 ISSN 2074-9414 (Print)
ISSN 2313-1748 (Online)

https://doi.org/10.21603/2074-9414-2021-2-395-401
Original article
Available online at http://fptt.ru/eng

Multi-Stage Method of Milk Powder Production: Energy Costs Analysis

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Received: December 08, 2020 *Accepted: January 15, 2021*

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Abstract.
Introduction. One of the promising methods in the production of dairy and other food in concentrated, condensed and dry forms is a consistent combination of dehydration methods. The subject of this research relevant now is approaches to the calculation of such processes. The work objective is to analyze the dehydration staging effect on the energy consumption in this process.
Study objects and methods. Liquid, concentrated and powdered dairy products: whole and skim milk, milk whey, whole milk substitutes, as well as their dehydration parameters at certain stages. The determination of moisture and solids mass fraction in products was carried out with a standard method.
Results and discussion. The feasibility of using a multi-stage dehydration method for the production of various types of powder milk products has been justified. The characteristic boundaries of solids mass fraction at different stages of the process were determined. The material-balance equation made it possible to define the formula for the total specific energy consumption relative to the unit of the final dry product at an arbitrary number of dehydration stages. The paper contains examples of a comparative efficiency assessment of the dehydration process carried out at different stages from the point of view of energy costs of its implementation.
Conclusion. The research featured various issues related to the use of dehydration methods in the production of milk powder products. An equation has been drawn up to estimate the specific energy consumption of the multi-stage dehydration process relative to a unit of the final dry product. The use of a multi-stage process allows to effectively reduce the specific energy consumption, as well as to generate new high quality products.

Keywords. Dairy products, skim milk powder, whole milk powder, dry whey, milk replacers, vacuum evaporation, spray drying, specific energy costs, dehydration

Funding. The research was performed on the premises of the All-Russian Scientific Research Institute of Dairy Industry (VNIMI) as part of the state assignment of the Ministry of Science and Higher Education of the Russian Federation (Minobrnauka) (No. AAAA-A20-120011500098-1).

For citation: Kharitonov VD, Asafov VA, Kuznetsov PV, Gabrielova VT. Multi-Stage Method of Milk Powder Production: Energy Costs Analysis. Food Processing: Techniques and Technology. 2021;51(2):395–401. https://doi.org/10.21603/2074-9414-2021-2-395-401.

https://doi.org/10.21603/2074-9414-2021-2-395-401
УДК 637.1
Оригинальная статья
http://fptt.ru

Анализ энергетических затрат при реализации многостадийного метода получения сухих молочных продуктов

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Дата поступления в редакцию: 08.12.2020 *Дата принятия в печать: 15.01.2021*

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Аннотация.
Введение. При производстве молочных и других пищевых продуктов в концентрированной, сгущенной и сухой формах одним из перспективных направлений является последовательное сочетание различных методов обезвоживания. Подходы к расчету подобных процессов являются предметом продолжающихся исследований и обладают актуальностью. Целью данной работы является анализ влияния стадийности обезвоживания на энергозатраты осуществления этого процесса.
Объекты и методы исследования. Жидкие, концентрированные и сухие молочные продукты: цельное и обезжиренное молоко, молочная сыворотка, заменители цельного молока, а также параметры процессов их обезвоживания на отдельных стадиях. Определение массовой доли влаги и сухих веществ в продуктах производили стандартным методом.
Результаты и их обсуждение. Обоснована целесообразность использования многостадийного способа обезвоживания при выработке различных видов сухих молочных продуктов. Определены характерные границы массовой доли сухих веществ на отдельных стадиях процесса. На основе уравнений материального баланса получено выражение для оценки общих удельных затрат энергии относительно единицы конечного сухого продукта при произвольном количестве стадий процесса обезвоживания. Приведены примеры сравнительной оценки эффективности процесса обезвоживания, осуществляемого в различное количество стадий, с точки зрения энергетических затрат на его осуществление.
Выводы. Рассмотрены вопросы, связанные с применением различных методов обезвоживания при получении сухих молочных продуктов. Составлено уравнение для оценки удельных затрат энергии на отдельных стадиях процесса многостадийного обезвоживания относительно единицы конечного сухого продукта. Применение многостадийного процесса позволяет в несколько раз уменьшить удельные затраты энергии, а также вырабатывать продукты высокого качества и организовать производство новых видов продуктов.

