INVESTIGATION OF THE FEASIBILITY OF MICELLE SEPARATION IN BONE MEAL PRODUCTION USING A SEDIMENTING CENTRIFUGE

Andrii Shkop[1] [0000-0002-1974-0290], Nataliia Ponomarova[1] [0000-0001-8931-5882], Oleksii Shestopalov[1] [0000-0001-6268-8638], Alona Bosiuk[1] [0000-0001-5254-2272], Antonina Sakun[1] [0000-0002-1079-7856], Andrii Romanchyk[1][0009-0007-1660-4676], Dmytro Matiss[1][0009-0009-1371-5877]
[1]National Technical University "Kharkiv Polytechnic Institute"
Email: Alona.Bosiuk@mit.khpi.edu.ua

Abstract - As a result of laboratory studies, it was established that the miscella formed after fat extraction from meat-and-bone meal contains approximately 130 g/l of suspended solids, which makes it impossible to purify it directly using a standard centrifugal separator. During processing in a laboratory centrifuge, the miscella separates into two phases: a solution of fat in hexane and a sediment, in which the concentration of suspended solids reaches 35-45%. In the centrifugate obtained after centrifugation, the suspended solids content decreases to 1.0%, which is an acceptable level for further purification in a separator. To enable continuous removal of insoluble impurities, the use of an industrial decanter centrifuge with screw discharge of sediment - the Ecomash SHS 312A model - has been proposed. This equipment is designed for the separation of two-phase suspensions based on component density. It is explosion-proof and non-hermetic, allows for nitrogen supply, but is not equipped with a heating system. The aim of the study was to experimentally confirm the efficiency of solid impurity sedimentation from miscella and to determine the optimal purification modes. As part of the research program, miscella was fed into the centrifuge operating at speeds ranging from 2400 to 3800 rpm, with subsequent removal of the clarified centrifugate. The process efficiency was evaluated based on the degree of solid impurity removal by comparing the suspended solids content before and after treatment.

Keywords: Bone meal, Mistella, Suspended solids, Sedimentation centrifuge, fugate, Mechanical dehydration, Purification, Environmental safety.

1. Introduction

Bone meal is a valuable by-product obtained through the thermal and mechanical processing of animal bones, primarily from pigs and cattle. As a rich source of protein and minerals, bone meal finds widespread use in agriculture (as a fertilizer and animal feed additive) as well as in certain technical processes. A critical stage in bone meal processing is the fat extraction phase, during which a micella is formed – a mixture of fat dissolved in hexane and various suspended organic substances. Efficient separation and purification of the micella are essential to ensure the quality of the final fat product and its subsequent industrial use. However, the presence of suspended organic impurities in the micella complicates the purification process, making it a significant area for engineering improvements. Modern trends in industrial sustainability and waste minimization further emphasize the need for efficient mechanical and physico-chemical separation methods in the processing of animal-derived by-products.

Throughout the development of industrial meat and poultry processing, the issue of recycling and utilizing non-edible waste – such as gastrointestinal tracts, feathers, dead birds, and bone frames from advanced carcass processing – has remained relevant. The importance of this issue is linked not only to the economic aspects of production but also to the environmental impact of such raw materials. Meat-processing and poultry enterprises often dispose of this waste through incineration, although a promising alternative is the processing of such waste into meat-and-bone meal – a valuable feed additive. Meat-and-bone meal is a good source of protein and macronutrients, containing up to 11.6% calcium, 5.9% phosphorus, and 1.6% natrium, and is also a source of vitamins B1, riboflavin, choline, nicotinic acid, and cobalamin.

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2. Analysis of Literature Data and Problem Statement

The processing of bone meal and related products, in particular mycelium, has been the subject of numerous studies due to technical problems associated with the removal of suspended organic matter. Traditional purification methods are based on sedimentation, filtration and centrifugation [1–4], often in combination with solvent recovery technologies such as evaporation and vacuum distillation [5].

Recent studies have investigated the potential of fine filtration systems and membrane technologies for micelle purification [6–8]. These methods offer higher selectivity but require optimisation for the viscosity and composition of micelles obtained from bones. Studies [9] and [10] report improved separation efficiency using polymer and ceramic membranes, although contamination and solvent compatibility issues remain critical.

