TEKA Kom. Mot. Energ. Roln. – OL PAN, 2009, 9, 259–266

ENERGY CONSUMPTION IN THE FREEZE - AND CONVECTION-DRYING OF GARLIC

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Summary. This study reveals the results obtained from an analysis of the impact exerted by the temperature of the lyophilisator plates (at temperatures of 20, 30, 40, 50, and 60ºC), as well as by the temperature (at 40, 50, 60, and 70ºC) and flow velocity of the drying air (0.3 and 1 m/s), on the unit energy consumption in freeze- and convection-drying, and on the aggregate energy consumption in these processes, for the independent variables under analysis. An increase in the hot plate temperature in the range of 20-70ºC triggers a decrease in the total energy expenditure of nearly 49%, whereas an increase in the drying air temperature from 40ºC to 70ºC allows for the energy consumption in the convection drying process to be lowered by 17% at 1 m/s, and by 13% at 0.3 m/s.

Key words: energy consumption, freeze drying, air drying, garlic.

NOMENCLATURE:

e - energy input [$MJ \cdot h^{-1} \cdot kg^{-1}$],
E - total energy input [$MJ \cdot kg^{-1}$],
t - drying time [h],
T - temperature [ºC].

INTRODUCTION

The amount of energy necessary to eliminate water from the material dried in both processes, i.e. in convection- and freeze-drying, usually accounts for 50% of the total energy expenditure connected with the drying process [Ratti 2001, Koyuncu et al. 2004, 2007]. The fixed energy costs result from the necessity of supporting the work of particular dryer sub-assemblies, as well as from external energy losses [Lis et al. 2003]. Usually, these costs do not depend on the conditions in which the drying process is conducted, but are merely contingent on the drying time [Kribs et al. 1999, Ivanova et al.2001, Krulis et al.2005, Sharma et al. 2006]. Due to the process-specific mechanisms, freeze drying is viewed as one of the most energy-consuming food preservation methods. The energy expenditure on freeze drying is several times higher, compared with convection drying

[Flink, 1977, Lorentzen 1980, Kumagai et al. 1991]. However, the overall analysis of the costs related to these two processes, as well as the considerably higher quality of dried garlic, point in favour of freeze drying [Adams 1991, Depata et al. 2001, Benali et al. 2006].

MATERIAL AND METHODS

The aim of this study was to analyse the impact exerted by the temperature and flow velocity of the drying air in the convection dryer, as well as by the temperature of the lyophilisator plates, on the energy consumption connected with the processes of the convection- and freeze-drying of garlic.

An analysis of the convection drying process was performed for two drying flow velocities, namely 0.3 and 1 m/s, at a temperature of 40, 50, 60, and 70ºC. The independent variables adopted in the process of the freeze drying of garlic comprised the lyophilisator plate temperature, at 20, 30, 40, 50, and 60ºC, with a constant pressure in the drying chamber of 63 Pa. The analysis focused on the spring *Jarus* garlic. Before being dried, the material was cut into 0.5 cm thick slices. The freeze- and convection-drying processes were carried out until a constant humidity of 12% was achieved. Both the freeze dryer and the convection dryer's load equalled 12 kg/m^2. The energy expenditure on the drying process was calculated at hourly intervals, and the costs of pre-freezing, which account for nearly 4% of the total costs of the freeze drying process, were not taken into consideration [Ratti 2001, Mujumdar 2007].

The convection drying of garlic was conducted using a vertical air-flow dryer. The heating assembly of the dryer consisted of three heating elements and, more specifically, of heaters in chamotte casings, with a total strength of 6.9 kW. One of these heaters was incorporated into the circulation system of the temperature regulator. The axial ventilator, powered by an electric engine with a multi-stage regulation of rotation, ensured the proper air flow.

The freeze drying process was conducted using the ALPHA 1-4 lyophilisator (Fig. 1). This is an integrated plant consisting of a drying chamber (1), cooling (8) and heating (10) systems, as well as a control and measuring system with an interface (9). The drying chamber allows for the process to be conducted using one or several (up to a maximum of 5) hot plates. The components of the vacuum system are a single-phase engine with 160 W of power, and a rotary vacuum pump (5) connected to the drying chamber by a flexible pipe, through an electro-magnetic valve (4). The opening and closing of the valve is controlled by the motion control of the lyophilisator, depending on the pressure in the drying chamber, and measured using a Pirani sensor. The freeze-out system consists of a spiral evaporator (ice condensator) (2), located outside of the drying chamber. Other elements of the cooling system are integrated within the plant. The work of the cooling system is regulated automatically, hence the temperature in the ice condensator cannot be regulated separately (and it usually equals -55ºC). The heating system consists of five hot plates (3) located on the support stand. The heat required for the phase transition is supplied to the material by direct contact. Both the measurement and the regulation of the hot plate temperature are conducted using the temperature sensor located inside one of the lyophilisator plates.

