CHURNING IN THE ABSENCE OF AIR

(KARNEN BIJ AFWEZIGHEID VAN LUCHT)

PROEFSCHRIFT

**TER VERKRIJGING VAN DE GRAAD
VAN DOCTOR IN DE LANDBOUWKUNDE
OP GEZAG VAN DE RECTOR MAGNIFICUS,
IR. W. F. EIJSVOOGEL,
HOOGLERAAR IN DE HYDRAULICA, DE BEVLOEIING,
DE WEG- EN WATERBOUWKUNDE EN DE
BOSBOUWARCHITECTUUR,
TE VERDEDIGEN TEGEN DE BEDENKINGEN
VAN EEN COMMISSIE UIT DE SENAAT
VAN DE LANDBOUWHOGESCHOOL TE WAGENINGEN
OP VRIJDAG 15 FEBRUARI 1963 TE 16 UUR**

DOOR

J. H. LABUSCHAGNE

DRUK: „DE VIKING" - OOSTERBEEK

NN08201, 340

STELLINGEN

I

Het karnen bij afwezigheid van lucht, uitgevoerd door room van een matig hoog vetgehalte tussen twee gladde, concentrische cylinders te brengen en een der cylinders te laten roteren, biedt mogelijkheden een continu proces voor boterbereiding te ontwikkelen, dat in principe voordelen heeft boven andere bestaande methoden.

II

De veronderstelling, dat bij het karnen van room de effectiviteit van een botsing tussen twee luchtbelletjes, of tussen een luchtbelletje en een vetbolletje, gelijksoortig is aan en even groot is als de effectiviteit van een botsing tussen twee vetbolletjes, is onjuist.

Vlodavets, I.(1952).Mol.Prom.13(12),30.

III

Bij het versnellen en het mechaniseren van de bereiding van cheddar kaas, dient men vooral de karakteristieke eigenschappen van cheddar kaas niet uit het oog te verliezen.

IV

De kwaliteit van boter, die bereid wordt uit room welke over lange afstanden wordt aangevoerd, zou verbeterd kunnen worden door:

a. Behandeling van de room in een "vacreator" zonder de room te neutraliseren, indien bederf door vetsplitsing is opgetreden.
b. Toevoeging van boterzuursel aan de room op de boerderij.

V

Vetsplitsing, die tengevolge van vervoer en behandeling in rauwe melk kan optreden, moet veeleer aan activering van het substraat worden toegeschreven dan aan activering van het enzym lipase.

Tarasuk, N.P. & Fraenkel, E.N., J.D.Sci.40,418.

VI

Met het oog op een snelle vermindering van het tekort aan eiwit in sommige landen, dient men meer belang te hechten aan een vergroting van de productie per koe, dan aan het fokken van koeien die melk met een hoger eiwitgehalte geven.

VII

De huidige organisatie van de markt voor zuivelproducten in Zuid-Afrika heeft als bezwaar dat boeren erdoor kunnen worden aangemoedigd melk te produceren in marginale, of zelfs in voor de melkveehouderij ongeschikte gebieden.

J.H. Labuschagne
Wageningen, februari 1963.

THEOREMS

I

Churning in the absence of air of a moderate fat content cream, contained between two smooth cylinders, coaxially arranged, with either of them rotating, offers a possibility of developing a continuous buttermaking process, which in principle has certain advantages over other existing systems.

II

The assumption made that the collision effectiveness between two air bubbles, or between an air bubble and a fat globule, is the same and equal to that between two fat globules, to describe the "kinetics" of aggregation during churning, is erroneous.

Vlodavets, I.(1952).Mol.Prom.13(12),30.

III

In the mechanization of the manufacturing process of cheddar cheese, or in methods to accelerate this process, full consideration should be given to the characteristics perculiar to cheddar cheese.

IV

Improvement of the quality of butter manufactured from cream transported over long distances could be accomplished by:-

a. Vacreation of the cream without any neutralization in the case of lypolitic deterioration.
b. Adding butter starter to the cream on the farm.

V

Induced lipolytic activity in fresh milk should be ascribed to activation of the substrate, rather than to activation of the lipase enzyme itself.

Tarasuk, N.P. & Fraenkel, E.N., J.D.Sci.40,418.

VI

For immediate relief of protein deficiency in certain countries, from a dairy point of view, greater importance should be attached to increased production, per cow, than in breeding cows for a higher protein content in the milk.

VII

The danger of the present marketing scheme of milk products in South Africa, is that it encourages farmers to produce milk products in marginal areas, or even in areas not suitable for dairying.

J.H. Labuschagne
Wageningen, february 1963.

Aan Betsie
Aan Ellen

Dit proefschrift werd bewerkt onder leiding van Prof. Dr. H. MULDER in het laboratorium voor zuivelbereiding en melkkunde van de Landbouwhogeschool. De auteur betuigt hierbij zijn diepe erkentelijkheid jegens zijn promotor.

CHURNING IN THE ABSENCE OF AIR

(met een samenvatting in het Nederlands)

by

J. H. LABUSCHAGNE

Laboratory of Dairying, The Agricultural University,

Wageningen, The Netherlands.

CONTENTS

	page
1. INTRODUCTION.	1
2. REVIEW OF LITERATURE.	2
2.1. Collisions between globules.	5
2.2. Local removal of the membrane.	6
2.3. Aggregation of globules.	6
2.4. Disruption of aggregates.	7
3. EXPERIMENTAL METHODS AND MATERIALS.	9
3.1. Construction of the churn.	9
3.2. Temperature control.	10
3.3. Treatment of the cream.	10
3.4. Experimental procedure.	13
4. THE GENERAL BEHAVIOUR OF CREAM CONTAINED BETWEEN TWO COAXIAL CYLINDERS AND THE INNER ONE ROTATING.	15
4.1. Flow characteristics.	15
4.2. Aggregation characteristics.	18
4.2.1. Irregular aggregation. (First zone)	19
4.2.2. Uniform aggregation. (Second zone)	21
4.2.3. Tendency of a "mechanical" emulsion. (Third zone)	21
4.2.4. "True" phase inversion. (Fourth zone)	22
4.2.5. General.	23
4.3. The course of aggregation during churning.	24
4.4. Microscopical examination.	25
4.5. Discussion.	27
5. THE INFLUENCE OF THE GRADIENT OF VELOCITY.	31
5.1. Theoretical considerations.	31
5.2. The influence of the circumferential speed.	33
5.2.1. Duration of churning.	33
5.2.2. Efficiency of churning.	35

page

5.3. The influence of the annular clearance. 35
 5.3.1. Duration of churning. 37
 5.3.2. Efficiency of churning. 39
5.4. The influence of the viscosity. 41
5.5. Discussion. 42

6. THE INFLUENCE OF THE TEMPERATURE. 45

6.1. Aggregation characteristics. 47
6.2. The relative position of similar aggregation characteristics with respect to speed. 48
6.3. Duration of churning. 50
6.4. Discussion. 53

7. THE INFLUENCE OF THE FAT CONTENT OF THE CREAM. 55

7.1. Theoretical considerations. 55
7.2. Duration of churning. 56
7.3. The efficiency of churning. 57
7.4. Discussion. 60

8. THE INFLUENCE OF THE ACIDITY OF THE CREAM. 62

9. THE INFLUENCE OF THE SIZE OF THE GLOBULES. 66

10. SUMMARY AND CONCLUSIONS. 68

SAMENVATTING. 71

ACKNOWLEDGEMENTS. 75

REFERENCES. 76

1. INTRODUCTION

Butter formation can be looked upon as a process of aggregation of fat globules. Churning is accompanied by the rupturing of the membrane at the area of contact between fat globules and, depending on the physical state of the fat phase, butter aggregates might form. When this is combined with mechanical impact and the incorporation of air, the essential requirements for the conventional method of churning are provided. The function of the air/plasma interface (VAN DAM 1934) and in addition, mechanical pressure in the interface, and between air bubbles (MULDER 1947) form the basic concept in the mechanism of aggregation.

The majority of commercially operated churning systems are mainly dependent on the incorporation of air in producing butter. However, phase inversion of highly concentrated cream, where the rôle of air is of no importance,has found successful adaption on a commercial scale. Foamless churning of cream of moderate fat content - at one time thought not to be possible (RAHN 1928) - has only recently been proved indisputably to be possible.

The process of aggregation of fat globules is probably analogous to the coagulation of colloids, provided that the collision frequency is evenly distributed in the cream, and that the collisions result in stable aggregates. It should be kept in mind, however, that the concentration of the dispersed phase is very high in cream. Without the additional aid of the air/plasma interface, churning will now be dependent only on the chances of collision and the probability of adhesion between fat globules. Since emulsions can be made or broken by agitation, depending, amongst others, on the adhesive properties of the fat phase, the possibility of disruption is thus a factor that will also have to be contended with.

Many churning systems could be applied for the purpose of this study, but it was realized that a system had to be used in which the flow pattern of the cream should not be of a complicated nature, such as for instance, in those systems where turbulent flow exists. For this reason cream contained between two smooth, coaxial cylinders with the inner one rotating seemed appropriate in studying the churning process for the purpose of this investigation. This investigation was carried out as a consequence of the work done by MULDER and SCHOLS (1953) and MULDER and HAANS (1953). The aim of this study was to investigate the phenomenon of aggregation and disruption, and to establish the relationship between:

a. the duration of churning;

b. the efficiency of churning;

and the various factors that are known to influence churning, in the absence of air.

