Experimental researches of atmospheric sublimation drying and analysis of economic efficiency its applications

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Abstract. This article presents the results of experimental studies and economic analysis in the field of atmospheric freeze drying (AFD), analyzes the features of the processes of sublimation of polydisperse materials of animal and vegetable origin. Using the results of this work will reduce energy intensity and increase the efficiency of sublimation technologies in industrial production. An economic analysis of the feasibility of atmospheric freeze-drying technology is carried out according to discounted indicators. The values of the terms of the project implementation are obtained and practical recommendations on the modes and parameters of drying are given.

1. Introduction

Improving the quality of products is a strategic task for both individual companies and many countries. The final result of production activities, for example, agricultural enterprises is the volume of food products of plant and animal origin. But to ensure the development of agriculture in market conditions only due to the growth of production volumes is impossible, since this indicator does not reflect the quality and competitiveness of manufactured goods. Improving the heat-technological installations of the production cycle is one of the main priority measures aimed at improving the competitiveness of products and the development of agricultural producers.

In recent years, there has been a tendency to the spread of vacuum-type freeze-drying ovens in many industries where quality control management standards are in place at all stages of food promotion to the consumer - from the production of raw materials, their processing, transportation, storage to sale to the public in the form of a finished product [1].

The use of harmonized standards contributes to improving the quality of agricultural materials and, as a result, increasing its competitiveness. Already, it can be stated that since the adoption of harmonized GOSTs in 2001, agricultural producers have gained some experience in the production of raw materials that meet the requirements of the standards of the EU member states. Maintaining high biological properties of products of plant and animal origin throughout the year is impossible without special equipment [2].
2. Freeze-drying of polydisperse materials

One of the most effective and promising methods of heat treatment of polydisperse materials is freeze-drying, which allows to obtain a high-quality product, convenient for storage and transportation [3], [4]. Freeze-drying is a progressive technology, in some cases without an alternative. This is one of the highest priorities in various industries. Such drying allows you to dry a large number of polydisperse materials to a given moisture content, and at the same time, maintains the maximum amount of nutrients in the dried product [5].

Technological sublimation lines are needed in many industries. They include the agro-industrial complex: processing fruit and vegetable products, meat plants, dairies, fish factories, preserving seed stocks, drying biologically valuable wastes from distilleries, use in biotechnological processes, in the pharmaceutical industry, in metallurgy, in the chemical industry, military, defense and space industries. In many industries, it is preferable to use the technology of sublimation dehydration when producing powder materials [6].

For example, the procedure for obtaining natural dyes consists of several main stages: extraction, filtration, concentration and lyophilization. Freeze-drying is one of the methods that allows you to get a good quality product from whole or partial plants, including without the addition of color stabilizers. Some interesting future methods may involve the use of industrial waste, fruit peels or petals of various colors in the production of natural pigments. The freeze-drying technique may be ideal for functional supplements that combine several functions (color, fiber, minerals and vitamins). The determination of the antiseptic properties of natural dyes obtained by freeze-drying is also valuable [7].

Also, in an article [8], an experiment was conducted on the example of persimmons of the Rojo Brillante variety by sorption of water and glass transition of sublimated slices.

A known method of pre-treatment in freeze-thaw cycles before vacuum lyophilization of garlic slices in order to improve the drying process and the quality of the final product. The results of the study [9] showed that pre-treatment reduced drying time (22.22–33.33%) and energy consumption (14.25–15.50%) due to water loss, an increase in the amount of free water and the formation of porous structures. Pre-treatment has improved thermostability, taste and chemical composition of dry foods. The antioxidant activity of polysaccharides extracted from pretreated dried products was higher than that of the untreated dried product due to a decrease in the molecular weight of the polysaccharide [9].

The advantages of sublimation processes include: a relatively high equilibrium separation coefficient; the possibility in the case of using gas mixtures to eliminate the evaporation of solvents (in contrast to absorption and rectification); lower operating temperature (than during distillation); the ability to receive the target products immediately in the commodity form [10].

Freeze drying occurs under conditions of phase transition over the entire temperature and pressure range at which solid and gaseous phases exist [11-12]. The ice goes into a gaseous state, bypassing the liquid phase until the vapor concentration reaches its maximum value at a given temperature [13-15].