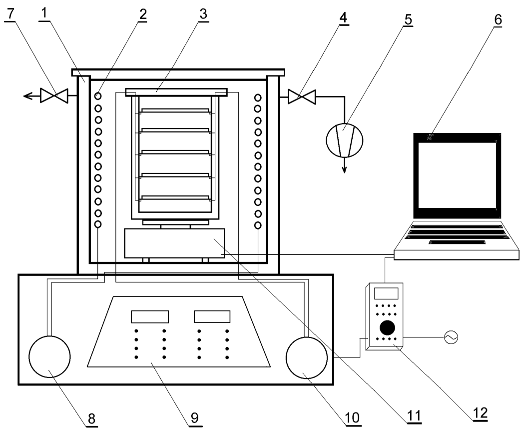

Fig. 1. Lyophilisator ALPHA 1-4: *1- drying chamber, 2- ice condensator, 3- hot plates, 4- electro-magnetic valve, 5- vacuum pump, 6- computer, 7- aeration valve, 8- cooling system, 9- control and measuring system, 10- heating system, 11- balance, 12 digital multimetre M-4660-M*

The measurement of the electrical energy distributed to particular sub-assemblies of the convection dryer, as well as to the lyophilisator, was registered as the total value of the power distributed during the drying process with a sampling constant of 0.5 s. The measurement was performed using digital M-4660-M (12) multimetre with DIGISCOP v. 2.05 software, ensuring compatibility with the computer. For each hour of the experiment the energy inputs (e) related to the mass of the processed material were established, and expressed in MJ/kgh units. It was done using the numerical integration method, based on the experimental data. The total energy distributed to the convection and freeze dryers, E (MJ/kg) constituted the sum of energy inputs during the whole period.

RESULTS, ANALYSIS, AND DISCUSSION

The average amount of electrical energy consumed at hourly intervals in the freeze drying process was determined using linear regression equations. The experimental data are compiled in Fig. 2, while the circumscriptive approximating functions are provided in Table 1.

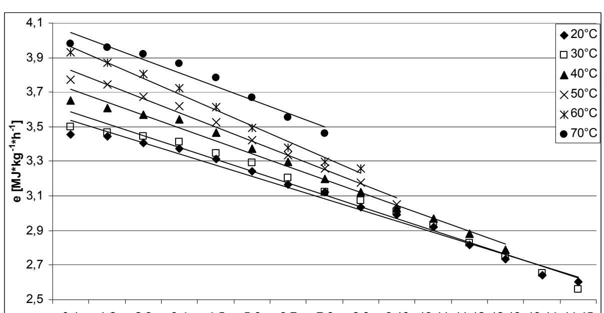

Fig. 2. The energy inputs involved in the freeze drying process

Tab. 1. Regression equation- the change of energy input in the freeze drying process

T [ºC]	Regression equation	R^2	Statistical error
20	e = -0,065·t + 3,6035	0,983	0,0389
30	e = -0,0686·t + 3,6547	0,981	0,03898
40	e = -0,0748·t + 3,7931	0,987	0,03385
50	e = -0,0817·t + 3,907	0,987	0,02995
60	e = -0,0913·t + 4,0533	0,988	0,02887
70	e = -0,0774·t + 4,1208	0,951	0,04641

At all the analysed levels of the hot plates' temperature, the amount of energy consumed in freeze drying decreased with the lengthening of the process duration. This is likely to result from the fact that ice sublimation is more rapid at the beginning of the drying process than at the end. For a given duration range for the freeze drying process, an increase in the hot plates' temperature in the range of 20-70ºC automatically increased the unit energy consumption. The highest energy consumption was observed in the first hour of drying at a hot plate temperature of 70ºC – nearly 3.98 MJ/kg, while the lowest amounted to 2.56 MJ/kg in the 14^{th} hour of drying at the temperature of 20ºC.

The average unit energy consumption values at the subsequent stages of convection drying (0.3 m/s, 1 m/s) are compiled in Figs. 3 and 4. The data obtained at each of the individual level of temperatures were described using linear regression equations which decreased in the convection drying time function. The regression equations are compiled in Tables 2 and 3, respectively.

