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OPTIMIZATION OF ENERGY CONSUMPTION IN THE FREEZE DRYING PROCESS OF CHAMPIGNON *(AGARICUS BISPORUS L)*

Paweł Kozak, Dariusz Dziki, Andrzej Krzykowski, Stanisław Rudy

Department of Thermal Technology, University of Life Sciences in Lublin,
Doświadczalna 44, 20-280 Lublin, Poland

Summary. In this paper, the influence of surface load of heating plates and degree of fineness of champignon fruits (*Agaricus bisporus* L) on the energy consumption in the freeze drying process was studied. The experimental researches were carried out for five material load levels of heating plates (6, 8, 10, 12, 14 kgm^{-2}) and at the constant temperature (323K) and pressure of heating plates (63 Pa), after preliminary freezing of raw material to 248K. When the heating load was low (form 6 to 8 kgm^{-2}), the degree of fineness of raw material had no influence on the specific energy requirements needed to heat of plates and to dry the raw material. However, the increase of heating load from 10 to 14 kgm^{-2} resulted in the increase of specific energy inputs with the increasing degrees of fineness.

Key words: freeze drying, energy requirements, champignon fruits**.**

INTRODUCTION

It is common knowledge that the freeze drying process is one of the most expensive methods of food conservation. The total cost of freeze-dried foods production is the sum of costs of equipment, materials, operating and energy consumption [Nastaj 1996]. The optimization of drying time and an increase of effectiveness of energy utilization could lead to a decrease of overall cost of freeze-drying [Millman 1984, 1985, Kumagai 1991, Yunfei 1996, Didukh, Kirchuk 2007, Liapis, Litchfield 1979].

The main costs of freeze-drying are divided as follows: the costs of freezing, ice sublimation and elimination of bound water, generation of hypoatmospheric pressure and condensation of water vapor [Lombrana i in. 1993, Ratti 2001].

The current costs of freeze-drying process are about four times higher than spry-drying and about eight times higher then convective drying. However, when the total energy consumption is taken into consideration, especially the preparation of raw material, these relations fundamentally change (the total coast of freeze-drying is only about 1.3 higher in comparison to convective drying) [Flink 1977, Lorentzen 1980, Benali, Amazouz 2006, Rudy 2009]. A decrease of energy consumption during the freeze-drying could be obtained by changing the conditions of the process – temperature of heating plates and pressure in the drying chamber [Lis 1999a, 1999b, Lis i in. 2001, Depta, Lis 2001, Kozak 2001, Ivanova, Andonov 2001].

MATERIALS AND METHODS

The aim of the work was to evaluate the influence of degree of fineness and the level of champignon load of heating plates on the freeze-drying energy consumption and the freeze-dryer capacity.

The scope of the work included the experimental research, relying on the freeze drying process of suitably prepared raw material samples, the analysis of energy consumption during drying and the statistical analysis of the obtained results.

The material for investigations was arable champignon (*Agaricus bisporus* L). The determination of dry matter in the fresh raw material was carried out according to PN–ISO 1026:2000. The champignons were taken directly after harvesting from mushroom growing cellar (600 kg capacity per 24 hours). The fresh fruits of first and second harvest phases were taken for investigations. Within the two hours after the harvesting, the raw material was washed in cold water, drained off water and selected according to cap diameter (from 25 to 35 mm) and appearance of fruits. The specimens of abnormal shape and exhibited signs of damage were discarded.

The experimental researches were carried out for five material load levels of heating plates (6, 8, 10, 12, 14 kg×m^{-2}). The heating plates were part of working area of freeze-dryer. The degree of fineness was as follows: chips, and cube (side length 4, 6, 8 and 10 mm). The freeze-drying process was carried out at the temperature of heating plates t = 50°C at the pressure in the drying chamber p = 63 Pa.

The champignon fruits were cut in order to obtain adequate degree of fineness (chips about 2 mm thickness). The laboratory food processor was used for mushrooms cutting. The ground samples of mushrooms were taken and formed according to the mass resulted form the level of load of freeze dryer heating plates. The samples were placed on aluminum plates in the freeze chamber. The process of preliminary freezing was monitored by using the thermocouple sensors placed in the geometrical center of samples. The freezing time of the individual samples was measured up to the temperature of -25°C. The freezing time ranged from 4.5 to 9.0 hours according to the thickness of sample layers. The samples were stored in the dryer freezing chamber of dryer with the temperature 25°C during the 48 hours.

