMBW), 2 Segment before boiling (SBB) and 3. Segment after boiling (SAB). Table 1 to 3 shows the moisture content of all samples for the three types during vacuum freeze drying.

Button Mushroom Sample Moisture Content (Without boiling)

By using the vacuum freeze drier, experiments were done and the results were obtained. Whole Button mushroom (Without boiling) sample was taken and it was kept in observation for 24 hours, as time passes the sample was taken and its weight was measured. And the variation of weight vs time was plotted in fig.4. The values were obtained as shown in the table 1.

Table 1: Moisture Content of mushroom without boiling during vacuum freeze drying

S. No.	Time (h)	Time Interval (h)	Weight (g)	Wt. of moisture (g)	% of moisture (W.B.)
1	00.00	00.00	36.12	31.34	100.00
2	01.00	01.00	26.05	22.60	72.12
3	02.00	01.00	21.13	18.33	58.49
4	03.00	01.00	15.51	13.45	42.93
5	04.00	01.00	10.54	09.14	29.18
6	06.00	02.00	08.31	07.21	23.00
7	08.00	02.00	06.51	05.65	18.02
8	16.00	08.00	05.71	04.95	15.81
9	24.00	08.00	05.68	04.93	15.73

Button Mushroom Sample Moisture Content (Segment before boiling)

By using the vacuum freeze drier, experiments were done and the results were obtained. Mushroom (Segment before boiling) sample was taken and it was kept in observation for 24 hours, as time passes the sample was taken and its weight was measured. And the variation of weight vs time was plotted fig. 5. The values were obtained as shown in the table 2.

Table 2: Moisture Content of mushroom Segment before boiling during vacuum freeze drying

S. No.	Time (h)	Time Interval (h)	Weight (g)	Wt. of moisture (g)	% of moisture (W.B.)
1	00.00	00.00	29.55	25.63	100.00
2	01.00	01.00	21.15	18.35	71.58
3	02.00	01.00	15.74	13.66	53.28
4	03.00	01.00	12.04	10.45	40.75
5	04.00	01.00	09.10	07.90	30.79
6	06.00	02.00	06.39	05.54	21.63
7	08.00	02.00	04.76	04.13	16.12
8	16.00	08.00	04.16	03.61	14.08
9	24.00	08.00	04.14	03.59	14.02

Button Mushroom Sample Moisture Content (Segment after boiling)

By using the vacuum freeze drier, experiments were done and the results were obtained. Mushroom (Segment after boiling) sample was taken and it was kept in observation for 24 hours, as time passes the sample was taken and its weight was measured. And the variation of weight vs time was plotted fig. 6. The values were obtained as shown in the table 3.

Table 3: Moisture Content of mushroom Segment after boiling during vacuum freeze drying

S. No.	Time (h)	Time Interval (h)	Weight (g)	Wt. of moisture (g)	% of moisture (W.B.)
1	00.00	00.00	33.15	28.76	100.00
2	01.00	01.00	24.32	21.10	73.37
3	02.00	01.00	19.11	16.58	57.66
4	03.00	01.00	13.99	12.14	42.20
5	04.00	01.00	10.99	09.54	33.18
6	06.00	02.00	07.30	06.33	22.01
7	08.00	02.00	05.46	04.74	16.47
8	16.00	08.00	05.05	04.38	15.24
9	24.00	08.00	05.03	04.37	15.18

Moisture content was reduced during vacuum freeze drying in all three samples but more moisture was reduced in Segment before boiling (SAB) than Segment after boiling (SAB). The moisture in whole button mushroom without boiling (WMBW) moisture was reduced less as compared to Segment before and after boiling as shown in fig.7.