Mechanical methods, in particular the use of sedimentation centrifuges, as shown in studies of liquid waste dewatering processes [11], are promising for the purification of mycelium formed during the extraction of fat from bone meal due to their efficiency, reliability and ability to operate under industrial loads.

Aspects of designing and numerical modelling of high-speed centrifuges capable of working effectively with heterogeneous media are considered in [12], which is relevant for improving the equipment used in the purification of localities obtained from bone meal. In addition, modern approaches to the extraction and purification of bioactive components from animal by-products, in particular enzymes, as shown in [13], emphasise the potential for comprehensive processing of bone raw materials with minimisation of waste and improvement of the overall environmental efficiency of production.

Researchers pay special attention to improving the processes of mechanical dewatering of complex dispersed systems in centrifuges, which is relevant for the purification of localities obtained from bone raw materials. In [14], the efficiency of purification and dewatering of coal sludge in centrifuges, which are similar in rheological characteristics to fat-containing suspensions, is considered. It has been established that the key factors are the optimisation of the hydrodynamic regime and the parameters of the suspension feed. The authors [15] investigated ways to intensify the process of dewatering polydisperse suspensions, proposing design solutions that promote better phase separation with minimal energy consumption. The relevance of these approaches is also confirmed by the results [16], which examine the patterns of cleaning and dewatering of gas cleaning sludge with coal dust at thermal power plants. These studies demonstrate that the effective operation of centrifuges depends not only on the geometric parameters of the rotor, but also on the properties of the suspension being processed and the modes of its supply.

The results presented in [17] also confirm the feasibility of using sedimentation centrifuges for mechanical dewatering of liquid waste in various industries, in particular at treatment plants, and indicate the potential for scaling up such approaches for processing local waste during bone meal processing.

Despite existing achievements in the field of processing animal by-products, in particular in the extraction and purification of fat from bone raw materials, there is still no universal, highly efficient and at the same time economically viable technological solution for purifying tallow, especially given the variable quality of raw materials, the heterogeneity of the suspension composition and the variability of production process parameters. In this regard, the implementation of integrated technological approaches based on a combination of mechatronic systems – in particular, modern high-speed centrifuges with optimised flow characteristics – with chemical monitoring and process control systems is becoming increasingly relevant. This symbiosis makes it possible to improve the quality of sludge treatment, reduce energy and resource costs, and ensure greater stability and repeatability of results in industrial production.

3. Aim and Objectives of the Study

Aim of the study is to establish the patterns of efficiency of purification and dewatering of bone meal with a high content of suspended solids in the process of treatment in a continuous-action sedimentation centrifuge.

To achieve this objective, it is necessary to:

– conduct laboratory studies of the composition and physical and chemical properties of the slurry obtained after fat extraction from bone meal;

– study the efficiency of separation and the degree of removal of solid impurities from the slurry in different operating modes of the sedimentation centrifuge;

– determine the optimal operating parameters of the centrifuge (rotation speed, feed rate) to ensure maximum purification and dewatering;

– evaluate the quality of the purified filtrate and sediment in terms of suspended solids content for further use or disposal.

4. Research Methodology

The study was conducted at a bone processing facility specializing in the production of bone meal.

In order to extend the shelf life and increase the protein content of the final product, the enterprise employs a hexane-based fat extraction process. This method enables defatting of bone meal through solvent extraction, allowing the processing of raw materials with elevated acidity levels. Hexane effectively dissolves both saturated and unsaturated fatty acids present in the greaves, converting them into extractable fat.

At the outlet of the extractor, two main products are obtained: defatted bone meal containing 25–30% residual hexane, and micelle—a mixture of 20–25% fat dissolved in hexane.