2. REVIEW OF LITERATURE.

RAHN (1928), the originator of the so-called foam theory of butter formation, claimed that foaming of cream is essential in order to produce butter. His churning experiments in the absence of air failed, leading him to make this statement. This claim by RAHN was partially disproved by MOHR and BROCKMANN (1930) who, under normal churning conditions, claimed to have obtained butter in the absence of air from aged sweet cream and acid cream, but not in the case of fresh sweet cream. These findings were later supported by PALMER and WIESE (1933). In these experiments there is no absolute surety whether air was completely excluded from their churn as no indications are given whether proper precautions were taken to remove the air from the cream or to prevent air from entering the churn during the churning process.

Working under similar conditions as that of MOHR and BROCKMANN, with a completely filled churn and at normal speed of the churn, MULDER (1947) was unsuccessful in obtaining butter, but maintained that this must be possible provided the conditions are favourable, as butter can be obtained by moderate agitation of a very high fat content cream, for instance in the Alpha continuous buttermaking process. Having this in mind, MULDER and SCHOLS (1953) later carried out experiments with vacuum de-aerated cream and a completely filled, hermetically sealed, Hollstein churn, and managed to obtain butter, but this time using higher agitator speeds. They managed to establish the influence of the agitator speeds, temperature and the percentage fat in the cream, on churning. The last-mentioned workers came to the conclusion that the earlier unsuccessful attempt was to be ascribed to an inadequate speed of the churn. Possibly, the same cause also applies in the experiments of RAHN. This could also have been the case in the experiments of MOHR and BROCKMANN (1930) on fresh sweet cream.

When churning in the absence of air, the mechanism of aggregation would be completely different to that when air is copiously incorporated in the cream. Aggregation will now be more dependent on the probability of direct collisions between globules and the probability of adhesion, without the presence of the air bubble which has the property of concentrating globules in the air/plasma interface. The part the air bubble plays during the process of churning forms the basis of the churning theory advanced by VAN DAM (1934), KING (1931, 1932) and others, which briefly is as follows: The incorporation of air bubbles in the cream leads to a large air/plasma interface, thus permitting fat globules to come into contact with this air/plasma interface. A part of the membrane as well as some of the liquid fat is spread out here. Close packing of the globules in the lamallae of the air bubbles, permit the globules to contact with each other and get attached by means of the liquid fat. On bursting of the air bubble the aggregate is flotated again, resulting in a further growth of the aggregate. On repeated bursting and formation of air bubbles - the membrane material and the liquid fat acting as a foam depressant - aggregates are repeatedly flotated, until they become visible.

The contentions held by MULDER (1947) are, that apart from the rôle of the liquid fat that spreads out in the air/plasma interface as mentioned above, the mechanical aspects in aggregation are just as well of great importance. The fat globules crowding in the air/plasma interface lose their freedom of movement and get pressed together not only here, but also between the air bubbles, thus rupturing their membrane. Aggregation can then occur by means of the liquid fat that is spread out in the air/plasma interface and also by direct fusion of the fat as a result of mechanical pressure. The larger the aggregate developes the greater the importance of the mechanical influence in aggregation.

It was realized by MULDER and SCHOLS (1953) that in order to obtain a clearer insight into the actual churning process in the absence of air, that at least the flow pattern of the cream must have a uniform or laminar characteristic, which then would greatly simplify matters, rather than have a flow pattern of a highly complicated type, such as that existing in the Hollstein churn. A churn was then devised in which the cream was contained between two vertical coaxial cylinders and the inner one rotating. Unpublished results by MULDER and HAANS (1953) of preliminary experiments showed promise of evaluating the kinetics of butter formation similar to the theory of VON SMOLUCHOWSKI (1917) for the flocculation of colloid particles in a laminar current.

Russian dairy scientists in their "macro-kinetical" investigation of butter formation often made use of foamless butter churning systems. VLODAVETS (1952) quotes GRISHCHENKO (1950) as having obtained butter in a turbulent zone (caused by stirrers) in the absence of air and observed that aggregation proceeds according to an equation of the first degree. In later experiments by GRISHCHENKO (1953) in the absence of foam and in the turbulent zone, probably caused by the stirrers of the churn, found that churning times are inversely proportional to churning temperatures (2^{o}-24^{o}C), peripheral speed of the beater, and fat in the cream. A minimum value of fat in the buttermilk was found at 14^{o}C, but a tendency to increase with increasing fat in the cream was also found, while it remained constant with an increase in the peripheral speeds. SHUVALOV and VLODAVETS' (1954) findings, which are based on the work of GRISHCHENKO (1953) and on their own results, have shown that a logarithmic dependence exists between the duration of churning and the fat content of the cream and the speed of the stirrer. FASTOVA and VLODAVETS (1956) using an apparatus similar to a concentric cylinder viscometer and with de-aerated cream, found the same tendencies in churning times.

VLODAVETS (1952) considered butter formation as a process of simple aggregation of fat particles analogous to the coagulation of colloids. He assumed that the flow pattern of the cream is laminar along a stationary smooth surface. An empirical formula is given for the rate of reduction in the number of fat "particles" by progressive conglomeration and also for the churning times,with the fat content of the cream and velocity of flow as variables. VLODAVETS deduces a formula in the case when air is incorporated, and assumes that the effectiveness of collisions between air bubbles and of air bubbles with fat globules is equal to that between globules. It is, however, highly improbable that the collision effectiveness is the same, and besides, the air bubbles have a completely different function and another phenomenon is here of much more importance. Worth mentioning also is a paper submitted by GRISHCHENKO (1959) at the Dairy International Congress which deals with the kinetics of the aggregation of fat globules in a vessel containing stirrers, filled at different levels with cream. He found that the duration of churning was affected more by the temperature than by the fat content of the cream and more by the latter than by the speed of the stirrer, provided, according to him, the degree of stability of the membranes is the same. He also deduced that between the speed constant of churning and the churning temperature an exponential relation exists, which may be expressed by means of the Arrhenius equation.

Churning in the absence of air and having a systematic flow pattern, not only simplifies matters, but creates an orderly system, thus providing a better possibility in finding some analogy to the basic and well-known theories in science e.g. coagulation of colloids, or in deriving some formula to describe the churning process. Generally, the mechanism of aggregation is determined by the possibility of collisions and the probability of adhesion. Most of the work on coagulation of colloids has been studied as a result of collisions due to the Brownian movement of particles. As a result of the large dimensions of the fat globules, the rate of diffusion is very small and the effect of Brownian collisions is thus of no significance. Agitation, or any other mechanical means,has to be applied in order to promote collisions and in doing so, cause adhesion between globules.

When considering all the factors that might influence churning, there are, however, some fundamental factors that will determine the duration and efficiency of churning. These factors are:

a. Collisions between globules.

b. Local removal of the membrane.

c. Aggregation of globules.

d. Disruption of aggregates.

2.1. COLLISIONS BETWEEN GLOBULES.

The probability of collision of a particle with another particle, per second during agitation, in which the fluid flow could be looked upon as locally a laminar current, was established by VON SMOLUCHOWSKI (1917), which is:

$$J = \frac{4}{3} N R^3 \frac{du}{dz}$$

in which N = number of particles per ml of uniform size and R = the sphere of attraction which is taken as the sum of the radii of two particles and $\frac{du}{dz}$ = the velocity gradient.

The collision chances are thus directly proportional to the gradient of velocity. Generally, two other aspects have also to be taken into consideration, them being: firstly the distribution of collisions throughout the cream and secondly the intensity of collisions. It is essential that in order to obtain efficient churning all globules should participate in aggregation and thus all have an equal chance in forming aggregates.

Collisions will be more frequent when there are more globules per ml i.e. when the fat content is high, whilst in cream of a low fat percentage the chances of collision are less. A high viscosity will have a tendency to diminish the collision intensity in those cases where globules are far apart, and also affects the general flow pattern, but on the other hand causes an increase in the shear stresses exerted on globules in contact with each other.

According to the above formula the size of the globules has a marked influence on the collision chance, which is proportional to the third degree of the sphere of attraction between globules. WIEGNER (1911) and MÜLLER (1926) investigated the effect of poly-dispersed systems on rapid coagulation of colloids and their findings might have some application in the aggregation of fat globules. The collisions of particles of different sizes are more probable than that between particles of equal sizes, and MÜLLER (1926) established that the collision chance of a small particle with a larger one (with radii r_i and r_j) is proportional to

$$\left[4 + \left(\sqrt{\frac{r_i}{r_j}} - \sqrt{\frac{r_j}{r_i}}\right)^2\right] D_1 \ r_1$$

In the theory of VON SMOLUCHOWSKI the probability of collision was taken as proportional to $4D_1r_1$ (appr. = $D_{ij}.R_{ij}$), for particles of equal size. D is the diffusion constant of the particles and R the radius of attraction. The larger the aggregate becomes the greater the rate of aggregation and it will also be influenced by the difference in aggregation rates of different particles. (MÜLLER 1928).