Ключевые слова. Сухие молочные продукты, сухое обезжиренное молоко, сухое цельное молоко, сухая сыворотка, заменитель цельного молока, вакуум-выпаривание, распылительная сушка, удельные энергетические затраты, обезвоживание

Финансирование. Работа выполнена в рамках государственного задания Министерства науки и высшего образования Российской Федерации (Минобрнауки России) (тема № АААА-А20-120011500098-1) на базе ФГАНУ «Всероссийский научно-исследовательский институт молочной промышленности» (ВНИМИ).

Для цитирования: Анализ энергетических затрат при реализации многостадийного метода получения сухих молочных продуктов / В. Д. Харитонов [и др.] // Техника и технология пищевых производств. 2021. Т. 51. № 2. С. 395–401. (На англ.). https://doi.org/10.21603/2074-9414-2021-2-395-401.

Introduction

In the production of various types of dairy and other food in concentrated, condensed and dry forms, one of the promising directions is a consistent combination of various dehydration methods. The feasibility is dictated by a number of circumstances related to the need to ensure a given final product quality taking into account its differences in physical-chemical and thermal-physical properties at various stages of dehydration [1, 2]. Due to the high complexity of these approaches calculating multi-stage processes, they are still the subject of ongoing research relevant today [3–6].

A combination of vacuum evaporation and spray drying [7–10] can be considered as a trivial example of the practical use of a multi-stage dehydration method. For a number of reasons, obtaining a dry product without a preliminary concentration step was recognized as unpromising. A consistent use of vacuum evaporating and spray drying plants in the production of dry dairy products and whole milk replacers (WMR) allows to increase the efficiency of the process. It also improves their storage capacity and reducing properties due to increased resistance to milk fat oxidation and the creation of the required structure of individual particles [11, 12]. The efficiency increase of the process is explained by the fact that the specific heat consumption for product dehydration in spray dryers is more than 10 times higher, than this indicator in vacuum evaporation plants. Thus, such scheme, being a successful solution to improve the quality of the final product and the process efficiency, became widespread in practice, and thereby opened up a promising direction to intensify dehydration processes.

The work objective is to analyze the effect of the dehydration staging in the production of concentrated, condensed and dry dairy products, as well as whole milk replacers, on the energy consumption of this process.

Study objects and methods

The objects of research were liquid, concentrated and dry dairy products: whole and skim milk, milk whey, whole milk replacers, as well as the parameters of their dehydration processes at individual stages. The determination of moisture and solids mass fraction in the products was carried out in accordance with State Standard R 54668-2011.

Results and discussion

The limiting factor that determines the rational level of the solids mass fraction in the product between evaporation and drying is viscosity. On the one hand, an increase in the degree of milk concentration as a result of vacuum evaporation contributes to the efficiency of dehydration in general. On the other hand, an excessive increase in the viscosity of the product is limited by the technical capabilities of spray devices and the difficulty of ensuring rational values of the average particle diameter and the degree of their polydispersity [7, 8]. The choice of a specific concentration of a condensed product before drying and its viscosity depends on a number of factors: the type of product, its temperature, drying method, etc. [7–9, 13, 14]. As a result, in practice, the solids mass fraction in condensed whole and skim milk aimed for drying is maintained in the range of 46–50%, and in milk whey – 50–56%. It should be noted that one of the most important efficiency characteristics of vacuum evaporation plants is the heat transfer coefficient, which subsequently decreases with increasing concentration [3, 15]. However, evaporation costs are still lower than that of spray drying ones. Thus, the research aimed at intensifying the milk condensation process currently goes on in the field of using multi-shell vacuum evaporators, and the use of mechanical compression of steam and finishers. One should note the increasingly widespread use of reverse osmosis units at the first stage of dehydration before vacuum evaporation [16].