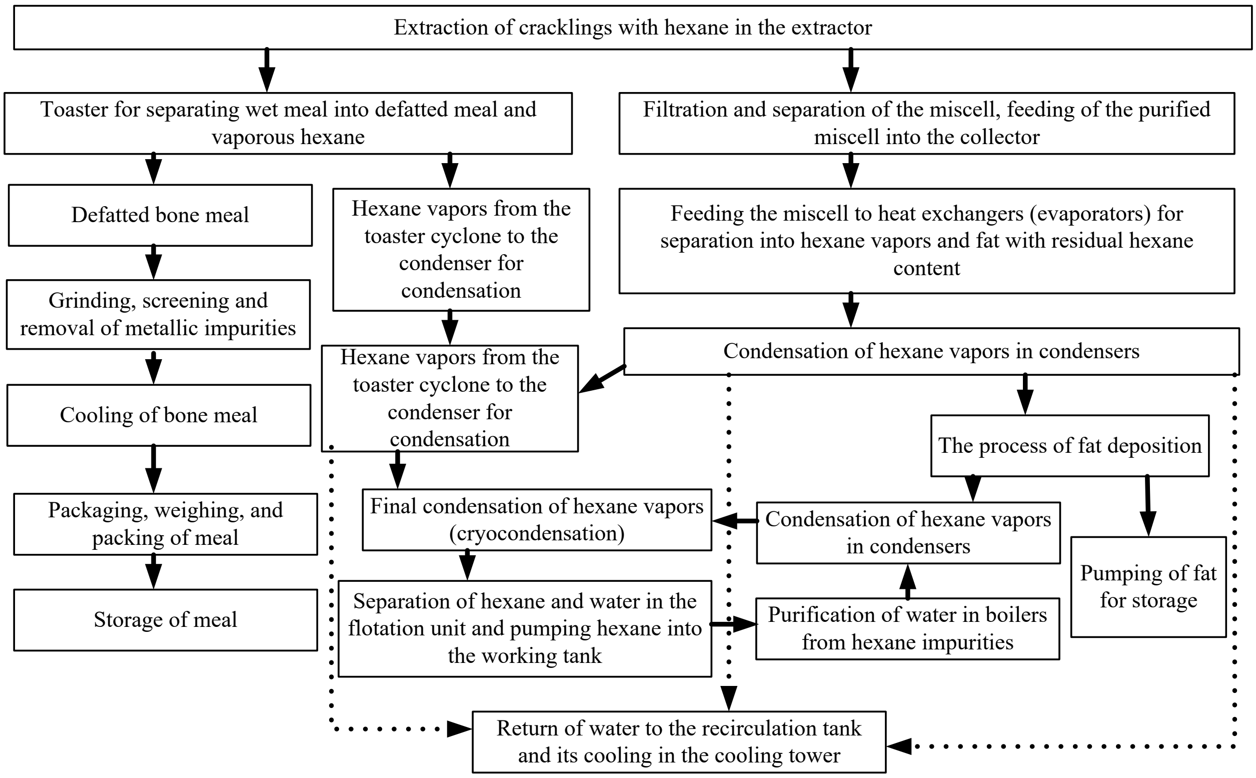

Figure 1: Schematic of Fat Extraction from Rendered Greaves

At the outlet of the extraction process, the resulting bone meal contains a low fat content (not exceeding 1%) and an acid number not higher than 5 mg KOH/g. This significantly extends the shelf life of the meal up to one year without the need for antioxidants. Additionally, the technical fat extracted with hexane contains both saturated and unsaturated fatty acids, which are of particular interest for use in the perfume industry.

The micelle exiting the extractor (a solution of fat in hexane with suspended organic matter) requires purification from suspended solids. Currently, this process is carried out using a filter with 250 μm mesh size, followed by a self-discharging centrifugal separator. However, the purification quality of the micelle is unsatisfactory. The separator's sludge chamber quickly becomes clogged with solid phase material, necessitating frequent discharges of the sediment, which leads to accelerated wear and eventual failure of the separator.

When processed in a laboratory centrifuge, the micelle separates into a two-phase system: a fat-in-hexane solution and sediment. The solid content of the sediment is approximately 35–45%. The centrifugate (supernatant) contains about 1.0% suspended solids. A centrifugate of this quality is suitable for further purification in a centrifugal separator to achieve the required level of clarity.

To improve micelle purification from the solid phase, a continuous sedimenting centrifuge with screw discharge of sediment — the Ecomash SHS 312A — was proposed. This machine is designed for the separation of two-phase suspensions into liquid and solid phases, where the liquid phase must have a lower density than the solid. The centrifuge is non-hermetic, equipped with explosion-proof electrical components and a nitrogen inlet nozzle. No heating system is provided for the centrifuge.