2.2. LOCAL REMOVAL OF THE MEMBRANE

The presence of a film or emulsifier on the surface of the dispersed phase has received much attention as regards the stability of dispersions. The emulsion stability of cream is mainly ascribed to the membrane, and, depending on the solidified state of the fat, it forms the main barrier in aggregation. The emulsion stabilizing substances - a complex consisting mainly of proteins and phospholipids - have at least to be locally removed i.e. at the point of contact, before globules are able to combine. In the air/plasma interface, membrane and liquid fat, are spread out on the surface, thus permitting adhesion of globules.

A high fat percentage in the cream will be an aid in the removal of the membrane due to the greater shear between globules as a result of them now being more closely packed, than in the case of cream having a low fat content. Hard particles in the cream, for instance precipitated casein, (MULDER 1947) will contribute in damaging the membrane and thus cause more rapid aggregation.

2.3. AGGREGATION OF GLOBULES

During the creaming of milk or ageing of cream, some aggregates are formed but with the membrane still intact. Aggregates of this type are in reality clusters of globules still retaining their original individuality and there is no direct contact between the fat portion of the globules.

Apart from the collision chances, efficient churning will be dependent on the effectiveness of such collisions in forming stable aggregates. When the forces occurring during a collision between two globules break the coherence of their surface, aggregation will occur and the resultant aggregate should be sufficiently stable to resist disruption by the existing shearing forces. The most stable form of aggregate is a globular one, i.e. when coalescence occurs. However, this is not always possible at the normal churning temperatures when taking into consideration the physical state of the fat. At low temperatures and even at normal churning temperatures aggregates will have a distorted form with easily identifiable globules adhering to each other.

It has often been stated that churning is dependent on the physical state of the fat. The area of contact between globules will determine the stability of such an aggregate. At low temperatures the area of contact is small due to the small amount of liquid fat present and vice versa at high temperatures. Higher forces will be needed to cause effective aggregation at low temperatures. The importance of the angle of collision (GORBATSCHEW 1935) and the time of contact (BARTOK and MASON 1959) might now be of importance in obtaining a stable aggregate at these low temperatures. Aggregation at high temperatures will readily occur, but as the fat is now less viscous, disruption will also occur easier.

The most ideal conditions would be that the process of aggregation should be continuous or progressive. A systematic rate of aggregation is possible when a systematic flow pattern exists. The rate of coagulation (irreversible coalescence) of spherical hydrophobic colloids of equal size and bearing no repulsion action was originally determined by VON SMOLUCHOWSKI (1916, 1917). By determining the probability of collisions between primary particles to give doublets, doublets and singlets to give triplets, and between doublets to give quadruplets, etc., established that the decrease in the total number of particles proceeds as a bimolecular reaction. The final equation being:-

$$Nt = \frac{No}{1 + \frac{t}{T}}$$

in which T is called the time of coagulation; giving the time in which the total number of particles is halved. No, is the original number of particles at time(t) = 0 and Nt the number at time = t.

2.4. DISRUPTION OF AGGREGATES

It is conceivable that disruption will always be present as it could not be expected that on every collision a stable aggregate will be formed. The question arises which one of two processes - aggregation or disruption - will predominate.

In general terms the stability of an aggregate will depend on the cohesive forces between two globules and when the hydrodynamic shearing forces exceed this force, trying to maintain an aggregate, disruption will take place. CLAY (1940), investigating the mechanism of emulsion formation in a turbulent field, established that the hydrodynamic forces will determine the state of dispersion, in that, coalescence and disruption will counteract each other and lead to an equilibrium, or to a stationary state of emulsion. According to CLAY (1940) a certain size of aggregate is thus possible, depending on the hydrodynamic forces present when any further growth in aggregate size is not possible due to disruption. The degree of disruption will be determined by the temperature and the physical state of the fat.

At low temperatures, as a result of insufficient liquid fat present, the area of contact between globules is small and disruption will occur easy. The same could also happen at high temperatures because of the low viscousness of the fat, although sufficient liquid fat is present, and a large area of contact exists.

In the literature cited the flow pattern has been described as either laminar or turbulent. When using churns containing beaters or stirrers, undoubtedly turbulence will be present but having a very uneven flow distribution throughout the churn. When using smooth surfaced cylinders, coaxially arranged, and the inner one rotating, no proper differentiation was made between the different patterns of flow. Flow between two concentric cylinders in comparison to that through a circular tube is marked by an intermediate stage between laminar and turbulent flow, which is, when vortices appear, and this phenomenon is fully described by TAYLOR (1923). This type of flow still has laminar flow characteristics (ROUSE 1959) and turbulence sets in at a much higher Reynolds number than in the case of flow through a circular tube.

3. EXPERIMENTAL METHODS AND MATERIALS

3.1. CONSTRUCTION OF THE CHURN

The churn that was used consisted of two coaxial cylinders of which the solid inner cylinder can be rotated. The outer one, being a double-walled cylinder, through which water can be circulated (water-jacket), is stationary. Through the double-walled outer cylinder two round "observation windows", vertically arranged, and made of clear perspex-glass, were fitted. The whole of the construction was of stainless steel and the inside wall of the outer cylinder (thickness $1\frac{1}{2}$–2 mm) and the inner cylinder surfaces were polished. The bottom end of the inner cylinder rested on a steel ball-bearing. The inner wall of the outer cylinder and the perspex-glass "windows" were smoothly finished off so as to ensure that no turbulence occurs due to roughness at the joints.

The top and bottom ends are of "Akulon" (a Nylon product) and can be screwed into the main body of the churn. The top and bottom end-clearances were maintained at 1–2 mm during the performance of the experiments. Full details of the construction of the churn are given in Fig. 1. The annular clearance could be varied by substituting with other cylinders having different diameters. Use was made of six inner cylinders having diameters of 4.90, 4.70, 4.30, 4.00, 3.60 and 2.80 cm, giving annular clearances of 0.15, 0.25, 0.45, 0.60, 0.80 and 1.20 cm, respectively.

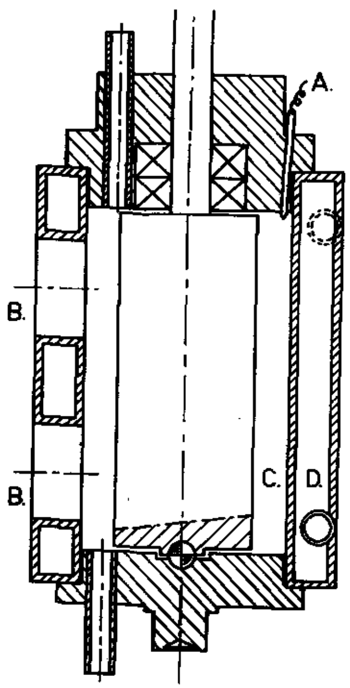


Fig. 1

Details of churn construction.

(a) Thermo-couple;
(b) Observation windows;
(c) Annular clearance;
(d) Water-jacket.

By means of the observation windows the churning process and butter formation could easily be observed in the annular clearance. In some cases, especially when low speeds were used, use was made of an outer cylinder (with water-jacket) which was completely constructed of perspex-glass having exactly the same dimensions as the steel churn described above.

The churn was driven by an electric motor ($\frac{3}{4}$ hp) and the power transmission was by means of a timing-belt and sprocket wheels, thus preventing any possible slip that might occur during experimentation. By means of a system of sprocket wheels of different diameters the speed of the inner cylinder could be varied. In order to obtain a wider selection of speeds, a system of double transmission was also made use of. The whole system of churn and electric motor, etc., was mounted on a heavy iron stand and the position of the electric motor was adjustable.

3.2. TEMPERATURE CONTROL

The temperature of the cream in the annular clearance could effectively be controlled with the aid of a thermo-couple and water circulation through the double-walled outer cylinder. The thermo-couple was inserted at the top of the churn to a depth of approximately 3 mm into the annular clearance.

A forced water circulation system was used, and the flow of the water could be regulated by varying the speed of the centrifugal pump. In this system a water reservoir was also used. A constant temperature of the cream could be maintained by either varying the flow of the water or by adding ice to the reservoir. In this manner temperature could be controlled within half a degree (centigrade) variation on either side of the desired temperature. In most cases, and especially after some experience, temperature could be kept at exactly the correct value. The thermo-couple and temperature recorder were checked and standardized at regular intervals.

3.3. TREATMENT OF THE CREAM

Fresh milk from the dairy herd of the Animal Husbandry Section was separated at a temperature of between 35 and 40°C. Standardization with skimmilk, from the same milk, to the desired fat percentage was then carried out. The cream was then gradually heated over a period of 20-25 minutes to 70°C and held at this temperature for ten minutes during which time the cream was also de-aerated. De-aeration was done by means of a vacuum and only sufficient vacuum was applied so as not to cause any boiling or foaming of the cream. The cream was then cooled to 4-6^{0}C and held at that temperature, and still under vacuum, for a minimum time of 18 hours. The average time it took for the cream to reach this temperature was approximately 45 minutes. This intermediate period of 18 hours between cooling and churning was allowed for crystallization of the fat.