Tab. 2. Regression equation- the change of energy input in the air drying process (0,3 m/s)

T [ºC]	Regression equation	R^2	Statistical error
40	e = -0,02802·t + 1,9664	0,974	0,0187
50	e = -0,06357·t + 2,5463	0,969	0,0365
60	e = -0,10766·t + 2,9608	0,997	0,0166
70	e = -0,1745·t + 3,4894	0,997	0,0229

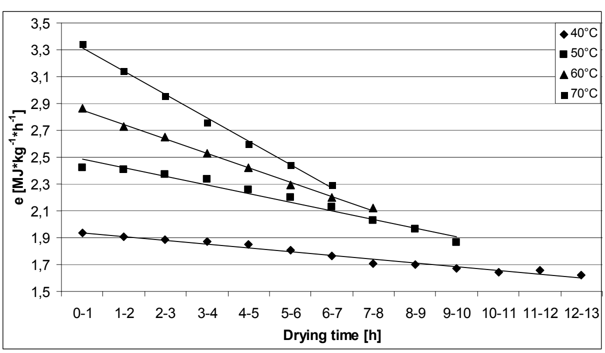

Fig. 3. The energy inputs involved in the air drying process (0,3 m/s)

In the entire measurement range, an increase in the drying air temperature from 40ºC to 70ºC for both flow velocity values automatically increases the unit energy expenditure. An increase in temperature from 40ºC to 70ºC in the first hour of the process duration (0.3 m/s) results in an automatic increase in the energy expenditure by nearly 1.4 MJ/kg. These differences are reduced in subsequent time ranges. Similar changes were also observed for the flow velocity of 1 m/s.

Tab. 3. Regression equation- the change of energy input in the air drying process (1 m/s)

T [ºC]	Regression equation	R^2	Statistical error
40	$e = -0{,}1475 \cdot t + 3{,}546$	0,973	0,0783
50	$e = -0{,}2019 \cdot t + 4{,}0349$	0,997	0,0284
60	$e = -0{,}2099 \cdot t + 4{,}2334$	0,992	0,0428
70	$e = -0{,}3101 \cdot t + 4{,}8527$	0,981	0,0907

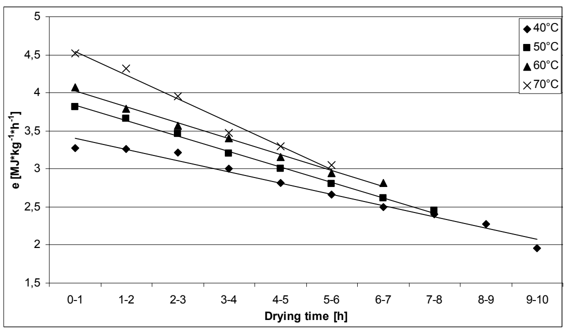

Fig. 4. The energy inputs involved in the air drying process (1 m/s)

An increase in the drying air flow velocity from 0.3 m/s to 1 m/s at a given temperature level contributes to an increase in the unit energy expenditure in the drying process. With an increase in the air flow velocity from 0.3 to 1 m/s, the electrical energy consumption in the first hour of drying grows by nearly 1.2-1.4. MJ/kg. At the end of the drying process these differences amount to nearly 0.4-0.6 MJ/kg.

The higher temperature of both the hot plates and the drying air results in a considerable shortening of the freeze- and convection-drying processes. Therefore, the total energy expenditure, necessary to dry 1 kg of garlic, decreases with an increase in temperature.

The one-factor variance analysis was conducted to determine the extent of the impact exerted by the hot plate temperature on the aggregate energy consumption in the freeze drying process. The obtained results are compiled in Table 4. The average energy consumption values depending on the hot plate temperature are shown in Fig. 5.

Tab. 4. The results of the analysis on the significance of temperature on energy inputs involved in the freeze drying process

	SS	*df*	*MS*	*F*	*p*	*Test F*
Temperature	1029,12	1	1029,12	5,366593	0,024079	4,006873

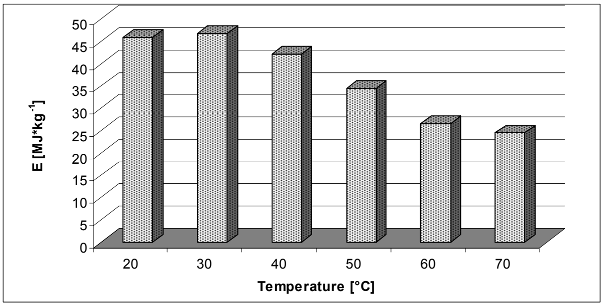

Fig. 5. Total energy inputs in the freeze drying process

The hot plate temperature has a significant impact (at a significance level of α 0.05) on the aggregate energy consumption in the freeze drying process.