The objective of the pilot-scale tests of the Ecomash SHS 312A centrifuge is to validate its technological performance in separating insoluble substances from the micelle and to evaluate the degree of purification under various operating conditions.

The test program involved feeding the micelle into a centrifuge operating at speeds ranging from 2400 to 3800 rpm, with continuous discharge of the purified centrifugate. The centrifuge performance was evaluated based on the efficiency of solid impurity (bone meal) removal from the feed, which required sampling the micelle before and after centrifugation to determine the solid content.

The centrifuge was installed according to the process flow diagram shown below (Fig. 2).

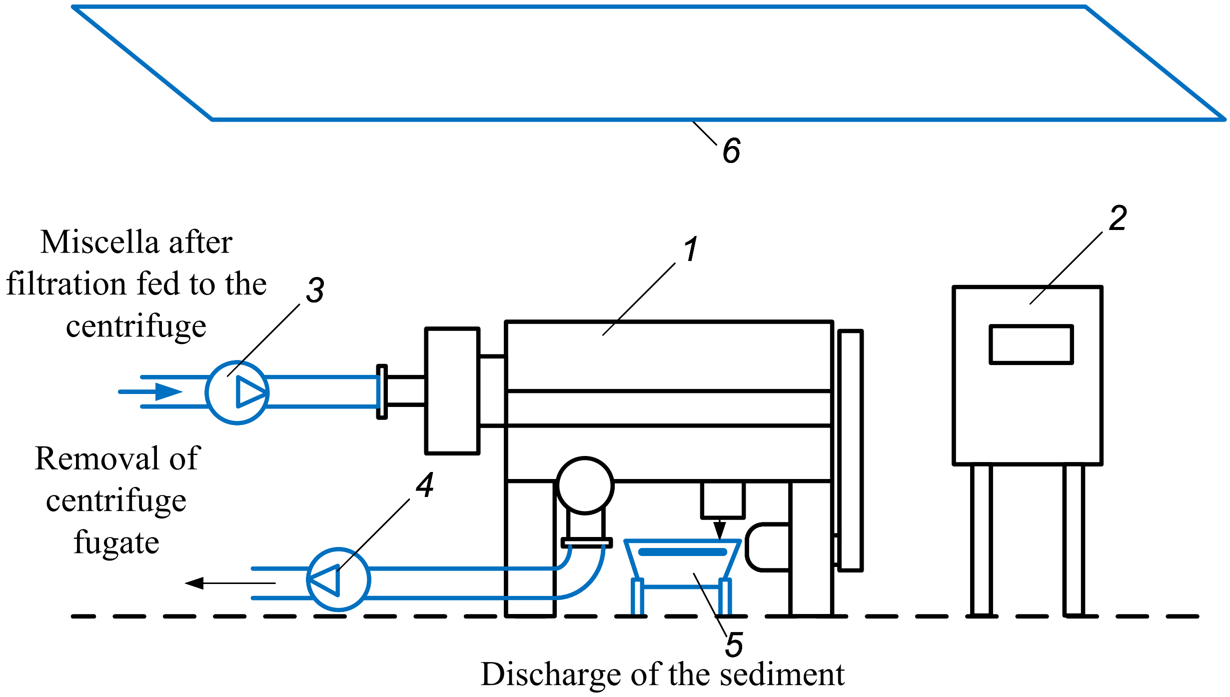

Figure 2: Equipment layout of the Ecomash SHS 312A centrifuge system for micelle purification: 1 – Ecomash SHS 312A centrifuge; 2 – centrifuge control cabinet; 3, 4 – feed pump for micelle input and discharge pump for centrifugate removal; 5 – collection cart; 6 – centrifuge enclosure.

After installation, hydraulic tests with water were carried out to verify the operability of the centrifuge and its associated piping. The results of the hydraulic tests are presented in Table 1.