The lophylization process of champignon fruits was carried out in properly instrumented freeze-dryer by contact method of heat supply. The diagram of freeze-dryer was presented in Figure 1.

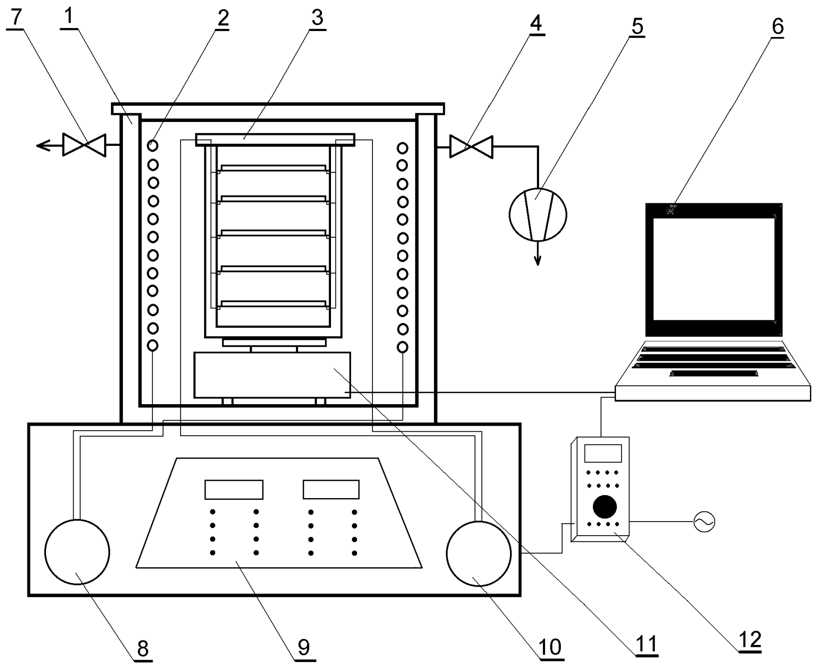

Fig. 1. Lyophilisator ALPHA 1-4: *1- drying chamber, 2- ice condenser, 3- frame with heating plates, 4- electro-magnetic valve, 5- vacuum pump, 6- computer, 7- aeration valve, 8- cooling system of ice condenser, 9- control and measuring system, 10- heating system, 11- tensometric balance, 12- electric meter*

The prepared and frozen samples were placed on the five heating plates with the total surface of 0,157 m^2. The plates' kit was located on the balance frame in the drying chamber of lyophilisator. Three thermocouples were placed inside a frozen sample as follows: close by the surface, in the geometrical center and in the layer adhered to the heating plate. Such distribution of measuring points enabled proper control of drying process and observation of moving sublimation front.

The drying process was started when the plates' kit with drying material was located in the lyophilisator drying chamber and vacuum system was started. The plates heating system was started automatically when the assumed pressure in the drying chamber was attained.

During the drying process the values of material mass and temperature were monitored and recorded with a sampling constant of 60 s. The samples were dried until the moisture content reached about 3% wet basis.

The measurement of the electrical energy supply to particular sub-assemblies of the lyophilisator, was registered as the power distribution during the drying process with a sampling constant of 0.5 s. The measurement was performed using digital M-4660-M millimeter cooperating with DIGISCOP v. 2.05 software which recorded and converted the measuring data.

The total value of energy supply for particular sub-assemblies of the lyophilisator during one cycle of drying was calculated by using the numerical integration method and spreadsheet.

The investigations were replicated five times for each combination of load and degree of fineness. The obtained data was further subjected to a statistical analysis and the consequent evaluations were analyzed for a variance analysis. Statistical tests were evaluated by using the Statistica 6.0 software (StatSoft, Inc., Tulsa, USA). All the statistical tests were carried out at the significance level of $\alpha = 0.05$.

RESULTS, ANALYSIS, AND DISCUSSION

The dry matter content in the fresh fruits of champignons was, on average, 9.7% w.b. The differences between the dry matter content of fruit selected according to the size and obtained from individual batches of first and second harvest phases were negligible (±0,1%). The higher moisture content is characteristic for raw material obtained in the subsequent harvesting phases and for fruits with the cap diameter lower than 25 mm and higher than from 35 mm.

