Study of centrifugal separation of milk whey and whey concentrates

E Chebotarev, A Maksimenko, S Emelyanov, A Malsugenov and A Lyamina
North-Caucasian Federal University, Stavropol, Russia

1 E-mail: eacheb@mail.ru

Abstract. The properties of dispersed systems in whey and whey concentrates, the features of the processes of their centrifugal separation and the main technological parameters of separation are considered. The properties of dispersed systems are defined through the concept of separability. The formation of a protein precipitation is of great importance in centrifugal separation processes. Technological schemes for separation depend on the origination of whey, the presence of fat and the necessity to isolate certain dispersed particles.

1. Introduction
The processes of centrifugal separation of whey and whey concentrates can be used at various stages of processing of this protein-carbohydrate dairy effluent. The study of these processes was carried out according to the scheme “properties of dispersed systems – centrifugal separation processes – separation technology”.

Moreover, the results of each previous stage of research were the basis for the further research, and properties of whey and whey concentrates determined a certain variety of a separation processes for these products.

2. Materials and methods
The density of whey and particles was determined by the bottle method. Viscosity was determined using a Höppler viscometer and a rotational viscometer. Moisture of protein particles (precipitate) was determined by drying after centrifugal separation and rinsing with water. Experimental separation was carried out on a special unit including a cream separator. The fat content of the original and separated whey was determined by the acid method.

3. Results and discussion
3.1. Properties of dispersed systems
Whey obtained in the production of defatted cottage cheese, rennet cheese, and casein can be considered as a suspension, the plasma of which forms a solution of lactose, mineral salts, and a colloidal phase of proteins. The dispersed phase is formed when the curd is disturbed and is called casein fines. Casein fines are referred to the particles of size less than 1 mm. However, regarding to the centrifugal separation, the particle size of this dispersed phase should be considered no more than 0.1 mm, since larger particles often precipitate on the bottom of the tank, in which whey is reserved before separation, and practically do not get into the separator. The content of casein particles in whey can be up to 1% or
even more. The size of suspended particles in whey is in the range of 10–100 μm with the most probable fraction of 40 μm [1].

When carrying out the separation process, it is necessary to ensure the separation of all casein particles with an equivalent diameter of 30 μm or more. In this case, the residual amount of particles in the separated product will not exceed 0.01%, which fully ensures high-quality clarification.

The separability of the system "casein particles – plasma" is characterized by the formula:

\[ E(W,d,t) = \frac{\rho_3(W,t,d) - \rho_2(t)}{\eta(t)} d^2, \]

where \( E(W,d,t) \) is a separability as a function of moisture content of particles \( W \), their equivalent diameter \( d \) and temperature \( t \), \( s \); \( \rho_3(W,t,d) \) is a density of dispersed particles as a function of particle moisture content, temperature and their equivalent diameter, kg/m\(^3\); \( \rho_2(t) \) is a plasma density as a function of temperature, kg/m\(^3\); \( \eta(t) \) is a plasma viscosity as a function of temperature, Pa\(\cdot\)s.

Usually, the density of dispersed particles is considered as a constant value. A more accurate approach to determining the density of casein particles in whey involves taking into account their moisture content:

\[ \rho_3(W,t) = \rho_1 - W[\rho_2 - \rho_2(t)], \]

where \( \rho_3(W,t) \) is a density of wet casein particles as a function of moisture content and temperature, kg/m\(^3\); \( \rho_1 \) is a density of dry casein particles, kg/m\(^3\).

The value \( \rho_2 = (1160±24) \) kg/m\(^3\) was obtained experimentally.

In addition, we should take into account the presence of a monomolecular adsorption layer of liquid (plasma) on the surface of protein (casein) particles:

\[ \rho_3(W,t,d) = \rho_2(t)[\frac{\rho_2(W,t)Sd + 6m}{\rho_2(t)Sd + 6m}], \]

where \( S \) is a surface occupied by one liquid molecule, m\(^2\); \( m \) is a mass of one liquid molecule, kg.

Since mainly water molecules are adsorbed on the surface of a casein particle in whey, then, based on the size and mass of a water molecule, we can assume \( S = 10.8 \cdot 10^{-20} \) m\(^2\) and \( m = 3 \cdot 10^{-23} \) kg [2].