3. Dehydration of products by sublimation at atmospheric pressure

To study the process of freeze-drying at atmospheric pressure and to study the thermophysical properties of wet materials by cooling, freezing, sublimation and drying, an installation was created in National Research University «Moscow Power Engineering Institute» at the Department of Heat-and-Mass Exchange Processes and Installations (Figure 1).
The technological process consists of: product preparation, freezing, freeze-drying, short-term removal of the remaining moisture in a thermo-radiation drying chamber, product packaging for subsequent long-term storage [16].

The products prepared for drying are shown in Figure 2.

The results of freeze-drying at atmospheric pressure of polydisperse materials are presented in Figure 3: pork loin (experiment 1 and 2), banana (experiment 3 and 4), seeds of Veronica Spicata (experiment 5 and 6) [17].

Figure 3 shows the results of the experiment.
Figure 4. Comparison of experimental results (humidity and costs)

Since freeze-drying and infrared drying chambers consume electrical energy for operation, the energy consumption for the entire drying period of the samples was determined to calculate the total energy consumption for moisture removal. The energy efficiency of the dehydration process is closely monitored by specialists, as is shown by the results of a study of drying cranberry juice using osmotic distillation (OD) in combination with lyophilization [18].

Figure 4 shows the results of the calculation of energy costs. Table 1 presents the unit cost of moisture removal.

Table 1. Calculation of the specific cost of moisture evaporation of all experiments.

| № measurement | The mass of evaporated moisture (kg) | The specific cost of evaporation of 1 kg of moisture (kJ / kg) |
|---------------|------------------------------------|----------------------------------------------------------|
| 1             | 0.059                              | 79.3                                                     |
| 2             | 0.067                              | 85.9                                                     |
| 3             | 0.104                              | 92.4                                                     |
| 4             | 0.101                              | 130.7                                                    |
| 5             | 0.096                              | 105.2                                                    |
| 6             | 0.096                              | 111.7                                                    |

According to the data obtained during the calculation, it can be seen that drying, carried out with the parameters of experiment No. 1, is the most effective for protein production, since the final humidity, as well as energy consumption for moisture removal, are the most optimal. For plant - the parameters of experiment No. 3 are applicable. However, for drying seeds, the parameters of experiment No. 5 should be used. The values of the relative error for each experiment does not exceed 10%, therefore, we can talk about the permissible accuracy of the experiment.
4. Economic analysis to assess risks in the implementation of the installation on the market for technical products

The discount rate (E) is the main economic standard used in assessing the effectiveness of an investment project. Based on the fact that we evaluate the commercial effectiveness of the project, we will use the commercial discount rate.

The project is aimed at introducing new products to the consumer market and is commercial in nature, therefore, the project will be implemented for 20 years, which is equivalent to the service life of the main equipment (atmospheric freeze-drying oven), in other words, the project implementation period, in this case, is determined by the regulatory period AFD services. After this, it is assumed that the AFD installation will come to a non-working state and it will need to be replaced. Reference point - investment of cash investments, i.e. money transfer to the manufacturer. A catastrophic condition for the termination of the project will be a breakdown of the AFD installation or freezer, premature production of a working resource. The investment project step is one year.

Let us determine the discount rate based on the estimated value of the risk premium depending on the type of risk: 1) since it is necessary to conduct R&D for less than 1 year, the risk premium will increase by 6%; 2) the project itself uses new, requiring the use of resources available on the free technology market, so the increase in risk premium will be 3%; 4) the project has little certainty in the volume of demand and prices, so the increase in risk premium will be 3%; 5) the volume of demand for products does not change depending on the season, so the increase in risk premium will be 0%; 6) the external environment during the implementation of the project (mining, geological, climatic and other environmental conditions, the aggressiveness of the external environment, etc.) has a negligible impact on risk, so the increase in risk premium will be 2%.

Taking into account all the above, we can conclude that the project carries a high risk (14%).

The refinancing rate (r) is 5.50%, the inflation rate (j) is 4%. Then the discount rate according to equation (1) without risk adjustment will be 1.4%.

\[ E_0 = [(1 + r/100)/(1 + j/100)]^{-1} \]  (1)

Since we are going to release a relatively new product, the correction amount will be 14%. Then, the discount rate will be \( E = 15.4\% \).