As a result of compositional variations of the butterfat, as well as possible variations in the treatment of the cream, it was found necessary to prepare a large amount of cream in order that a complete series of experiments could be conducted using the same cream. Before churning was commenced the cream was allowed to warm-up gradually, over a period of one hour, to the desired churning temperature. The cream was then held at that temperature for subsequent churns. The cream was prepared in batches; each batch having sufficient cream for approximately 6-8 churns. Depending on the duration of churning, the cream was seldom held at its churning temperature longer than 6 hours. A batch was only used once and not for instance cooled and then used again.

It was experienced that when the cream was warmed-up too fast to the desired churning temperature, churning was longer than when the warming-up was done gradually, as will be noticed in Table 1. Holding the cream for long periods at its churning temperature had practically no influence on the churning times as will be noticed in the same Table.

TABLE 1. The effect of the warming-up period and the period of holding at its churning temperature (18^{o}C) on the churning time (min) (40% cream; speed 450 cm/sec; annulus 0.45 cm; refractive index of butter fat (Nd) = 42.3)

Time held at churning temperature	Warming-up period (min)		
	$\pm$ 5'	30'	60'
Immediately after warming-up period.	$7\frac{3}{4}$	$6\frac{1}{2}$	5
$\frac{1}{2}$ hr.	-	$4\frac{1}{2}$	-
1 "	$6\frac{1}{2}$	$5\frac{1}{4}$	$4\frac{3}{4}$
2 hrs.	-	$5\frac{1}{2}$	-
3 "	$7\frac{1}{2}$	-	5
4 "	-	$5\frac{1}{4}$	-
7 "	-	-	5

From these results it seems that a certain warming-up period is necessary. This may be ascribed to the state of equilibrium between the different fat fractions as regards their solidification and melting properties. As a safety measure it was then decided to warm-up gradually over a period of one hour before churning and then keep the rest of the cream at its churning temperature for the next churns.

Due to possible variations in the physico-chemical properties of the fat and variations in the pre-treatment of the cream it was thought advisable to prepare sufficient cream to be able to conduct a series of experiments using the same cream and thus also the treatment being the same. In order to complete a series of experiments it was found necessary to hold a batch of cream at 4-6°C as long as 3 to 4 days which meant that the time of crystallization varied for that particular series. A small investigation was then conducted to establish whether the time kept at this temperature did not affect the churning times. The results of two experiments are given in Table 2.

TABLE 2. The effect of the period the cream was kept at crystallization temperatures, on churning. (Churning temp. 18°C; annulus 0.45 cm; speed 320 cm/sec)

Exp. 1 (% Fat - 40.5)			Exp. 2 (% Fat-39.7)	
Crystal-lization time/hrs.	Time held at churning Temp./hrs.	Churning time/min.	Crystal-lization time/hrs.	Churning time/min.
22	-	17½	4	25
52	-	15½	22	26½
52	2	17	70	22
54	-	14½	94	22½
70	-	18		
71	-	18½		
71	5	15½		
96	-	17		

Although variations in the churning times are encountered it could, however, not be ascribed to the time of crystallization. These variations were considered quite normal for these experiments as will be seen in Table 3. The cream was prepared in one batch and then divided into different smaller batches and a new batch used the next day or when a sub-series of experiments was started.

3.4. EXPERIMENTAL PROCEDURE

When filling the churn, precautions were taken not to include any air. The churn was completely filled and then properly stoppered. A close-fitting rubber seal around the axle of the inner cylinder, where it passes through the top end of the churn, prevented leakage of the cream.

At the start of this investigation use was made of a perspex-glass double-walled outer cylinder, but due to poor heat conductivity of the perspex-glass, experiments were only limited to the low speeds; at the most 1000 revolutions per minute. Later a steel churn was constructed with which practically all experiments were conducted. The perspex-glass churn was, at times, used at low speeds or when some of the characteristics of flow was investigated, e.g. the number of vortex bands along the axis of the churn, etc.

As an aid in establishing the moment butter is formed, sudan III was added to the cream. A certain time elapsed before sudan III (in powder form) was absorbed by the fat, but towards the end of churning, the rate of absorption increased considerably. The absorption of sudan III by the fat seems to be correlated with the de-stabilization of the fat globules. Churning was stopped immediately the moment butter was formed and not allowed to continue after the butter had formed.

To prevent any end-effects to the general flow pattern of the cream, the top and bottom clearances of the inner cylinder were kept as small as possible. Butter would then form much faster in the end-clearances and form a "seal", thus diminishing end-effects and also possible mixing of the cream with the buttermilk in the annular clearance, than in those cases when the end-clearances were too large. Immediately after the churn was stopped, the cream remaining in the in- and outlets was first removed to prevent this cream mixing with the buttermilk. Even after taking all these precautions a small percentage of cream e.g. in the bearings etc., mixed with the buttermilk. The buttermilk was filtered through a sintered glass filter (40-60 μ pores) before determining the fat content. The method of Gerber was used in determining the fat content.

The reproducibility of results concerning the churning times and the fat content of the buttermilk was not as good as was hoped. In Table 3 the variations of results of a few typical experiments at a constant circumferential speed, are given.

TABLE 3. Reproducibility of results of churning experiments.

Exp.	Churning time. (min.)		% Fat in the buttermilk	
	mean	sd	mean	sd
1/6	19	3.0	4.6	1.5
19/1	25	2.5	-	-
5/6	11	2.2	2.9	1.0
12/6	15	2.9	3.9	0.7

sd = standard deviation.

These results shown in Table 3 were obtained in a region where normal churning was encountered, but results obtained in those cases, other than when this condition existed, exhibited much greater variations. In such cases the results were not considered for calculating purposes. Generally, the coefficient of variation varied between 5 and 30 per cent. The standard maintained in this investigation was 15 to 20 per cent and this was considered quite normal for these experiments. In view of this the range of conditions was chosen as wide as possible so that the variations in relation to the churning times over the whole range were in fact small. In the case of the fat content of the buttermilk, greater variations were experienced, and this aspect will be dealt with later.

The results, where found necessary, were subjected to statistical analysis according to the methods prescribed by SNEDECOR (1956).

4. THE GENERAL BEHAVIOUR OF CREAM CONTAINED BETWEEN TWO COAXIAL CYLINDERS AND THE INNER ONE ROTATING.

4.1. FLOW CHARACTERISTICS

The cream contained between two coaxial cylinders and the inner one rotating, arranges itself in a series of equidistant "bands" perpendicular to the axis of rotation. When sudan III is added to the cream these bands can easily be seen and they are alternately arranged in white and red bands (Plate 1). The red band, being the much wider, is divided into two equal parts, which are characterised by pronounced left and right rotating vortices. As the churning progresses, the aggregates make an imprint on the wall - leaving a featherlike pattern - which indicates plainly the contra-rotating direction of these vortices accross the annular clearance.

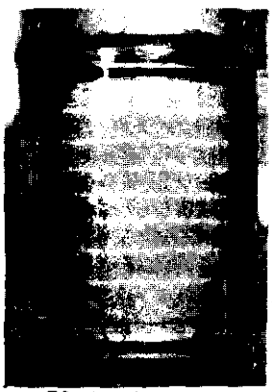


Plate 1.
Vortice bands during churning

The width of these bands have a certain degree of variation and usually, as the churning process progresses, the red band decreases and the white band increases in width.

In certain instances, usually when a bigger annular clearance was used, a smaller red band was noticed in the middle of a white band.

TAYLOR (1923) in his investigation concerning the stability of a viscous liquid contained between two rotating cylinders, established that the spacing of these vortices is equal to the distance between the two cylinders, and that they are alternately arranged in left and right rotating vortices. These vortices according to TAYLOR are approximately arranged in squares accross the annulus. In these experiments it seems that the vortices, mainly on account of the presence of the white band, have an ellipsoidal form. This is particularly noticed towards the end of churning. In Fig. 2 the general pattern of the flow arrangement of the vortices is given.

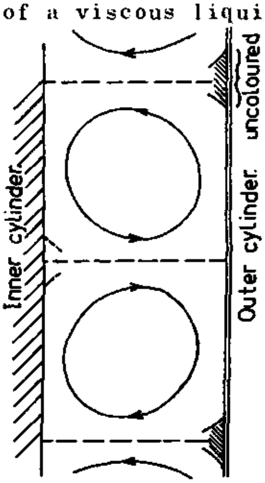


Fig. 2.
Flow arrangement of vortices.

Immediately before butter formation, sudan III is dissolved at an increased rate, and coupled with a form of turbulence (pulsating movement of the vortice bands); this indicates that excessive shear of globules and aggregates takes place. The narrowing of the red bands (containing the fat) as churning progresses might be due to aggregates concentrating towards the centre of such a vortice.

Often during churning the amount of rings would change, especially at low speeds. At higher speeds the number of bands remained more constant and the flow seemed more stable. The variation in the number of bands and the average width of the vortices for the annuli are given in Table 4.

TABLE 4. Number of bands and average width of a vortex for the different annuli. Cylinder height - 9 cm.