The density \( \rho_2, \) kg/m\(^3\) and the whey plasma viscosity \( \eta, \) mPa\(\cdot\)s as a function of a temperature \( t, \) °C can be determined by the obtained formulas:

\[ \rho_2(t) = 1027.56 - 0.17t \quad \text{and} \quad \eta(t) = 3.32 - 1.53\lg t \quad \text{– for rennet cheese whey}; \]

\[ \rho_2(t) = 1029.52 - 0.20t \quad \text{and} \quad \eta(t) = 2.98 - 1.34\lg t \quad \text{– for cottage cheese whey}. \]

In whole whey there are two dispersed systems: "milk fat – plasma (whey)" and "casein particles – plasma (whey)". The first contains light dispersed particles and can be considered an emulsion, the second contains heavy dispersed particles and, therefore, is a suspension.

Cheese whey obtained in the production of rennet cheese contains 0.2 – 0.6% milk fat. The fat content in whey and its particle size distribution are not constant at different stages of the processing.

The transfer of fat into whey [3] is carried out most intensively at the first stages of obtaining and processing of the curd grain. The dispersity of fat globules increases with whey processing, as indicated by an increase in the number of small fat globules. Therefore, the whey recovered after obtaining of cheese grain is the most important from the point of view of milk fat extraction.

When calculating the process of whey skimming, the value of 1 μm should be taken as the minimum separable diameter of the fat globule. In the case of centrifugal separation of fat globules with a diameter of 1 μm or more, the residual amount of fat in whey will not exceed 0.01%.

The fat content of the curd whey is usually minimal in the curd bath, but much higher in the whey
that is separated during pressing (self-pressing) [4].

The separability of the "milk fat – plasma" system is determined with taking into account the effect of the thickness of the fat globule shell [5].

After the separation of fat and casein particles, whey is a kinetically stable system containing the major part of milk whey proteins in the dissolved form. As a result of disruption of kinetic stability, which can be caused by coagulation of proteins, whey becomes a coarsely dispersed system.

The secondary dispersed phase is protein particles with the inclusion of fat, mineral salts and some other components. The dispersion medium of this system is an aqueous solution of lactose and mineral salts with a residual amount of proteins, fat and other components.

Studies of the dispersed composition of protein particles in cottage cheese whey subjected to non-reagent heat treatment [6] showed that the studied system had a high degree of polydispersity with the most probable fraction of suspended protein particles with an equivalent diameter of 15–22 μm (maximum of the distribution function).

To calculate the separability of the system "whey – suspended protein particles", the value of the equivalent diameter of 30 μm can be used as the determining size of protein particles, since the particles less than 30 μm account for less than 0.8% of the total volume of suspended proteins.

To calculate the separability of this dispersed system, one can use the dependence density (ρ, kg/m³) and viscosity (η, mPa∙s) plasma (clarified whey) versus temperature (t, °C):

\[ \rho(t) = 1026.5 - 0.26t \quad \text{and} \quad \eta(t) = 2.48 - 1.05 \lg t \quad \text{for rennet cheese whey}; \]

\[ \rho(t) = 1023.7 - 0.31t \quad \text{and} \quad \eta(t) = 2.32 - 0.97 \lg t \quad \text{for cottage cheese whey}, \]

and \( \rho_s = (1136 \pm 17) \text{ kg/m}^3. \)

Concentration (vacuum evaporation) of non-fat non-clarified whey leads to the formation of a dispersed system (suspension) that is qualitatively different from those considered earlier.

In the process of concentration, the conditions favor coagulation of proteins, and therefore the formation of a dispersed system "protein particles – plasma" takes place. Then, during storage, due to the crystallization of lactose, another dispersed system is formed, consisting of milk sugar crystals and plasma. The formation of these dispersed systems leads to the destabilization of condensed whey [7], which can be briefly characterized as follows.

A stable (clearly visible) protein precipitate is present immediately after the production of whey condensed to a mass fraction of dry matter of about 30% or more. Storage at a temperature of 20 – 25 °C leads to the formation of a protein-crystalline precipitate. At 30% dry matter protein prevails over crystals, and a further increase in dry matter increases the proportion of lactose crystals more and more. The predominance of crystals over protein particles is observed during storage in a cooled state (5–10 °C) even for a dry matter content of 30%.