The average energy consumption, necessary to dry 1 kg of garlic, was the highest at the temperature of 30ºC, reaching 46.7 MJ/kg. It was discovered that the higher the hot plate temperature, the lower the energy consumption, which reached its lowest value of -24.4 MJ/kg at 70ºC.

The two-factor variance analysis was conducted to determine the extent of the impact exerted by both the temperature and flow velocity of the drying factor on aggregate energy consumption in the freeze drying process. The obtained results are compiled in Table 4. The average energy consumption values are shown in Fig. 6.

Tab. 5. The results of the analysis on the significance of temperature on energy inputs involved in the air drying process

	SS	*df*	*MS*	*F*	*p*	*Test F*
Temp.	88,8	3	29,595	301,696	1,55E-23	2,90112
Pressure	132,9	1	132,917	1354,96	9,12E-28	4,149097
Interaction	4,169	3	1,3897	14,166	4,78E-06	2,90112

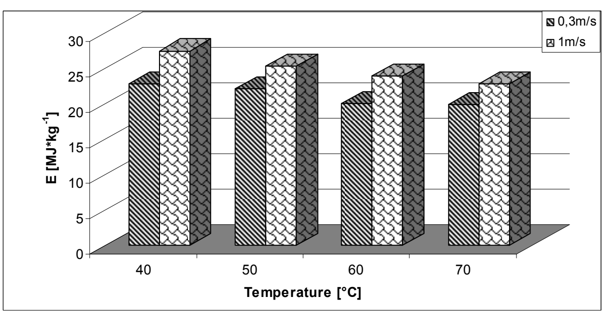

Fig.6. Total energy inputs on the air drying process

The air temperature and its flow velocity proved to have a significant impact on the aggregate energy consumption in the convection drying process. The decline in energy consumption for both the analysed flow velocity values was observed with an increase in the drying air temperature. At all the analysed temperature levels, the energy expenditure necessary to obtain the dried garlic was lower for a flow velocity of 0.3 m/s. The lowest average energy consumption of nearly 19.8 MJ/kg was obtained at the temperature of 70ºC for the flow velocity of 0.3 m/s. The drying process conducted at the temperature of 40ºC and at the flow velocity of 1 m/s proved to be the most energy-consuming of all the analyzed options.

The following figure compares the energy consumption in the convection- and freeze-drying processes. The dried garlic obtained in the freeze drying process (at the temperature of 40ºC) required an energy expenditure twice as high as convection drying. These differences diminished the higher the temperature was, and, eventually, the difference in terms of energy consumption between freeze drying and convection drying at 70ºC declined to nearly 4.6 MJ/kg.

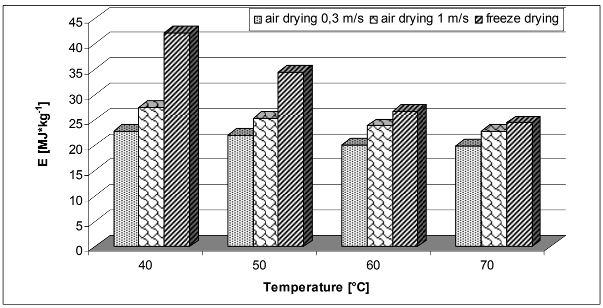

Fig. 7. Comparison of total energy input on the freeze and air drying

CONCLUSIONS

Based on the conducted analyses, we can draw the following conclusions:

1. The unit energy expenditure in the freeze- and convection-drying process decrease linearly, the longer the process duration, and are included within the scope of: 2,5-4,1 MJ·h^{-1}·kg^{-1}- freeze drying and 1,6-4,5 MJ·h^{-1}·kg^{-1}- convective drying.
2. The hot plate temperature, as well as the temperature and the flow velocity of the drying air, exert a significant impact (at a significance level of α 0.05) on the aggregate energy consumption connected with the process.
3. An increase in the hot plate temperature in the range of 20-70ºC triggers a decrease in the total energy expenditure of nearly 49%, whereas an increase in the drying air temperature from 40ºC to 70ºC allows for the energy consumption in the convection drying process to be lowered by 17% at 1 m/s, and by 13% at 0.3 m/s.
1. The dried garlic obtained at the temperature of 70ºC with the drying air flow velocity of 0.3 m/s was marked by the lowest aggregate energy consumption of 19.8 MJ/kg.