Unlike milk condensation in vacuum evaporators, the spray drying process has a number of specific features. It is characterized by drying curves, which are fundamentally general for liquid biological objects, including those based on milk. The drying curves of such materials have two main periods [3, 17]. In the first period, the drying rate is constant. The intensity of moisture removal in this period is determined only by the parameters of the drying agent and practically does not depend on the physical-chemical properties of the dried product.

In the second period, the intensity of the drying process decreases as the moisture content of the product decreases. In this case, the temperature of this process increases, and the temperature of the product to be dried monotonically increases, tending to approach the temperature of the spent drying agent. The reason for this is the need to remove bound moisture during the drying period. The end of this period is the achievement of an equilibrium moisture content in the dried product. As a result, the drying process practically stops.

Heat consumption during a constant drying rate remains constant, and increases during a period of a decreasing drying rate. At the final stage, starting with the mass fraction of moisture in the product, energy consumption increases many times [18–20]. This makes the spray drying process ineffective. The circumstance is the basis for using a more economical dehydration method at this stage. For example, drying in a fluidized or aerovibroboiling bed.

Taking into account the above, we will consider the process of obtaining dry milk products by assessing the relationship between the specific energy consumption relative to the amount of received products and the change in the mass fraction of solids at various process stages. Based on the analysis of the material balance, the effectiveness of the dehydration process in the production of dry milk products was assessed [14]. Specific energy consumption at individual stages of the multi-stage dehydration process can be determined using the following expression:

$$q = \frac{\sum_{i=1}^{k}\left(M_0 - W_{i-1}\right)\cdot\left(1-\frac{c_{i-1}}{c_i}\right)\cdot q_i}{G} \qquad (1)$$

where q – specific energy consumption of the finished product, kJ/kg; q_i – specific energy consumption of evaporated (removed) moisture at the i-stage, kJ/kg ; M_0 – initial product consumption, kg/s; W_{i-1} – productivity of evaporated (removed) moisture at the i-stage of the process, kg/s; $W_0 = 0$; c_i – mass fraction of solids in the product at the end of the i-stage of the process,% ; c_0 – mass fraction of solids in the original product,%; G – finished product productivity, kg/s; k – the total number of dehydration stages.

Based on this dependence, a comparative analysis of energy consumption at different dehydration process stages was carried out. The main stages of the dehydration process of various dairy products and the specific energy consumption, reduced to the amount of moisture removed from the product, are presented in Table 1. The range of change in the mass fraction of solids at individual stages of dehydration are given in Table 2.

The data presented in Table 1 indicate that the energy consumption at the stages of spray drying significantly exceeds the energy consumption at the stages of membrane processing and vacuum evaporation. The data were obtained for the ranges of changes in the mass fraction of solids at individual stages of dehydration, shown in Table 2.

For the same range of solids mass fraction, the diagrams in Fig. 1 show the calculated values of the specific (relative to the amount of final dry products) energy consumption at dehydration individual stages. It should be noted that in the case of a one-stage process, unit costs are several times higher than similar costs when using a two-stage process (in the production of SMP – 5.2–7.5 times, WMP – 4.4–5.8 times, DCW – 8.5–14.0 times, milk replacer – 5.5–8.5 times). In this regard, the indicated data are absent in the diagrams in Fig. 1. Further, a one-stage process being unpromising is not considered.