The dispersed composition of protein particles in condensed whey is similar to that obtained by coagulation of proteins in non-concentrated whey, and the size of lactose crystals can be in a fairly wide range, since this parameter is influenced by a number of factors, such as concentration factor, storage temperature and duration, protein coagulation rate, etc.

The density of protein particles in concentrated whey is slightly higher than in non-concentrated one. This is due to the adsorption of various molecules on the surface of particles. Those comprise not only water, but also lactose, since the concentration of the latter has already become quite high [8].

The density of crystals is 1360 kg/m³.

Plasma properties in condensed whey (density and viscosity) are unstable, as they are influenced by the degree of crystallization of lactose and, as crystals form, both of these parameters decrease.

It was found that the plasma of the condensed whey immediately after production, i.e. even before the onset of crystallization, has a density which can be determined by the formula

\[ \rho = 1000,1 + 4,56c - 0,17t, \]

where \( c \) is a mass fraction of dry matter in concentrate, %; \( t \) is a temperature, °C.
Viscosity of the same product in the temperature range \( (t) \) 20–70 °C and a mass fraction of dry matter \((c) \) 20–40 % changes according to the formula:

\[
\eta = 1.87 \times 10^{-2} t + 6.44 \times 10^{-3} c + 6.05 \times 10^{-4} t^2 + 4.08 \times 10^{-3} c^2 - 2.3 \times 10^{-5} tc .
\]

Crystallization of lactose reduces the content of solids in solution (plasma), which in turn increases the separability of dispersed systems. Taking into account the above, it can be assumed that in condensed whey, the separability of dispersed systems, in addition to the temperature and particle size, also depends on the content of dry matter and the degree of crystallization of lactose \((k)\)

\[
E(t,d,c,k) = \frac{\rho(t,c) - \rho_s(t,c,k)}{\eta(t,c,k)} d^2.
\]

3.2. Centrifugal separation processes

Considering the processes of centrifugal separation, the following can be noted. To isolate fat and casein particles from whey, special separators with two-section drums are used.

The drum of the two-section separator has a combined package of plates: in the lower part there are clarifying plates, in the upper part there are separating plates, and between them there is an intersectional separating plate. There is a gap between the flanging of the intersectional separating plate and the inner surface of the slurry space (movable bottom). This gap should, on the one hand, ensure the passage of the resulting casein sludge to the discharge ports, and, on the other hand, prevent mixing of the streams of initial and skim whey.

The role of the sludge formation in the sludge space of the separator is noted as one of the important factors influencing the results of separation [9].

This was confirmed in the course of our research. It was found that the whey skimming is directly affected by the accumulation of casein sludge formed in the slurry space of the drum due to the precipitation of casein particles.

The relationship between the time of precipitate accumulation \((\tau)\) and the radius of its location in the sludge space \((R)\) is expressed by the following relationship

\[
\tau = \frac{10^7 \pi (R_{\text{max}} - R) (R_{\text{max}}^2 + R_{\text{max}} R - 2R^2) (tg \alpha + tg \beta)}{3M \Delta c} \left[ W + (100 - W) \frac{\rho_w}{\rho_s} \right],
\]

where \(R_{\text{max}}\) is maximum radius of the sludge space, m; \(\alpha\) and \(\beta\) are inclination angles of the sludge space generatrices, °; \(M\) is separator capacity, \(\text{m}^3/\text{s}\); \(\Delta c\) is the difference in the concentration of casein particles in the original and separated whey, %; \(W\) is moisture of the resulting sludge, %; \(\rho_w\) and \(\rho_s\) are densities of whey and dry casein particles, \(\text{kg}/\text{m}^3\).

In turn, the moisture content of the sludge depends on a sealing pressure \((P_{\text{com}})\), i.e. actually from the radius of its location. The influence of the magnitude of the centrifugal sealing pressure in the separator drum on the moisture content of precipitation has been studied experimentally.

As a result of mathematical processing of the obtained results, it was found that this influence can be described by an equation of the form

\[
W = a P_{\text{com}}^b,
\]

where \(P_{\text{com}}\) is a sealing pressure, MPa; \(a\) and \(b\) are coefficients which values are as follows:

\[
a = 61.206 \text{ and } b = -0.101 \quad \text{– for rennet cheese whey};
\]

\[
a = 60.633 \text{ and } b = -0.089 \quad \text{– for cottage cheese whey}.
\]

Thus, using the obtained formulas, it is possible to analyze the precipitate accumulation in the sludge.
space of the separator. E.g., it was revealed that the gap between the flanging of the intersectional separating plate and the inner surface of the movable bottom of existing whey separators remains open for the sludge passage for most of the time between discharges.