The electric energy inputs on freeze drying process are the sum of energy inputs of all lyophilisator systems necessary for the process realization. Thus the specific electric energy inputs (e) is a sum of energy supply to ice condenser, vacuum and heating system, and automatic with reference to 1 kg of dried raw material.

The two-factor variance analysis was made for the evaluation of the significance of influence of degree of fineness and the load of heating plates on the specific energy inputs. The results showed that degree of fineness had a significant influence on e, however the level of load of heating plates was insignificant (Table 2). An increase of e with the decrease of degree of fineness resulted mainly from the increase of freeze drying time (Fig. 2).

Table 1. The results of variance analysis of degree of fineness and the load of heating plates on the specific energy inputs in the process of freeze drying of champignon

Variance source	SS	df	MS	F	p-value	F
Degree of fineness	7767,7	4	1941,9	4048,6	$1,3\times10^{-109}$	2,462613
Load	2,2171	4	0,5543	1,1556	0,33508	2,462613
Interaction	5,9307	16	0,3707	0,7728	0,71214	1,745647

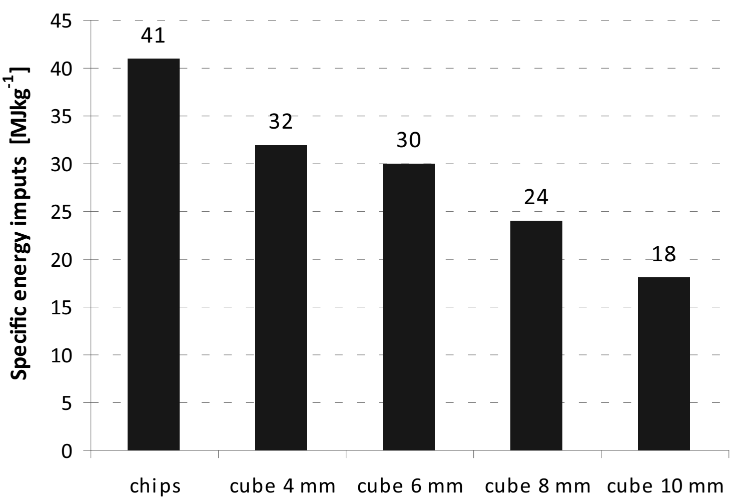

Fig. 2. The relation between the degree of fineness of champignon and the specific energy inputs in the process of freeze drying

The obtained average values of specific energy inputs can be useful only for proportional comparison between the energy consumption during the processes carried out in the given lyophilisator and in the changeable conditions of load of heating plates. Thus it can be concluded that the absolute values of specific energy inputs obtained in the laboratory-scale could not be comparable with the specific energy inputs obtained in the industrial conditions. However, the results showed that as the degree of fineness of champignons increases the energy consumption of freeze drying process increases, too. This tendency was also observed by other researches during the freeze-drying process of vegetables [Adams 1991, Genina et al 1996].

The measurements of the amount of energy supplied to the individual lyophilisator subassemblies showed that only the amount of energy supplied to the heating plates significantly depends on the analysed variables, such as the degree of fineness, load of heating plates and interactions between them. This energy is used for water phase change – at the beginning for ice sublimation and then vacuum evaporation. This was confirmed by the two-factor variance analysis (Table 2). The amount of electrical energy supplied for the other lyophilisator subassemblies resulted only from the running time.

Table 2. The results of variance analysis of degree of fineness and the load of heating plates on the specific energy inputs supplied to the heating plates of lyophilisator during the freeze drying process of champignon

Source of variance	SS	df	MS	F	p-value	F
Degree of fineness	6,0407	4	1,5102	5,5898	0,000421	2,462613
Load	58,694	4	14,673	54,313	3×10^{-24}	2,462613
Interaction	25,5362	16	1,596	5,9075	$7,02\times10^{-9}$	1,745647

The results and analysis of energy used for heating of drying material (the energy supplied to heating plates) have proved that an increase of degree of fineness caused an increase of energy requirements of heating plates relatively to the unit of mass of dried material.

On the basis of the numerical data presented in Table 2 it can be stated that the decrease of specific energy inputs supplied to the heating plates of lyophilisator resulted in 82.5% form variation of plates load (range of load 6-14 kgm^{-2}), in 8.5% from degree of fineness, and in 9% form the interactions of these two variables.