The presented diagrams indicate the possibility of reducing the energy consumption for the dehydration process by dividing it into separate stages, the parameters of which correspond to the changing characteristics of the dried product. Further reduction of energy consumption for the dehydration process should be considered in the direction of choosing the boundaries of the mass fraction of solids at individual stages, as well as optimizing the methods and parameters of product processing within each

Table 1. Stages of the dehydration process of various dairy products

Stages of the dehydration process	The process driving force	Specific energy consumption reduced to the amount of moisture removed from the product, kJ/kg
1. Moisture removal by membrane methods (nanofiltration, reverse osmosis)	Pressure	250–420
2. Vacuum evaporation	The difference between the enthalpies of steam at the entrance to the vacuum evaporator and condensate at the exit	800–1000
3. Spray drying (1st stage of drying)	The difference in enthalpies of drying air at the inlet and outlet of the drying chamber, equivalent to the difference in enthalpies of steam at the inlet to the main steam heater for the preparation of drying air and condensate at the outlet	6400–8300
4. Drying in a fluidized bed (additional drying of the product – 2nd stage of drying)	The difference in enthalpies of drying air at the inlet and outlet of the aero- or vibro-apparatus of the fluidized bed, equivalent to the difference in enthalpies of steam at the inlet of the steam heater for air preparation of drying the product and condensate at the outlet	6000–6700

Table 2. Change range in mass fraction of solids at each stage of dehydration

Produced product	Stages of the dehydration process	Mass fraction of solids in the product by stages (beginning – end), %			
		1	2	3	4
Skimmed milk powder (SMP)	Membrane moisture separation	–	–	–	9–22
	Vacuum evaporation	–	9–48	9–48	22–48
	Spray drying	9–96	48–96	48–92	48–92
	Fluidized bed drying	–	–	92–96	92–96
Whole milk powder (WMP)	Membrane moisture separation	–	–	–	12–24*
	Vacuum evaporation	–	12–48	12–48	24*–48
	Spray drying	12–96	48–96	48–92	48–92
	Fluidized bed drying	–	–	92–96	92–96
Dry crystallized whey (DCW)	Membrane moisture separation	–	–	–	5–22
	Vacuum evaporation	–	5–52	5–52	22–52
	Spray drying	5–95	52–95	52–92	52–92
	Fluidized bed drying	–	–	92–95	92–95
Whole milk relacer (WMR)	Membrane moisture separation	–	–	–	5–22**
	Vacuum evaporation	–	8**–48	8**–48	22**–48
	Spray drying	8**–96	48–96	48–92	48–92
	Fluidized bed drying	–	–	92–96	92–96