3.3. Separation technologies

Depending on the type of non-concentrated whey, the presence of fat and the necessity to isolate certain dispersed particles, various separation schemes for this product are possible. In general, technological schemes for the separation of dispersed phases from whey can have four fundamentally different directions of the centrifugal separation process:

- milk fat and casein particles;
- casein particles;
- particles of casein and whey proteins together;
- whey protein particles.

The separation of fat and casein particles involves whey defatting in a cream separator followed by the utilization of casein sludge. Centrifugal separation of casein particles alone is advisable when the quality of the recovered sediment does not allow its further use.

To isolate fat and casein particles from whey, it is most advisable to use special separators of a combined type (separator-clarifier) with centrifugal periodic discharge of sediment.

The conducted research of the whey separation process made it possible to determine the separation parameters, namely the temperature of the initial product depending on the fat content in it: 0.4 % – 30 °C; 0.5 % – 35 °C; 0.6 % – 50 °C.

The same studies make it possible to recommend the modes of separation of whey concentrates. Taking into account the increase in the viscosity of whey in the process of concentration, and, despite the fact that the separability of the system "fat globules – plasma" in concentrated whey is still quite high, the separation temperature for these products should be set within 50–60 °C. A further increase in the separation temperature is unreasonable for dispersing the fat globules directly in the separator drum [10].

Thus, the possibility of varying the separation temperature depending on the fat content of the initial product is excluded and the only technological factor that regulates the defatting process, in this case, is the performance of separator.

Obviously, when defatting concentrated whey in a two-section separator drum, designed (and calculated) for non-concentrated whey, the capacity of the apparatus should be reduced.

Based on the analysis of whey concentrates as the objects for separation, it is recommended to determine the performance of the given separator by the formula

\[ M_e = 9M_cC_e^{-1} \]

where \( M_e \) is separator capacity for defatting whey concentrate, m\(^3\)/h; \( M_c \) is separator capacity for non-concentrated whey, m\(^3\)/h; \( C_e \) is mass fraction of dry matter in whey concentrate, %.

4. Conclusions

The obtained formulas for the separability of dispersed systems in whey and its concentrates make it possible to calculate the separation processes (centrifugal separations) used at different processing stages of this dairy effluent.

The nature of the separation of whey and its concentrates is largely associated with the dynamics of precipitate accumulation in the separator sludge space.

When implementing the technology for separating whey, it is necessary to set the temperature corresponding to the fat content of the original whey, and, when separating concentrated whey, the performance of the separator must be reduced.
References

[1] Chebotarev E, Sugarov Kh and Bratsikhin A 2018 Milk and its properties as an object of separation Journal of Hygienic Engineering and Design 24 101-6

[2] Kovalev P G and Khliyan M D 1975 Physics (molecular physics, electrodynamics) (Rostov-on-Don: Rostov University Publishing House) p 24

[3] Vasilisin S V, Chebotarev E A and Akhtyamova S M 1979 The transition of milk fat into cheese-like serum Proceedings of VNIIMS XXXI 49-51

[4] Belousov A P and Garmash V A 1976 Loss of fat with whey during the production of curd J Dairy industry 1 19-20

[5] Chebotarev E A 1997 Influence of the size of the fat globule shell on the separability of the fat-plasma system in cheese whey J News of Higher Educational Institutions: Food technology 1 48

[6] Borisov A T 1982 Extraction of protein substances from curd whey on a nozzle separator with recirculation and parabolic trays (Moscow) 101-10

[7] Sinelnikov B M, Khramtsov A G, Evdokimov I A, Ryabtseva S A and Serov A V 2007 Lactose and its derivatives (St. Petersburg: Profession) p 236-8

[8] Khramtsov A G 2011 Whey phenomenon (St. Petersburg: Profession) p 216

[9] Lipatov N N and Novikov O P 1975 Self-emptying separators (Moscow: Mechanical Engineering) p 31-4

[10] Lipatov N N 1971 Separation in the dairy industry (Moscow: Food industry) p 265-6