Annular clearance - cm	Number of red bands		Width of vortice - cm
	Variation	Average	
0.15	16 - 20	18	0.20
0.25	11 - 14	13	0.30
0.45	8 - 10	10	0.45
0.60	6 - 8	8	0.55
0.80	4 - 6	5	0.80
1.20	3 - 4	?	-

No uniformity as regards these changes in the number of vortices could be detected and it seems that it occurs arbitrarily. Flow between two concentric cylinders, R_1 and R_2, ($R_2 > R_1$) with the inner one rotating at a circumferential speed of U.cm/sec is characterised by the appearance of annular vortices at a certain critical Reynolds-number. This transition from stable to unstable flow, i.e. when annular vortices appear, is dependent on the ratio $(R_2 - R_1)/R_1$ according to TAYLOR (1936) and SCHLICHTING (1955). According to PRANDTL (1956) these vortices appear when.

$$U(R_2-R_1)/\nu = 41.3\sqrt{R/(R_2-R_1)}$$

where U is the circumferential speed, (R_2-R_1) the annular clearance, R the average radius of the two cylinders and R_2 and R_1 the radius of the outer and inner cylinders, respectively, and ν the kinematic viscosity. This type of disturbance, according to TAYLOR (1923), is symmetrical. The flow still has laminar flow characteristics or to quote "... when instability initially occurs the flow does not directly turn turbulent, but goes into another mode of laminar motions" (ROUSE 1959). These vortices are strongly stabilized by centrifugal forces with the result that turbulence occurs at a much higher Reynolds-number than usually is expected.

This type of flow differs from that through a circular tube, in that, this phenomenon forms an intermediate stage between laminar and turbulent flow. In this investigation all experiments were conducted in a region where vortices were always present. According to TAYLOR (1935) a large gradient of velocity in the case of instable flow is confined to the walls of the cylinders, and over the major part of the clearance (83% in this case) a small velocity gradient is present. In addition, secondary flow also being present as a result of the vortices, a gradient of velocity exists in an axial plane. The centre of such a vortice, according to TAYLOR (1923), has the highest velocity and decreases at a constant rate towards the walls of the two cylinders. The resultant condition is that particles of cream will flow in complicated three dimensional curves.

The motion of flow is controlled by the inertial and viscous forces. The similarity, or the behaviour of flow can be described by means of the Reynolds-number, which is, a certain dimensionless group of variables. The Reynolds-number is the ratio of the inertial forces to the viscous forces which then makes it possible to describe the flow behaviour of fluids.

The viscous forces acting on an area df. are given by τdf. where $\tau = \eta \frac{du}{dz}$ represents the shear stress, η the dynamical viscosity (a fluid constant) and $\frac{du}{dz}$ the velocity gradient. The inertial forces acting on a volume dv. are given by $\rho \frac{du}{dt} dv$, where ρ the mass density of the fluid and $\frac{du}{dt}$ the acceleration. The ratio of both forces is therefore given by $\rho \frac{du}{dt} dv \Big/ \eta \frac{du}{dz} df$

or in unit dimensions representing, speed by V, length by L as the following group of variables: $Re = \frac{\rho VL}{\eta}$.

In this case the characteristic speed is given by the circumferential speed of the inner cylinder U. As a characteristic length the annular clearance (R_2-R_1) was chosen. Therefore in this case the Reynolds-number will be: $Re = U(R_2-R_1)\rho \big/ \eta$. When the annular clearance is decreased or when the kinematic viscosity is increased, a higher velocity is needed to be able to obtain the same behaviour. In this investigation it can be reasoned that, in order that the motion of particles is the same, the ratio of these forces acting on the particles must be the same.

4.2. AGGREGATION CHARACTERISTICS

In a series of churns at different speeds of the inner cylinder it soon became obvious that butter formation was not uniform throughout the whole range of speeds used. In preliminary experiments in which churning was conducted at normal temperatures it was found that, depending on the speed, two main "types" of behaviour could easily be recognised. In addition it was noticed that at high speeds and also when the refractive index of the fat was high, churning times, instead of continuing to decrease, started to increase again; thus a third difference or behaviour became apparent. As this occurred only at the maximum speeds (4350 Revolutions per minute) that could be attempted with the apparatus, no proper results could be obtained to illustrate this third behaviour. It was reasoned, however, that the same effect could be obtained if higher churning temperatures were used.

At 22°C using the same cream and the same annular clearance, but varying the speed of the inner cylinder, four main characteristics in churning behaviour were encountered. These differences concerned mainly the manner and extent of aggregation and also the trends in churning times and could be divided into four zones. The behaviour or characteristics of churning of each of the four zones are given in concise form in Table 5.

TABLE 5. The main characteristics of successive churning zones arising at 22°C as the circumferential speed of the inner cylinder is increased.

Speed zone	Trends in churning times	Homogeneity of aggregation	Fat in buttermilk
First (slow speed)	Decreasing	Irregular	High
Second	Decreasing	Uniform	Low
Third	Increasing	Uniform	Low
Fourth (high speed)	Decreasing	Uniform - (Water-in-fat-emulsion)	-

In Fig. 3 are illustrated the trends in the churning times at different circumferential speeds of the inner cylinder as well as the approximate limits of the different zones. This condition, considered also in Table 5, existed only when the churning temperature was higher than normal (22°C and higher). At normal temperatures (16°C and lower) only two zones arose within the limits of the speeds attainable in this investigation. The position of these zones relative to the speeds of the inner cylinder is greatly affected by changes in the churning temperatures, the composition of the fat, etc.

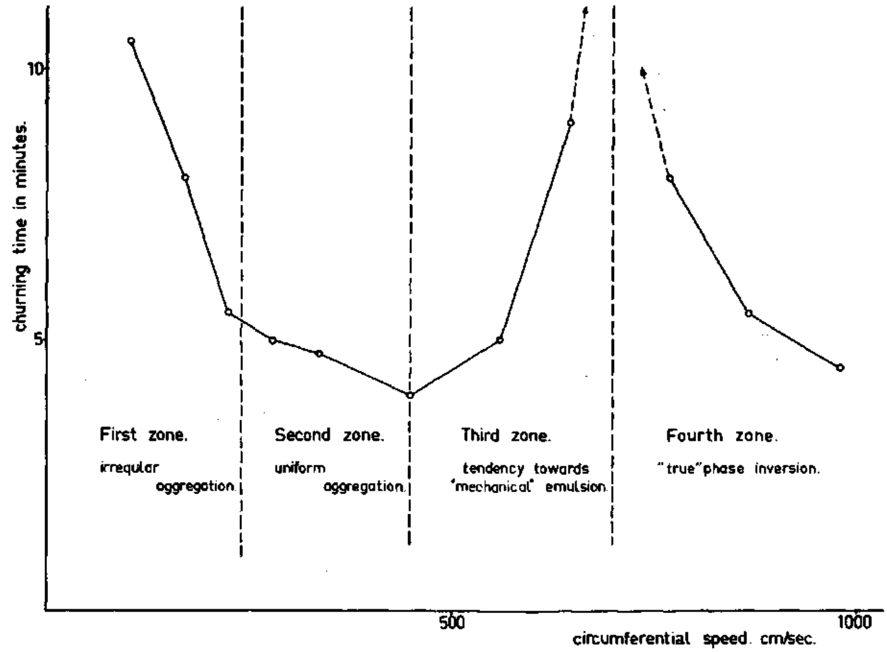


Fig. 3. The churning zones, indicated by differences in churning characteristics developing as the speed is increased. (% Fat 39.8; Annulus 0.45 cm; Temp. 22°C; Nd = 42.1)

The aggregation characteristics of each zone can be describe as follows:

4.2.1. Irregular aggregation. (First zone)

The main differences compared with the other zones are:

a. Irregular distribution of globules aggregating in the cream, i.e. only certain globules participate in aggregation.

b. Globules aggregate erratically during the churning process.

c. Aggregates vary considerably in size at all stages during the churning process.

d. Gradual butter formation.

In this zone aggregates are formed at various times during the churning process and eventually they become visible in the annular clearance as free-moving granules. The actual number visible will depend on the speed. As churning progresses more appear, and at any instant during the churning process, aggregates are in various stages of formation. The rate of growth of the bigger aggregates is much faster than that of the smaller, with the result that disproportionate aggregation is characteristic of churning in this zone. With continued churning more appear and further growth of aggregates occur until eventually, depending on the annular clearance, they stick to the side of the churn. This then interferes with the smooth flow pattern of the cream, causing localized turbulence, and, in addition temperature control as a result of aggregates sticking to the thermo-couple, becomes difficult.

The combined effects of localized turbulence and dilution by the buttermilk that has already been churned, serve to considerably alter later churning conditions from those existing at the start. However, despite these conditions more butter is steadily formed until a big percentage of the globules have aggregated, as illustrated in table 6.

TABLE 6. Aggregation during churning in a case when irregular aggregation was encountered.

Times of sampling (min)	% Fat in "buttermilk"	Remarks
0	30.5	
10	22.5	Visible aggregates
15	19.8	
20	19.0	Granules sticking to side of churn and turbulence setting in.
25	14.0	
30	11.1	
40	4.0	

The "buttermilk" was separated from the granules by filtering through a sintered glass filter (size of pores 40 - 60 μ). It is thus obvious that in this zone complete churning will eventually be obtained, but that in the process eveness of flow and temperature control are impeded. Thus, in order to adhere to those conditions existing at the start of churning and particularly those conditions aimed at in this investigation, churning was stopped as soon as aggregates became visible and were reasonably well distributed throughout the annular clearance. Normally only a limited proportion of the globules has participated in aggregation at this stage. All globules will eventually participate in the formation of butter, and the faster rate of aggregation is partly attributable to the altering of the steady flow pattern of the cream. Because of these difficulties no definite way could be found of establishing the duration of churning and it was therefore not included for consideration in this investigation. The term to be used forthwith to describe this condition, existing in this zone, will be "irregular aggregation".