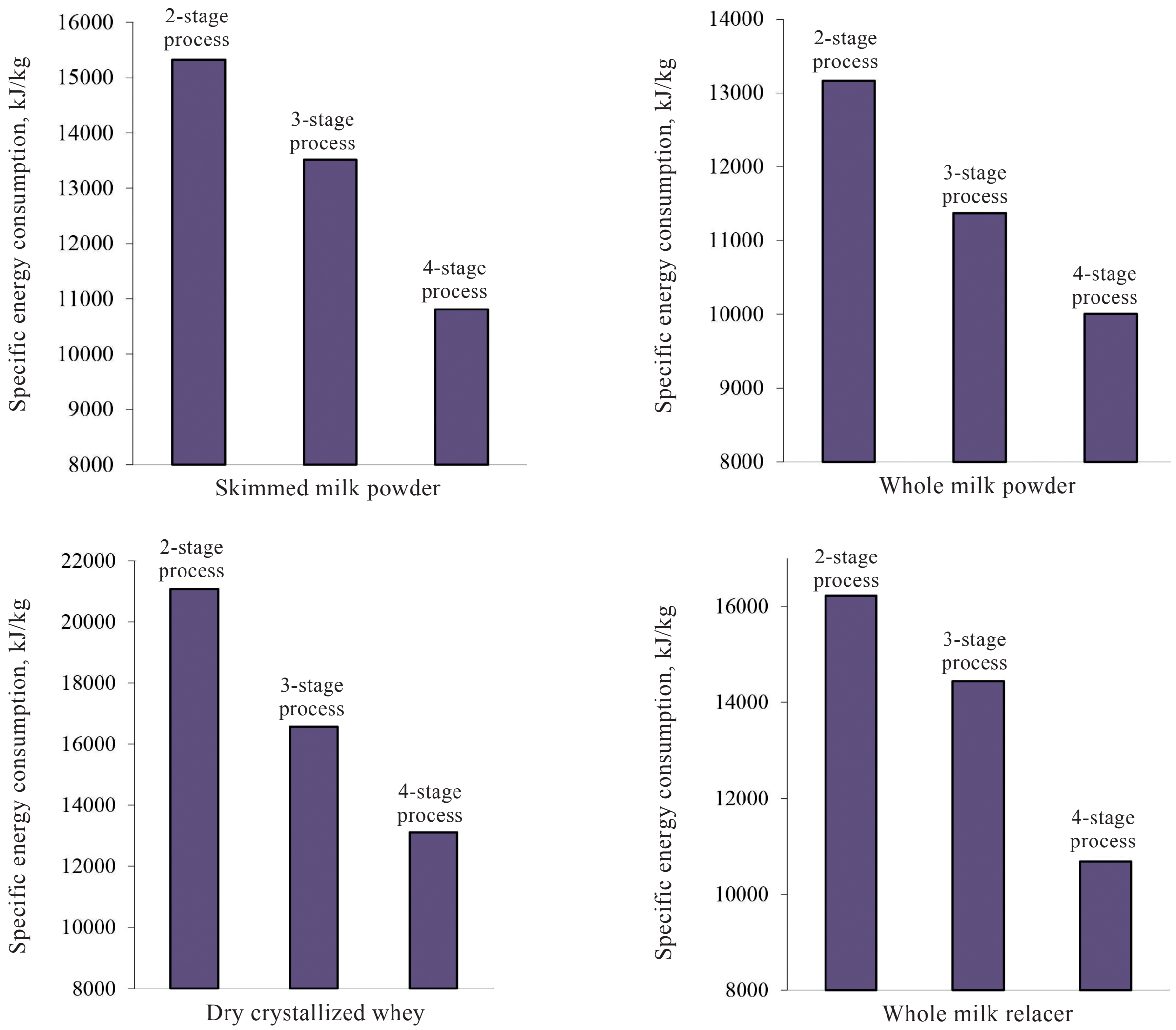
* – taking into account the solids entering the product when the mixture is normalized;

** – taking into account the solids entering the product when mixing according to the milk replacer formula (WMR).

of the stages. Hereinafter, the numbering of individual stages will be carried out in accordance with the numbering indicated in Table 1.

Dividing the dehydration process into two stages (vacuum evaporation and spray drying) provides the required quality indicators of the products produced, and allows to much reduce energy costs. Due to this, the two-stage method of dehydration is most widely used in practice.

When implementing this two-stage scheme, a vacuum evaporation of the initial product begins with a mass fraction of solids of 5–12% and ends at the level of 48–52%. It is possible to intensify the process of vacuum evaporation both by increasing the number of bodies of the vacuum apparatus, and by improving their design. It should be noted that the use of more than three or four cases is not advisable, since the metal consumption and the cost of equipment significantly increase, while the gain from reducing energy consumption is small.



2-stage process – vacuum evaporation, spray drying; 3-stage process – vacuum evaporation, spray drying, fluidized bed drying; 4-stage process – membrane separation of moisture, vacuum evaporation, spray drying, fluidized bed drying

Figure 1. Specific energy consumption at each stage of dehydration relative to the amount of various final dry products

Methods of intensifying the process of spray drying in the periods of constant and decreasing speed are carried out by increasing the monodispersity of the spray, reducing the product viscosity, etc. However, they are not directly related to the process of multi-stage dehydration, and therefore, are not considered in this work. On the other hand, this process includes the implementation of the drying process until the content of the mass fraction of moisture in the product is 6–8%, that is, slightly higher than the standard. This requires the product additional drying to a standard moisture content of 3–5%, which can be considered as the final dehydration stage (the fourth in Table 1). The estimation of the unit costs at this stage of dewatering can be considered as the difference between the unit costs of spray drying to increased moisture content of the product and drying in two stages. Reducing the specific energy consumption for the implementation of a three-stage dehydration process (middle rows in the diagrams in Fig. 1), compared to a two-stage process (left rows in the diagrams), depending on the product being dried, is 10–15%. Considering the possibility of organizing the final drying process in a device structurally combined with a spray dryer, the cost of additional equipment is minimal and has little effect on its payback. A decrease in energy consumption when using this process will be observed with the further increase in the mass fraction of moisture up to 9–10%. At the same time, the stability of the process of additional drying of milk powder decreases due to an increase in the plasticity of the fluidized bed. The main factors influencing the energy efficiency of the spray drying and post-drying processes are the effect of the temperature of the drying agents supplied for drying, at the outlet from the spray dryer and after completion of the drying process, as well as the effect of the mass fraction of solids in the dried products.