Table 1. Results of Hydrostatic Tests of the Ecomash SHS 312A Centrifuge

Water flow rate supplied to the centrifuge,	Rotor speed of the centrifuge / Relative screw speed	Rotor drive motor current / Screw motor current	Rotor drive motor current under load
m^3/h	rpm	A	A
1,1	3400/15	12,8/6,8	14
2,1			16
3,3			17
4,5			19
0,9	3800/16	14/6,8	15
1,5			16
2,6			17,7
4,5			21

The product fed into the centrifuge (micelle) is a suspension containing 13–17% (130–170 g/L) bone meal at a temperature of 15–20ºC. This product had accumulated due to the intermittent operation of the processing plant. For testing purposes, settled micelle was used, which had remained in the extractor without the addition of fresh portions of meat-and-bone meal or quicklime (CaO). The processing capacity of the unit for purified micelle ranged from 900 to 1500 L/h. Visually, the micelle appeared as a low-viscosity liquid suspension with a strong hexane odor and dark brown color, containing visible suspended solids.

The operation of the equipment chain proceeded as follows: the accumulated micelle from the extractor was first fed to a coarse filter. The micelle, prefiltered from particles larger than 250 µm, was then conveyed through an uninsulated steel pipeline (approximately 29 meters long) to the centrifuge. The centrifuge operated at pre-set rotor and screw rotation speeds. For all tests, the centrifugate discharge radius was fixed at 101 mm. The centrifugate was collected in a sealed tank, from which it was periodically pumped out. The flow rate of the centrifugate was determined by measuring the time required to fill the tank. The separated sediment from the centrifuge was discharged into an open cart. For enhanced operational safety, nitrogen was supplied into the centrifuge at a pressure of 0.05–0.015 MPa, measured using a manometer.

During centrifugation, the following parameters were recorded: centrifugate flow rate, electric current load of the centrifuge drive motors, and the rotation speeds of the rotor and the screw conveyor. At steady-state operation in each mode, samples of feed, centrifugate, and sediment were taken for subsequent analysis of fat and solid content.

Sampling of the micelle, sediment, and centrifugate was carried out by the plant's production laboratory staff. Prior to analysis, the collected samples were thoroughly mixed. An aliquot of 30–50 mL was taken, weighed, and centrifuged in a laboratory centrifuge (7000 rpm, 5–7 min). The liquid phase was decanted and evaporated under a fume hood at 70ºC to remove hexane. The remaining fat was weighed and its percentage content in the sample was calculated. The solid phase (bone meal sediment and fat) was dried until the hexane odor was completely removed, weighed, and its content in the sample was determined. The fat and solids content were calculated as the ratio of fat or sediment mass to the sample mass, expressed as a percentage. The residual hexane and fat content in the centrifuge sediment were also determined.

The efficiency of centrifugation in removing solid phase from the micelle was calculated as follows:

$$\varepsilon = \frac{C_{sp} - C_c}{C_{sp}} \tag{1}$$

where C_{sp}, C_c – the efficiency of centrifugation for micelle purification from the solid phase was calculated based on the concentration of solids in the centrifuge feed and in the centrifugate.

The calculation did not take into account the increase in solid and fat concentrations in the centrifugate caused by partial hexane evaporation. If the evaporated mass of hexane were considered, the actual centrifugation efficiency would be higher than the value calculated using Equation (1).

5. Research Results

During micelle centrifugation in the laboratory centrifuge (5–7 minutes), three distinct layers were obtained: a sediment of bone meal at the bottom, a middle layer of insoluble fat (whitish in color), and a top layer of transparent amber-colored hexane (Fig. 3).

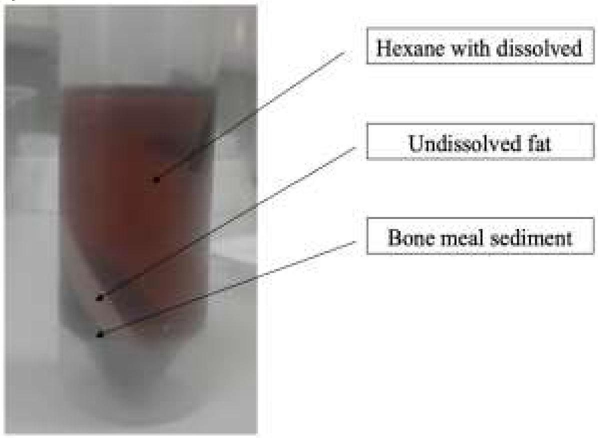

Figure 3: Photographs of the sample after centrifugation in the laboratory centrifuge

The results of the pilot-scale tests of the centrifugal unit are presented in Table 2.