The variation of electric energy requirements used for the heating of lyophilisator plates was shown in Figure 3.

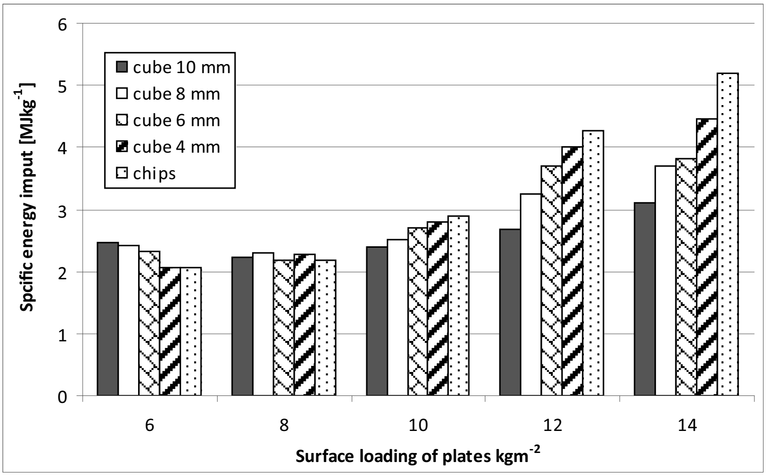

Fig. 3. The relation of specific energy input into surface loading of heating plates of lyophilisator to heating load and degree of fineness

The result showed that the degree of fineness of champignons has a negligible influence on specific energy inputs supplied into the lyophilisator when the heating load is 6 and 8 kg×m^{-2}. An increase of heating load of plates resulted in an increase of specific energy inputs with the increase of degrees of fineness.

CONCLUSIONS

On the basis of the obtained results the following conclusions can be formulated:

1. When the heating load was low (form 6 to 8 kgm^{-2}), the degree of fineness of champignons had no influence on the specific energy inputs needed to heat the plates and to dry the material. The increase of heating load from 10 to 14 kgm^{-2} resulted in the increase of specific energy inputs with increasing degrees of fineness.
2. When the heating load of lyophilisator was 6-8 kgm^{-2}, the lower energy consumption for heating of drying material and for water phase change was observed. The increase of the load form 8 to 14 kgm^{-2} caused the increase of electric energy used for heating by approximately two times.
3. The theoretical energy requirements for water phase change in the raw material and at the drying chamber conditions are higher than the ones obtained during the experimental studies, and for the heating load below 8 kgm^{-2}. The real amount of supplied energy to the plates ranged from 2.1 to 2.4 MJkg^{-1} in the range of load from 6 to 8 kgm^{-2}.
4. The significant increase of energy requirements for water phase change is caused by the increase of heating plates load above 10 kgm^{-2} and the increase of the degree of fineness of raw material.

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OPTYMALIZACJA NAKŁADÓW ENERGETYCZNYCH W PROCESIE SUBLIMACYJNEGO SUSZENIA OWOCNIKÓW PIECZARKI (*AGARICUS BISPORUS* L)

Streszczenie. Zbadano wpływ obciążenia powierzchni płyt grzejnych i stopnia rozdrobnienia owocników pieczarki *Agaricus bisporus* na energochłonność procesu sublimacyjnego suszenia. Badano wpływ warunków procesu sublimacyjnego suszenia na energochłonność procesu. Badania przeprowadzono dla pięciu ustalonych poziomów obciążenia płyt grzejnych surowcem (6, 8, 10, 12, 14 $kg \cdot m^{-2}$) i stałe temperatury płyt grzejnych (323 K) i ciśnienia (63Pa) po wstępnym zamrożeniu materiału do temperatury 248K. Kiedy obciążenie płyt grzejnych było niskie (od 6 do 8 kgm^{-2}) stopień rozdrobnienia materiału nie miał wpływu na nakłady energii potrzebne do ogrzania płyt grzejnych. Jednakże wzrost stopnia obciążenia z 10 to 14 kgm^{-2} powodował zwiększenie nakładów energii wraz ze wzrostem stopnia rozdrobnienia.

Słowa kluczowe: suszenie sublimacyjne, energochłonność procesu , owocniki pieczarki.