Another possibility to reduce energy consumption for the dehydration process of dairy products and milk replacer is the use of additional processing of the feedstock by membrane methods (reverse osmosis, nanofiltration) before the thickening stage, i.e., the organization of a four-stage process. The total energy consumption for maintenance (for example, the reverse osmosis process) depends on the hydraulic losses in the modules of the respective plants. In absolute terms, per unit of moisture removed from the product is 250–479 kJ/kg, which is 2–4 times less than the analogous indicator of the vacuum evaporation process (Table 1). Due to this, the specific energy consumption per unit of the final dry product produced according to the four-stage scheme (right categories in the diagrams in Fig. 1), depending on the type of product, is reduced by 12–33%, compared with the three-stage scheme, and by 22–38% for compared with two-stage. The calculations were carried out taking into account the fact that the maximum possible mass fraction of solids in products after membrane treatment is 20–22%. It should also be noted that the use of membrane methods at the first stage of dehydration allows several times to reduce the required productivity of vacuum evaporation plants, as well as their metal consumption and costs. In addition, during the operation of membrane plants, the moisture removed from the product is industrial water, which can be used, for example, for equipment cleaning. Consequently, the use of membrane methods at the first stage of dehydration is justified both from the point of view of reducing the energy consumption of the process as a whole, and from an environmental point of view. The application scale of the multi-stage dehydration method, especially in the case when the main basic stage of the process is spray drying, is increasing every year in this country and abroad. This is due to the ability to obtain high quality products with relatively low energy and resource consumption in comparison with the same indicators when using a traditional drying process [17, 19]. The advantage of this dehydration method also includes the possibility of obtaining products with new consumer properties and variable composition, as well as with acceptable indicators of environmental impact.

The last stage of dehydration (additional drying) can be divided into two stages: the first is carried out in a fluidized bed built into the drying chamber, and the second - in an additional vibrating convection apparatus. The installation of finishers at the last stage of vacuum evaporation also has a positive effect on the process efficiency. This allows a further increase of solids concentration in the mixture sent to the spray drying stage.

When solving the issue of the dehydration staging of multicomponent products, including whole milk, whole milk relacers, etc., it is necessary to take into account the presence of additional technological process operations for the introduction of components and appropriate processing (homogenization, emulsification, fermentation, hydrolysis, etc.). The variability of these processes, especially in view of the diversity of the component composition of the raw materials used, complicates the conditions for obtaining multicomponent products, and in most cases requires additional experimental studies.

Conclusion

We considered the issues related to the use of various dehydration methods in the production of dry dairy products and whole milk replacers. An equation was drawn up to estimate the specific energy consumption at individual stages of the multi-stage dehydration process relative to a unit of the final dry product.

Specific energy consumption in a one-stage process (spray drying) was 4.4–14.0 times higher than its costs in a two-stage process (spray drying and vacuum evaporation). The transfer of the dehydration process to a three-stage scheme (spray drying, vacuum evaporation and additional drying of the product) provides energy savings of 10–15%, in comparison with a two-stage process, while the transfer to a four-stage scheme (spray drying, vacuum evaporation, additional product drying and membrane processing initial product) – of 22–38%.

Contribution

V.D. Kharitonov and V.A. Asafov co-supervised the project. P.V. Kuznetsov prepared the design materials. V.T. Gabrielova reviewed scientific literature and prepared the manuscript.

Conflict of interest

The authors declare that there is no conflict of interest regarding the publication of this article.

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