Table 2. Results of Industrial-Scale Tests of the Ecomash SHS 312A Centrifugal Unit

No	Centrifuge operating mode		Miscella		Centrifugate			
	n_r, rpm	Δn_{screw}, rpm	C_{sp}, %	Fat, %	Q_c, m³/h	C_c, %	Fat , %	Purification efficiency, %
1	3400	15	18,9	8,6	0,9	14,4	10,4	23,4
2	3400	15	18,7	8,8	1,2	9,8	9,8	47,6
3	3400	17	17,2	8,7	0,4	17,1	11,3	0,5
4	3600	19	17,3	8,6	0,4	16,8	13,0	3
5	3800	10	17,2	9,3	0,5	16,7	12,5	3
6	3800	10	17,7	9,2	0,5	16,4	11,7	7,3
7	3800	8	18,3	9,6	0,5	15,7	12,5	2,6
8	3800	6	19,7	8,9	0,5	18,5	12,3	6

Approximately 50 kg of sediment was obtained from 1.5–2 m³ of centrifuged micelle processed in the centrifugal unit. The sediment had a high fat content (up to 20%) and residual hexane content (up to 30%). The sediment appeared loose and dusty (Fig. 4), while the centrifugate was whitish in appearance (Fig. 5).

Figure 4: Photographs of the sediment under the centrifuge lid and after discharge into the collection cart

Figure 5: Photographs of the centrifuge feed and centrifugate

Figure 6: Photographs of fat deposits in the centrifugate discharge ports

Tests with optimization of purification parameters continued under continuous operation mode (Table 3).

Table 3. Results of Industrial-Scale Tests of the Ecomash SHS 312A Centrifugal Unit in Continuous Operation Mode

Sampling time	Results of miscella purification							
	Operating mode of the centrifugal unit		Miscella		Centrifugate			
	n_r, rpm	Δn_{screw}, rpm	$C_{sp.}$, %	Fat , %	Q_c, m³/h	C_c, %	Fat , %	Purification efficiency, %
10^{20}	2400	5	16,5	8,9	1,0	1,6	11,5	90,3
10^{40}	2400	5	16,1	9,1	0,5	10,1	9,7	37,3
11^{00}	2800	8	13,5	8,9	0,65	9,0	9,8	33,3
11^{05}	2800	8	14,4	9,0	0,65	11,3	9,7	21,5
11^{25}	2800	8	12,3	9,0	1,5	10,5	9,3	14,6
11^{40}	3200	13	12,2	9,1	2,0	10,6	9,4	13,1
14^{45}	2600	70	15,5	9,1	1,0	14,6	9,7	5,8
14^{55}	3000	73	14,5	9,3	1,0	13,4	9,7	7,5

During the operation of the centrifuge, significant hexane evaporation was observed. Measurements of vapor concentration in the working area of the unit revealed hexane vapor levels ranging from 45.0 to 49.3%, which exceeds the maximum permissible concentration (MPC) by a factor of 300–500.

6. Discussion of Results

The average solid phase concentration in the centrifuge feed was 17.7%, ranging from 14.4% to 19.7%. The fat content remained nearly constant, between 8.5% and 9.7%, indicating that the hexane concentration in the feed did not vary significantly throughout the day. The purification efficiency fluctuated widely, reaching up to 90%. However, an increase in rotor speed led to a drop in purification efficiency to as low as 0.5–7.3% due to micelle emulsification inside the centrifuge. Overall, there was no clear correlation between centrifuge operating parameters and purification efficiency.

In all trials, the fat content in the centrifugate increased by 2–5% relative to the feed, regardless of the centrifugation mode. This effect is attributed to partial hexane evaporation, which reduced the relative proportion of hexane in the centrifugate, thereby increasing the relative concentrations of both solids and fat. It was not possible to directly measure the amount of evaporated hexane in each specific trial.

Under the influence of the centrifugal field, the original micelle separates into three phases: hexane, fat, and sediment. The unstable purification performance of the centrifuge can be explained by micelle stratification, in which fat that is not dissolved in hexane forms a separate phase. This product is incompatible with conventional micelle extraction and solid phase separation technologies. In such cases, the centrifuge operates on a three-phase suspension, for which it was not designed. Hexane evaporation, and the resulting increase in fat content, contributes to greater micelle emulsification and, consequently, reduced centrifuge efficiency.