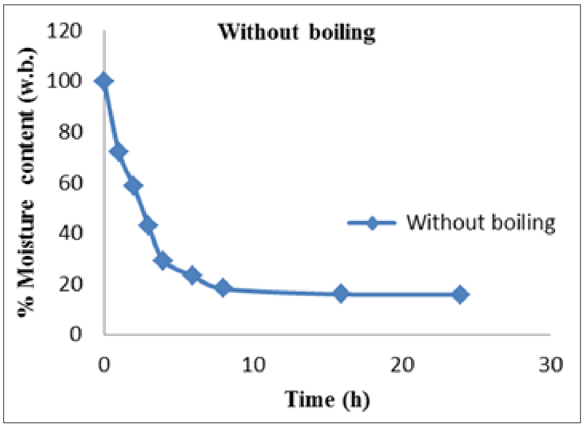

Fig 4: Whole Button Mushroom without boiling

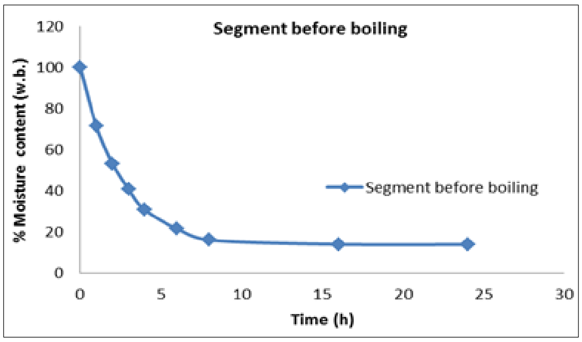

Fig 5: Segment before boiling

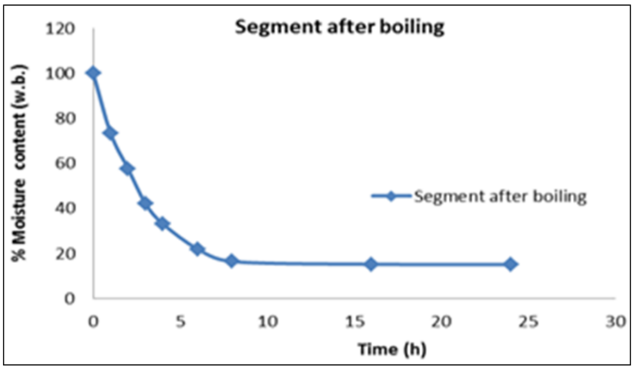

Fig 6: Segment after boiling

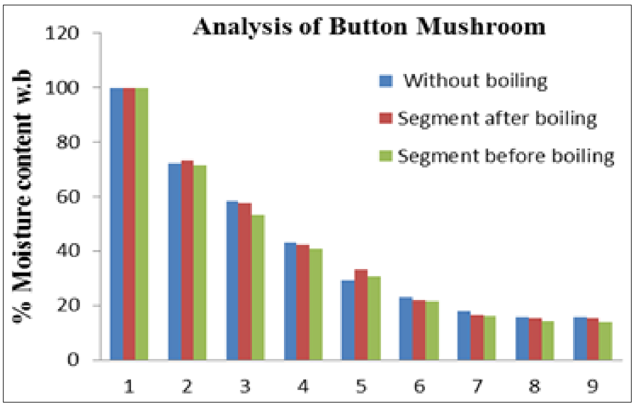

Fig 7: Analysis of three sample Button Mushroom

Mathematical calculation of Energy Consumption

Analysis of freeze-drying process will be solved here using

1. Ice made from distilled water and
2. Frozen mushroom as the model foods. A Laboratory freeze dryer was used for the drying. The dryer had the provision to fix heating platen temperature at any desired

value and measure the surface temperature of food during its drying.

Saturation temperature T_s (°C) of ice at present at pressure P_s (Pa) prevailing inside freeze-drying chamber can be expressed by the equation from (4).

T_s = –20.27 °C

Average temperature T_{ic} (°C) of ice existing between heating platen and sublimation ice front will be. Tic (°C) can be calculated from eqn. (5).

= –10.133 °C

Density of ice ρ_{ic} (kg/m^3) can be expressed as function of temperature Tic (°C) as, can be calculated from equ. (6)

ρ_{ic} = 918.16 Kg/m^3

Rate of freeze-drying R_c (m/s) of ice made from distilled water can be obtained from the calculated equ. (7)

R_C= 8.123*10^{-7} m/s

Sublimation temperature T_1 (°C) of ice present in mushroom at pressure P_s (Pa) prevailing inside freeze drying chamber can be obtained from calculated eqn. (8)

T_1 = –21.67 °C

Density ρ_{ai} (Kg /m^3) of mushroom before freezing or freeze drying can be expressed as equ. (9)
= 1071.428 Kg /m^3

Initial thickness a (m) of mushroom sample kept inside Petri dish can be obtained from the value of ρ_{ai} from the calculated equ. (10).
= 0.00643m

Porosity ε of this layer can be expressed from the calculated equ. (11)
= 0.217

Density ρ_{ao} (Kg/m^3) of freeze-dried layer of mushroom can be expressed as from equ. (13)
= 1063.63 Kg/m^3

b_m (m) of freeze-dried layer of mushroom from the calculated eqn (14).
= 0.01748 m.