4.2.2. Uniform aggregation. (Second zone)

Both the first and second zones show a decreasing trend in churning times, and can be differentiated only on the basis of their aggregation characteristics and the fat content of the buttermilk. These are for the second zone:

a. Uniform aggregation involving "all" globules in the cream.

b. A tendency towards a more even-sized aggregate.

c. "Instantaneous" butter formation.

Operation within this zone is easily recognized by the fact that butter formation occurs suddenly (breaking of the emulsion) in contrast to the continuous aggregation occurring in the previously mentioned zone. This condition could be compared with the "breaking point" in the conventional method of churning. Butter is formed throughout the whole annular clearance and, then the butter, partly or completely comes to a standstill, which makes further churning impossible. The fact that butter formation is "instantaneous" presents an excellent means of determining the end of churning.

When churning in this zone, the amount of fat remaining in the buttermilk is low. It is thus obvious that practically all globules participate at about the same time in the initial growth of aggregates, and that aggregate formation occurs evenly and uniformly throughout the cream. It seems therefore that when such conditions exist clumping suddenly occurs when a certain critical aggregate size has been reached.

The transistion from a condition where irregular aggregation is encountered to a condition of uniformly distributed aggregate formation, appears to occur at a definite speed of the inner cylinder. Because of the system used in varying the speed of the inner cylinder, this "transition point" could not be established accurately, but it was nevertheless possible to place it between two limits, involving a relatively narrow range of speeds. At the transition from irregular to uniform aggregation the fat content of the buttermilk is almost at a minimum and does not diminish further to any significant extent at higher speeds. This aspect of the investigation is dealt with in more detail later. In addition the sizes are more or less the same, becoming even more so as the speed increases. At the point just before butter is formed the granules are smaller at greater speeds which is to be expected since depending on the speed only a certain size of aggregate is possible.

4.2.3. Tendency of a "mechanical" emulsion. (Third zone)

With a further increase in the speed a stage is reached when the churning time starts increasing. This is particularly noticeable when the churning temperatures are high e.g. 22°C and higher. The same increase was also encountered at 18°C in cases when the refractive index of the fat was high, for instance during the summer period. At temperatures below 18°C this was not obtained even at the maximum speeds attainable in this investigation. However, the possibility that it might occur at high speeds cannot be ruled out. Aggregation in this case could be divided into two stages; an initial fairly rapid aggregation followed by a second stage during which further aggregation ceases or is apparently greatly retarded. After this stage a slow building-up of aggregates does continue until eventually, and accompanied usually by some turbulence, butter is formed. Sometimes, when at a stage where aggregates were already visible, butter would form immediately the moment the churn was stopped or restarted. The fat content of this buttermilk was low which indicates that all globules have already participated in aggregation, although butter would actually only be formed at a later stage. When the aggregates are very small, i.e. at the high speeds, stopping or restarting would not always cause butter to form.

It is thus obvious that in this zone of speeds that the process of disruption has increased to such an extent that a tendency of obtaining a "mechanical" emulsion becomes possible. Eventually aggregation will predominate and butter is obtained.

4.2.4. "True" phase inversion. (Fourth zone)

At still greater speeds a decrease in the churning times is again noticed. Particularly is noticed a decrease in the amount of buttermilk, although the fat content remains the same, until a point is reached when no buttermilk at all is released. Thus a condition has been reached where complete phase inversion occurs and the fat-in-water-emulsion has been converted to a water-in-fat-emulsion. The churning times for the third and fourth zones have not been connected since the latter was found only in other experiments where the churning process was continued for a long time. In this case disruption would predominate completely and thus no stable aggregates to withstand the disruptive forces are possible.

The values obtained in the third and fourth zones are subjected to considerable variations and the values plotted on the graphs are averages of two and sometimes three churns. This type of experiment was repeated a few times using different creams, but the same result was obtained. In an experimental series conducted at 26°C (Fig. 9) the same trends were found. There is therefore no doubt that "mechanical" emulsion and phase inversion tendencies exist, although quantatively they mean little and the underlying reasons for the fluctuations in times when butter is formed are not quite clear.

4.2.5. General.

In the second zone described above, churning can be regarded as normal i.e. a high percentage of the globules participate in aggregation and the level of disruption is relatively small. Disruption will in fact be limited to those aggregates in which the globules are weakly attached to each other. When determining the influence of various factors on churning by means of a system of flow in an annulus, care must be taken to see that observations are made when the churning characteristics are the same.

The transistion from irregular to uniform aggregation occurs at a much higher Reynolds-number than either the Re-number at which vortices appear or the Re-number for the transition from true laminar flow to unstable laminar flow. The following results, illustrating this point, are shown in Table 7.

TABLE 7. The Reynolds-numbers indicating the transition from laminar to unstable flow and the transition from irregular to uniform aggregation. (For a 0.45 cm annulus)

Details	Exp. 1		Exp. 2
%Fat in cream	39.8	39.8	40.2
Temperature of cream ^{o}C	18	22	18
Viscosity (cP)	25	15	30
Re-number for transition from irregular to uniform aggregation	648	335	488
Re-number when vortices appear [x]	95	95	95

x According to the formula by PRANDTL (1956), Re-number when vortices appear = $41.3\sqrt{\frac{R}{R_2-R_1}}$.

The possibility cannot be ruled out, however, of obtaining uniform aggregate formation in a laminar flow by making use of a smaller annular clearance, thus inducing annular vortices at a higher Reynolds-number.

4.3. THE COURSE OF AGGREGATION DURING CHURNING

A systematic flow pattern which exists within the cream contained between two concentric cylinders, creates the possibility of a systematic rate of aggregation. For determining the rate of aggregation the theories connected with the flocculation of colloids could perhaps be applied. The formula given by VON SMOLUCHOWSKI (1916, 1917) for the rate of coagulation of colloids was therefore applied to determine the rate of aggregation of butterfat globules.

The course of aggregation with time at normal temperatures was determined by counting, with the aid of a microscope the total number of particles, i.e. globules and aggregates, in samples taken at intervals during the churning process. One to three drops of cream, depending on the stage of churning, were removed from the churn, weighed and diluted with water ($\pm$ 1:500 for a 30% cream). A suitable quantity of the mixture was then placed in a special round, glass chamber, 165 μ deep and 3 mm in diameter. This counting chamber was then completely sealed with the aid of a cover glass and vaseline to prevent evaporation and "flowing" of the mixture. This also ensured that the uniform distribution of globules and aggregates remained unaltered in the counting chamber for long periods. Making counts on a series of samples from one churning took two to three hours to complete and thus this type of counting chamber was found ideally suited for this purpose.

The diluted sample was placed in a counting chamber as soon as possible, thus preventing the formation of aggregates by creaming in the flask. At least half an hour was allowed for the globules to rise to the top before counting commenced. Selection of the field was done at random over the counting chamber. By moving the stage the number of globules passing between a suitable interval (27 μ) on the ocular micrometer scale, and between two parallel lines on the cover glass, was counted. From 800 to 1000 globules and aggregates were counted per preparation, using at least two different fields.

Table 8 presents the number of globules and aggregates counted at different times during churning (N_t) together with the calculated times when the total number of globules were exactly halved. For the sake of convenience these times are referred to as "aggregation-time", which corresponds with the term coagulation-time used in colloid science.

At speeds of 450 & 504 cm/sec, "aggregation-times" increased towards the end of churning, whilst the opposite occurs at the higher speeds. At the two lower speeds, which lie in a region of irregular aggregate formation, aggregation is somewhat retarded towards the end of churning. At the higher speeds, involving regions of uniform aggregation, aggregation is accelerated, in comparison to that formulated by VON SMOLUCHOWSKI.

From these findings it is obvious that a condition will be

TABLE 8. Rate of aggregation of globules during churning at different speeds.

450 cm/sec			504 cm/sec			651 cm/sec			845 cm/sec		
Time (min)	Nt	T	Time (min)	Nt	T	Time (min)	Nt	T	Time (min)	Nt	T
0	2.67	-	0	2.62	-	0	2.60	-	0	2.72	-
3	2.62	(149)	3	2.56	(149)	3	2.44	(43)	2	2.10	6.1
6	1.84	13	6	2.04	21	6	1.62	9.8	4	1.54	5.1
9	1.70	16	9	1.76	19	8	1.16	3.8	6	1.04	3.7
12	1.70	22	12	1.68	20	10	0.74	3.9	8	0.86	3.8
15	1.58	21	15	1.94	(40)	12	0.52	3.0	10	0.36	1.5
18	1.64	29	18	1.56	27	$13\frac{1}{2}$	0.44	(2.8)	12	0.08	0.4
27	1.48	33	21	1.46	26				$12\frac{1}{2}$	0.16	(0.8)
33	1.04	(22)	24	0.92	(13)						

Nt = number of particles per mgr. cream ($x10^7$) at time = t.
T = period when total number of fat particles (globules + aggregates) is halved.

reached, somewhere between speeds of 504 and 651 cm/sec, where VON SMOLUCHOWSKI'S theory for rapid coagulation becomes applicable. The rate of aggregation at the start of churning is less than that at a later stage, which can be ascribed to the marked effect of increasing aggregate size in accelerating the process of aggregation. In cases where irregular aggregation is encountered the rate of aggregation increases at the beginning, but towards the end it is retarded again. Aggregation is thus not consistant throughout the churning process.