Given the heterogeneity of the fat and its prolonged storage, it is difficult to predict its behavior at varying temperatures. Moreover, as the micelle cools (the extraction process typically occurs at 50–55ºC, while the micelle temperature during the industrial trials was approximately 15ºC), fat solidification may occur. In such cases, the fat can behave as a solid phase—particularly since its density is higher than that of hexane. The combination of solidified fat and other solid particles results in unstable purification performance.

Thus, the reduction in purification efficiency observed in the centrifuge is primarily due to the presence of a fat fraction that is insoluble in hexane, leading to emulsification of the centrifugate, as well as to hexane evaporation inside the centrifuge, which increases the relative fat content.

The nature of the phenomena occurring inside the centrifuge is illustrated in Fig. 7.

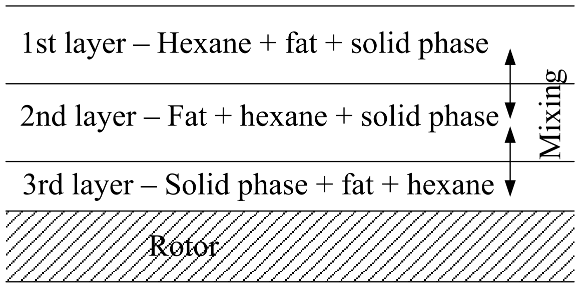

Figure 7: Micelle layer structure in the rotor of the decanter centrifuge

Inside the rotor, due to the combined action of the centrifugal field and the agitating effect of the screw conveyor, a three-phase medium forms consisting of three dynamic layers.

– The upper layer (Layer 1) consists mainly of hexane with some dissolved fat.

– The middle layer (Layer 2) is a mixture of fat, hexane, and solid particles.

– The bottom layer (Layer 3) is composed predominantly of solid particles and fat.

The dynamic viscosity of the layers varies—from a minimum in Layer 1, which is close to the viscosity of pure hexane, to a maximum in Layer 2, which approaches the viscosity of fat. Layer 3 no longer behaves as a liquid but instead exhibits the properties of a plastic-like material.

When fat is dissolved in hexane, the viscosity of the solution is governed by hexane as the primary component. However, when fat becomes the dominant phase, the viscosity is determined by the fat itself. The sedimentation of solid particles in viscous fat is very slow, resulting in low purification efficiency. Due to the hydrodynamic flow of the suspension and the mixing action of the screw, the layers partially intermix, forming a stable emulsion that is difficult to separate. Solid particles from the lower layers are entrained into the upper layer (Layer 1) and are subsequently carried away with the centrifugate.

A gradual decline in centrifugation efficiency over time has been observed. The likely cause is the progressive formation of a three-phase system, as described above and illustrated in Fig. 8, which gradually expands throughout the rotor. Another contributing factor may be the accumulation of fat and solid particles on the screw surface. These phenomena result in unfavorable hydrodynamic conditions for the sedimentation of solid particles. At the beginning of the workday, when the interior of the centrifuge is clean, significantly higher purification efficiency is observed compared to later periods of operation.

7. Conclusions

Industrial-scale tests demonstrated the fundamental feasibility of micelle purification from suspended solid particles. During the trials, a solid retention efficiency of up to 90% was achieved. At this level of efficiency, the concentration of suspended solids in the centrifugate was reduced to 1.6%, which fully meets the requirements for the downstream operation of centrifugal separators.

The reduction in purification efficiency during centrifugation is primarily due to the presence of a fat fraction that is insoluble in hexane, leading to micelle emulsification during operation. The feed material represents a three-phase system, which explains the instability of purification performance when using a centrifuge designed for two-phase separation.

As the micelle cools (from the extraction temperature of 50–55°C to around 15°C during the industrial trials), fat solidification may occur. In such cases, the fat can behave as a solid phase, especially since its density exceeds that of hexane. The combination of solid fat and solid particles leads to instability in purification efficiency within a two-phase centrifuge.

To eliminate hexane evaporation, improve working conditions, and enhance fire safety, it is recommended to use a sealed (hermetic) centrifuge.

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