Overall heat transfer coefficient during freeze drying
Amount of heat λ_{T1} (J/kg) required for sublimation of ice at temperature T1 (°C) is given by, λ_{T1} can be calculated from eqn. (16).
λ_{T1} = 2.537x10^6 J/kg

Thermal conductivity of ice kc (W/m°C) at its average temperature T_{av} can be estimated from the regression equ. (17).

k_c= 2.305 w/m°c

Thermal conductivity k_f(W/m°C) of the mushroom can be computed from the consideration that the components of vegetable exist parallel to direction of heat flow (*Lewis 1987*) i.e. kf can be calculated from equ. (18).

k_f = 1.1030 w/m°c

Overall heat transfer coefficient
Overall heat transfer coefficient U (W/m^2°c) at the lower surface of frozen mushroom can now be obtained from the equation (19).

U = 62.68 (W/m^2°c)

Heat transfer inside the dryer
It is based on a sophisticated albeit empirical technology. Heat transfer in a vacuum freeze dryer is by conduction. The time required for warm up is not a significant fraction of total time, and it is assumed that the moisture removed is not limited by diffusion of the vapor from inside to the surface of the solid.

$$t_R = \frac{\lambda m_B \Delta m}{A_D U \Delta T} = \frac{\lambda m_B (m_i - m_f)}{A_D U (T_p - T)}$$

But the heat area can be determined from residence time equation. Suppose we are drying button mushrooms in the dryer, and the average moisture content of button mushroom is 90%. So one kg of button mushroom contains 0.90 kg of water and the dry matter is 0.10 kg. If we dry 10 kg button mushrooms then the water will be 9 kg. And dry matter will be 1 kg. So here B_m = 1 kg and Δm = 9 kg Let drying time is 1hr. (3600sec.).

$$A_D = \frac{\lambda m_B \Delta m}{t_R U \Delta T}$$
= 5.580 m^2

That major amount of moisture that has already been transformed to ice is removed during primary drying. After primary drying, temperature of ‘heating platen’ is raised by few degrees above ambient temperature (to 40 to 50 °C) such that moisture content of food is reduced to its safe storage value.

Then ΔT = (50-(-20.27)) = 70.27°C
$Q = UA\Delta T$
=24578.90 W
= 24.57 kw

Table 4: Energy Consumption Analysis in vacuum-freeze drying of Button mushroom

S.N.	Parameter	Symbols	Value
1	Pressure (Pa)	P_a	100 (0.75 Torr)
2	Saturation Temperature (°C)	T_s	-20.27
3	Temp. bet exiting platen & Sublimation (°C)	T_{ic}	-10.13
4	Density of ice (kg/m³)	ρ_{ic}	918.16
5	Rate of Freeze drying (m/s)	R_c	8.123×10^{-7}
6	Sublimation of ice front Temp. (°C)	T_1	-21.67
7	Average temperature (°C)	T_{av}	-10.83
8	Density of mushroom before freezing (kg/m³)	ρ_{ai}	1071.428
9	Initial thickness of mushroom (m)	a	.00643
10	Thickness of freeze dryer layer (m)	*bm*	0.01748
11	Porosity of mushroom	ε	0.220
12	Density of freeze dryer layer of mushroom (kg/m³)	ρ_{ao}	1063.63
13	Amount of heat (j/kg)	λ_{T1}	2.53×10^6
14	Thermal conductivity of ice (w/m°c)	k_c	2.305
15	Thermal conductivity of Mushroom (w/m°c)	k_f	1.1030
16	Duration of freeze drying (s)	θ	3600
17	Over all heat transfer coefficient (w/m² °c)	U	62.68
18	Total Residence Time(s)	t_R	3600
19	Effective Temp. difference (s)	ΔT	20.27
20	Dryer surface Area (m²)	A_D	5.580
21	Batch size' Kg of bone dry solids (kg)	m_B	1
22	Total quantity of moisture removed from solid in Time(kg)	Δ_M	9
23	Over all Temp. difference (°C)	ΔT	70.67
24	Heat transfer (w or kw)	Q	24578.90 W 24.57 kw.

Conclusion

The important conclusions drawn from these results are given below.

- Energy consumption during vacuum freeze drying on working pressure 0.75 TORR or 100 pa and -28 °C temperature for product and residence time of 60 min (3600s) is found to be 24578.90w. Total heat transfer area is 5.580 m², Overall heat transfer coefficient is 62.68 (W/m2 °c)
- The energy losses of five operations, namely freezing, primary drying, secondary drying, vacuum pumping and vapor condensation, were evaluated at various operating parameters. On the basis of the calculation and analyses conducted, the following conclusions can be drawn:
- The energy losses of the system increase with an increase of the chamber pressure over the calculation range used in this study.
- Moisture content was reduced during vacuum freeze drying in all three samples but more moisture was reduced in Segment before boiling (SAB) than Segment after boiling (SAB). The moisture in whole button mushroom without boiling (WMBW) moisture was reduced less as compared to Segment before and after boiling.

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