4.4. MICROSCOPICAL EXAMINATION

At intervals during the process of churning, samples were removed, diluted, placed in a counting chamber and then examined under a microscope. From these observations it became obvious that marked differences exists with respect to both aggregate size and the way the globules adhere to each other under different conditions. In Plate 2 can be seen the effect of circumferential speeds on the eveness of aggregate sizes, and the uniformity of aggregation.

At a circumferential speed of 225 and 450 cm/sec irregular aggregation was encountered whilst at 651 and 867 cm/sec aggregation was uniform. The butterfat content of the buttermilk was 20.3, 14.1, 2.5 and 1.1 per cent, respectively.

Under conditions of irregular aggregation, many globules do not participate in aggregate formation and very few aggregates are seen, whilst those that have formed are of various

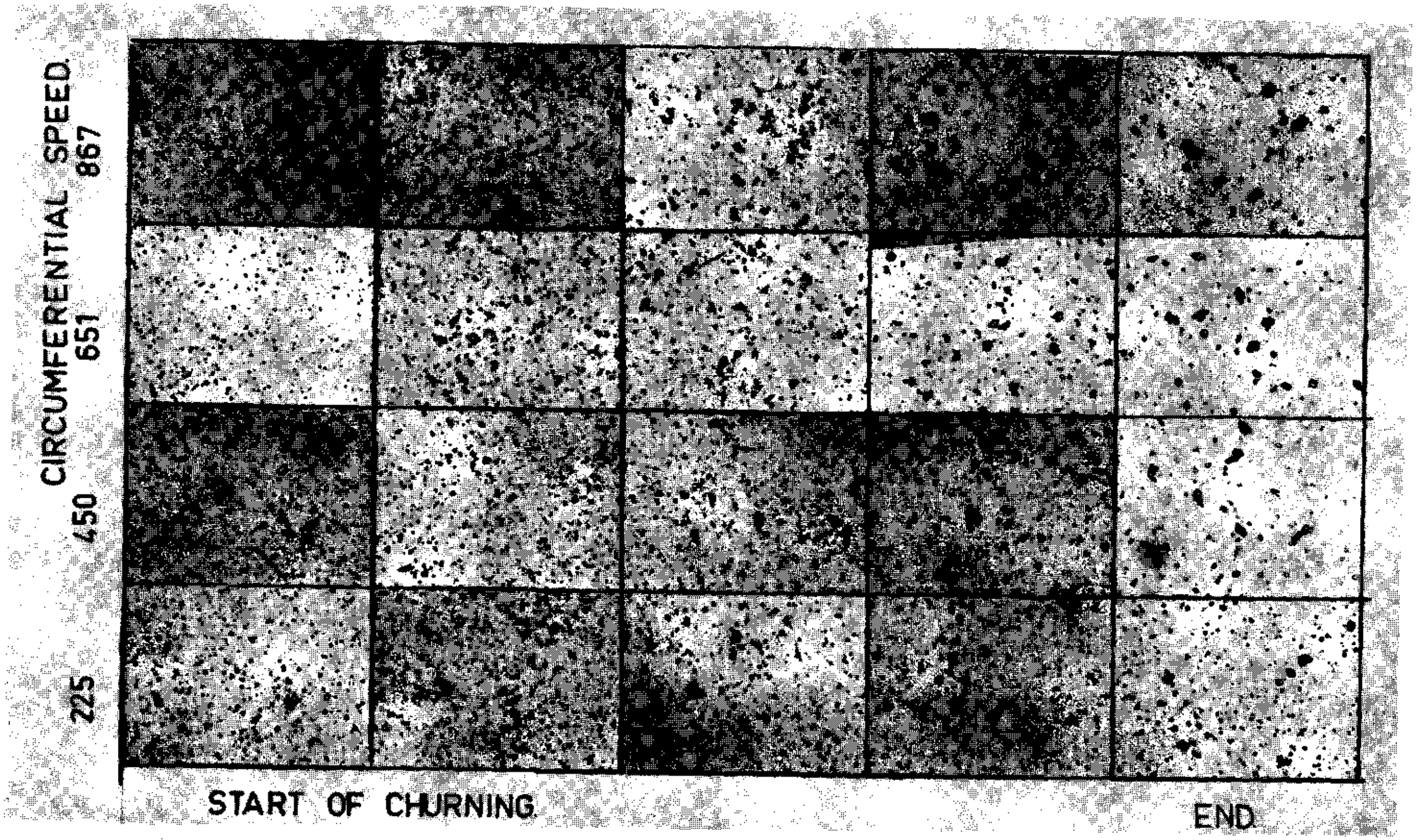


Plate 2. Aggregation characteristics at different circumferential speeds.
(Magnification 100x.)

sizes. In contrast to this, where aggregation occurs uniformly many more aggregates are seen and they are all of more or less the same size. Only very small globules remain in the buttermilk and these cause little loss of butterfat. The higher the speed the smaller and more even are the aggregates.

The type of aggregate formed in each of the four different zones differs noticeably from that obtained in any other zone, particularly with regard to the manner of adhesion. At the lower speeds the globules can still easily be distinguished within the aggregate, but at the higher speeds the original globules have partially or completely lost their identity. In Plate 3 are four photographs showing aggregates representative of the four zones.

As the speed or temperature is increased the aggregates gradually pass from a condition in which they are composed of clusters of distinct globules through one in which they are partly fused until finally they coalesce completely.

When irregular aggregation is taking place, clusters of globules are predominant whilst in the case of uniform aggregation the majority of globules have partly fused. This partial fusion of globules in the case of the second zone is only noticeable towards the end of churning; "clusters" being found at the start of churning. Thus as churning progresses, a gradual change in the manner of adhesion occurs towards a condition at which the aggregates apparently attain greater stability. Comparing the aggregates at the start of churning at the different speeds it is noticed that globules in the third and fourth zones are mainly fused together, whereas at the lower speeds they adhere together, but still retain their original form.

4.5. DISCUSSION

The system of churning used in this investigation showed clearly that in a region of stable laminar flow efficient churning was not possible within a reasonable short time. Efficient churning was only possible when three-dimensional flow existed, which is characterized by the presence of regularly spaced vortices. Within the limit of the speeds used in this investigation no turbulence of flow occurred. However, some form of turbulence, characterized by a pulsating movement of the vortice bands did occur just before the butter was formed. Certain aspects of the behaviour of fluid motion in an annulus, such as the fluctuations in the number of vortice bands, and the relationship between aggregate size and turbulence, are quantitatively not well understood. These changes will obviously have an influence on churning and might be the reason for the variations in the churning times.

As the speed is increased the process of churning shows markedly different characteristics. These are reflected mainly

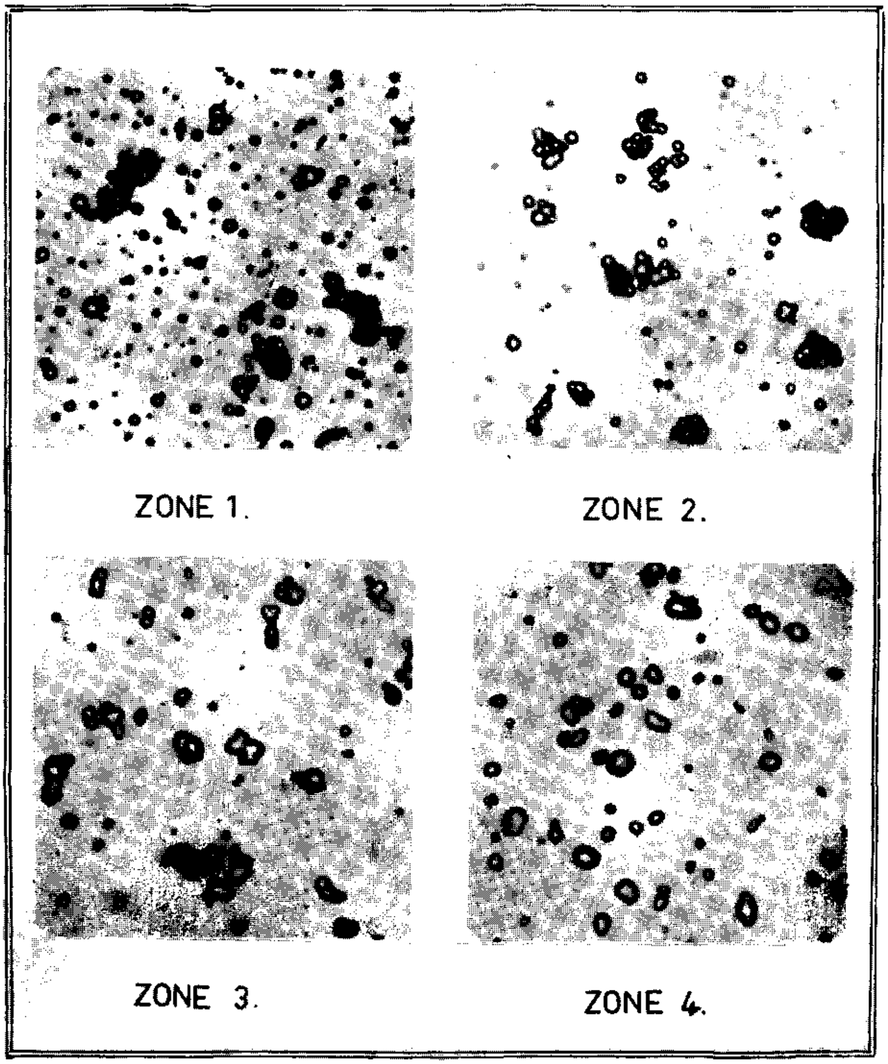


Plate 3. Type of aggregates representative of the churning zones. (Magnification 300x.)

in the manner of aggregation and the trends in the churning times. The condition where all globules participate in effective aggregation which then increases progressively is considered to be ideal for churning. This condition can only be obtained over a certain range of speeds; the lower limit being where irregular aggregation occurs and the upper limit being when disruption of aggregates has taken such proportions that an increase in the churning times now occur.