REFERENCES

Adams G.D.J.: "Freeze-drying of biological materials", Drying Technology, 9(4), 1991, pp. 891-925.

Benali M., Amazouz M.: "Drying of vegetable starch solutions on inert particles: Quality and energy aspects", Journal of Food Engineering, Volume 74, 2006, pp. 484-489.

Depta M., Lis T.: "Wpływ sposobu suszenia czosnku na jednostkowe zużycie energii i wskaźniki jakości suszu", Inżynieria Rolnicza, nr 2, 2001, pp. 25-29.

Flink J.: "Energy analysis id dehydration processes". Food Technology, Volume 31, 1977, pp. 77-84.

Ivanova, D.; Andonov, K.: "Analytical and experimental study of combined fruit and vegetable dryer". Energy Conversion and Management, Volume: 42, Issue: 8, May, 2001, pp. 975-983

Koyuncu, T.; Pinar, Y.; Lule, F.: "Convective drying characteristics of azarole red (Crataegus monogyna Jacq.) and yellow (Crataegus aronia Bosc.) fruits", Journal of Food Engineering, Volume: 78, Issue: 4, February, 2007, pp. 1471-1475.

Koyuncu, T.; Serdar, U.; Tosun, I.: "Drying characteristics and energy requirement for dehydration of chestnuts (Castanea sativa Mill.)", Journal of Food Engineering, Volume: 62, Issue: 2, April, 2004, pp. 165-168.

Kribs, J. D.; Spolek, G. A.: "Drying Energy Conservation for Deep-Bed Barley-Malt Kilns", Journal of Agricultural Engineering Research, Volume: 68, Issue: 4, December, 1997, pp. 367-373.

Krulis, M.; Kühnert, S.; Leiker, M.; Rohm, H.: "Influence of energy input and initial moisture on physical properties of microwave-vacuum dried strawberries", European Food Research and Technology, Volume: 221, Issue: 6, November 2005, pp. 803 – 808.

Kumagai H., Nakamura K., Toshimasa Y.: "Rate analysis of the freeze-drying of liquid food by a modified uniformly retreation ice front model", Agric. Bilo. Chem., Volume 55(3), 1991, pp. 737-742.

Lis M. M, Lis H. Kropornicki W.: "Zapotrzebowanie i koszt energii w suszarce przemysłowej przy ciągłym oraz przerywanym cyklu suszenia", Inżynieria Rolnicza, nr 8(50), 2003, pp. 263-270.

Lis M.M., Lis H.: "Zużycie oraz koszt energii elektrycznej i cieplnej suszenia owoców w suszarce Leśniczanka, w zależności od nośnika energii", Inżynieria Rolnicza, nr 10(52), 2003, pp. 83-91.

Lorentzen J.: "Nowe metody suszenia i zagęszczania żywności, Materiały Sympozjum zorganizowanego przez JUFoST. Nowe kierunki rozwoju liofilizacji". WNT, Warszawa 1980.

Mujumdar, A. S.: "An overview of innovation in industrial drying: current status and R&D needs", Transport in Porous Media Volume, 66, Issue: 1-2, January 2007, pp. 3 – 18.

Ratti C.: "Hot air and freeze-drying of high value foods: a review", Journal of Food Engineering, Volume 49, 2001, pp. 311-319.

Sharma, G.P.; Prasad, S.: "Specific energy consumption in microwave drying of garlic cloves", Energy, Volume: 31, Issue: 12, September, 2006, pp. 1921-1926.

ENERGOCHŁONNOŚĆ SUBLIMACYJNEGO I KONWEKCYJNEGO SUSZENIA CZOSNKU

Streszczenie. W pracy przedstawiono wyniki badań dotyczące wpływu temperatury płyt liofilizatora (w zakresie 20, 30, 40, 50 i 60ºC) oraz temperatury (40, 50, 60, 70ºC) i szybkości przepływu powietrza suszącego (0,3 i 1 m/s) na jednostkowe zużycie energii w czasie trwania suszenia sublimacyjnego i konwekcyjnego suszenia oraz sumaryczną energochłonność procesu. Wzrost temperatury płyt grzejnych, w zakresie 20-70ºC powoduje zmniejszenie całkowitych nakładów energetycznych o około 49%, natomiast wzrost temperatury powietrza suszącego od 40ºC do 70ºC pozwala na zmniejszenie energochłonności procesu konwekcyjnego suszenia o 17% - 1m/s i 13% - 0,3m/s.

Słowa kluczowe: energochłonność procesu, suszenie sublimacyjne, suszenie konwekcyjne, czosnek.