The calculation of net income taking into account the time factor is presented in table 2.
Table 2. Evaluation of the economic efficiency of the project for the production of freeze-dried meat products

| Step (year) | 0 | 1 | … | 20 |
|-------------|---|---|---|----|
| Step duration, months | 12 | 12 | … | 12 |
| Capital costs (K), thousand rubles | 1155 | 0 | … | 0 |
| Revenue (R), thousand rubles | 0 | 960 | … | 960 |
| Current costs (3rek), thousand rubles | 0 | 667 | … | 667 |
| Profit before tax (P-3rek), thousand rubles | 0 | 293 | … | 293 |
| Profit tax | 0 | 58.60 | … | 58.60 |
| Net profit | 0 | 234.40 | … | 234.40 |
| Cash flow (P-(3rek+K)), thousand rubles | -1155 | 234.40 | … | 234.40 |
| 1+E | 1.154 | 1.15 | … | 1.15 |
| α = 1/(1 + E)^t | 1 | 0.87 | … | 0.06 |
| Discounted cash flow, thousand rubles | -1155 | 203.04 | … | 13.26 |
| Discounted cash flow on an accrual basis, thousand rubles | -1155 | -951.96 | … | 277 |

Assessment results: 1) according to the data of table 1 NPV = 277 thousand rubles; 2) we calculate the discounted return on investment index (ARR) according to equation 2 [19].

\[ ARR = \frac{1}{K} \sum_{t=0}^{T} \left( P_t - 3_{\text{rek}}^t \right) \left/ \left(1 + E\right)^t \right. \]

(2)

As a result, ARR > 1.

We calculate the internal rate of return or profitability (GNI) according to equation 3.

\[ \sum_{t=0}^{T} \left( \frac{P_t - 3_{\text{rek}}^t}{(1+E)^t} \right) = \sum_{t=0}^{T} \frac{k_t}{(1+E_{IRR})^t} \]

(3)

Then, the internal rate of return for this project will be 19.7%.

The payback period is determined (Figure 5) by sequentially summing up the net profit for the years of the billing period, until the amount received is equal to the amount of capital investment.

Figure 5. Discounted payback period for AFD meat products

Thus, the payback period for pork loin is 9 years and 11 months, and for Veronica Spicata seeds - 7 years and 6 months.
5. Conclusions

It was found that drying protein products with experiment parameters No. 1 to a moisture content of 20.1%, followed by processing in an infrared drying unit up to 14%, is less expensive electricity and therefore gives a better result. In this case, the energy consumption is 12.28 kWh (79.32 kJ / kg counting by evaporated moisture), the time for removing moisture is 16 hours 15 minutes. This combination allows significantly reduce energy consumption and improve process efficiency. Drying plant products with the parameters of experiment No. 3 to a moisture content of 11.2%, followed by processing in an infrared drying plant up to 7.9%, requires less energy under comparable conditions, increasing the efficiency of the process compared to experiment No. 4. In this case, the energy consumption is 25.26 kW ∙ h (92.36 kJ / kg based on evaporated moisture), the time for moisture removal is 48 hours 28 minutes.

The use of atmospheric freeze-drying is extremely profitable in the Far North. In most regions of our country, the average daily temperature is negative for seven months of the year. Based on this, it is possible to use natural cold for the process, which minimizes the consumption of electrical energy.

During the economic analysis, the net present value was obtained (for meat products - 277 thousand rubles, for seeds – 488.13 thousand rubles), the discounted profitability index (for meat products – 1.24, for seeds – 1.42), the discounted payback period (for meat products - 9 years and 11 months, for seeds - 7 years and 6 months), the internal rate of return (for meat products – 19.7%, for seeds – 22.9%).

According to the results of an experimental study of the parameters of an atmospheric freeze-drying unit during dehydration of animal and vegetable products, it can be concluded that the project on the use of an atmospheric freeze-drying dryer for processing raw materials of plant and animal origin is economically feasible and recommended for practical implementation.

Analyzing the technical and economic indicators, the following recommendations can be made: 1) the use of AFD for the production of sublimated products is a costly but acceptable project, since it has good performance indicators; 2) the project is applicable for industrial production of products; the higher the output, the higher the performance indicators. Atmospheric freeze-drying is a modern and progressive direction in the development of dehydration methods. Using this technology allows you to save the organoleptic properties of the products, almost unchanged chemical composition, useful substances. An important role is played by the use of sublimation to increase the germination of plant seeds.

An analysis of the commercial viability of the design of an atmospheric freeze-drying oven for the production of plant and animal products has confirmed the feasibility of implementing such a technique in the segment of heating technology equipment.

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