The forces to be applied must therefore be sufficient to induce aggregation of these globules offering the greatest resistance to aggregation (i.e. of small globules) in such a way that the aggregates formed are permanent. By permanent aggregates are meant a condition in which the aggregates are stable and are able to withstand disruption by the existing forces. When irregular aggregation is encountered the formation of aggregates is mainly restricted to the bigger globules as the collision intensity and the collision chances will be different for globules of different sizes. In such a case practically all globules will participate in butter formation eventually, but gradually and over a long period. Lumps of butter sticking in the annular clearance will probably accelerate the process. Where the formation of aggregates occurs uniformly throughout the cream the eventual butter formation is "instantaneous". The bigger the aggregate becomes the more rapid the process of aggregation.

The transition from irregular to uniform aggregation indicates that the minimum collision chances and collision effectiveness for efficient churning have been applied. In a hydrodynamic field a certain size of aggregate is possible (CLAY 1940) which in turn will be dependent on the physical state of the butterfat. Furthermore, the fact that aggregates are more or less of the same size, indicates that disruption of those aggregates developing out of proportion to the rest does occur. Those aggregates in which the globules are weakly attached to each other will be disrupted. There is thus a tendency towards an equilibrium between aggregation and disruption with aggregation predominating as a result of a tendency of the aggregates eventually to achieve a stable form which can resist disruption.

With regard to the rate of aggregation, the formula advanced by VON SMOLUCHOWSKI for the coagulation of colloids is probably only applicable in the limited region of transition from irregular to uniform aggregation. Except for this one particular instance the theory does not adequately describe the other cases. This is probably due to the fact that the conditions originally laid down by VON SMOLUCKOWSKI are not strictly adhered to. On the other hand this theory also has its limitations, as was pointed out by TENDELOO (1931, 1932). Furthermore, MÜLLER (1926, 1928) established that the probability of collisions is greater in a poly-dispersed system than in a system where particle sizes are all the same and also that an increase in the rate of aggregation depends on the

The duration of churning will thus be inversely proportional to the collisions per unit time (c) and the effectiveness of collisions (α). Thus:

$$\text{churning time}(t) \backsim \frac{1}{\alpha . c.}$$

Under ideal conditions every collision will result in a stable aggregate and the effectiveness of collisions could then be taken as unity. The churning times will, when this condition applies, be inversely proportional to the collision chances only. If this problem is approached by way of the theory of VON SMOLUCHOWSKI for the coagulation of colloids in a laminar current where the collision chances are directly proportional to gradient of velocity, then the churning times will be inversely proportional to the gradient of velocity. It is obvious that these conditions mentioned above do not quite apply in this investigation and several assumptions had to be made. These assumptions are:

a. At every collision a stable aggregate will be formed. This is not quite the case as only a certain proportion of collisions are effective.

b. No disruption. This also does not apply, since a certain degree of disruption of aggregates occurs during the churning process and increases as the speed is increased.

c. Globules of equal size. In cream globules are of unequal sizes and according to MÜLLER (1926, 1928) will have a better chance of colliding than globules of equal size.

d. Globule sizes are very small in relation to the distance between globules. In approximately 35 per cent cream globules would touch each other, however.

e. The conditions remain the same. However, conditions change, as the speed is increased, which gives rise for instance, to possible changes in the flow pattern due to the aggregates causing a disturbance of the smooth flow pattern. Different aggregate sizes at the various speeds will have the effect that different rates of aggregation will be encountered.

Every effective collision will result in a diminishing of the amount of globules or particles, leading to less collisions per unit time as churning progresses, but on the other hand the bigger the aggregate becomes the greater its chances of collision. It is thus obvious that some of these factors will have a compensating effect on the churning times. In order to avoid having to deal with some of these factors, only the conditions prevailing at the start of churning will be considered. If the problem is approached from this point of view, the formula derived for such ideal conditions can then be compared with the values actually obtained and any deviations from the formula investigated.

In an arbitrarily taken locally laminar current the collision chances and the effectiveness of collisions will be directly proportional to the gradient of velocity. Thus the change in the duration of churning can be regarded as being proportional to

$$\frac{1}{f(\frac{du}{dz}) \cdot g(\frac{du}{dz})}$$

where $f(\frac{du}{dz})$ is proportional to the collision chances and $g(\frac{du}{dz})$; to the effectiveness of collisions.

By accepting that the effectiveness of collisions is unity, thus the term $g(\frac{du}{dz})$ becomes 1, and assuming that an increase in the speed of the inner cylinder will cause a proportional increase in the velocity gradient, the equation can be written as follows:

$$-\frac{dt}{du} = kt.$$

where k will be a rate constant. On intergrating this becomes:

$$-\ln.t = kU + \text{constant}.$$

Thus the logarithm of the churning times as the speed of the inner cylinder is increased should describe this relationship, provided ideal conditions exist.

5.2. THE INFLUENCE OF THE CIRCUMFERENTIAL SPEED

5.2.1. Duration of churning.

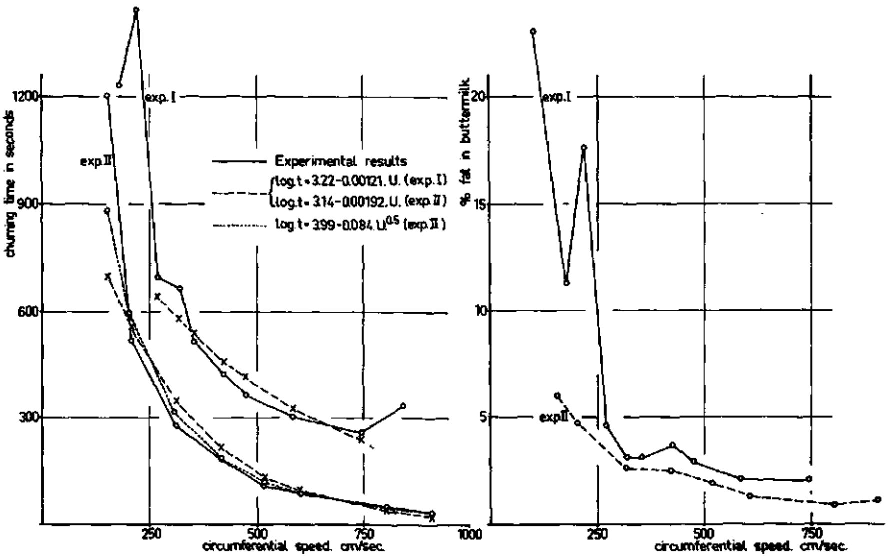
The trends in the churning times and also the fat content in the buttermilk in relation to the circumferential speeds are shown for two experiments in Fig. 4. The regression equations for these particular experiments using the logarithmic relationship, are:

Exp. 1. $\text{Log}(t) = 3.215 - 0.001212.\ U.$

Exp. 2. $\text{Log}(t) = 3.140 - 0.00192.\ U.$

In calculating the regression equation only those values have been used which apply to zones where aggregation was progressive and uniformly distributed throughout the cream. The actual experimental values obtained in the regions of irregular and uniform aggregate formation, in the case of Experiment 1, are also plotted in Fig. 4. In this case, at a circumferential speed of 850 cm/sec disruption of aggregates rose to such proportions that an increase in the duration of churning was experienced. All the values in the case of Experiment 2 were obtained in a region where aggregation was uniformly distributed throughout the cream.

The values calculated from the regression equations are



<u>Fig. 4.</u> The relation between the circumferential speed and the duration and efficiency of churning.
(Temp. 18^{0}C; % Fat $\pm$ 40; Annulus 0.45 cm.)

also given in Fig. 4 (shown by a dotted line). These curves calculated from the regression equations do not quite describe the general tendency of the churning times at increasing speeds, obtained by experiment. As the speed is increased the actual rate of decrease of the churning time diminishes in comparison with that of the logarithmic relationship. It seems therefore, that some additional function must be included in the general formula in order to describe the influence of the effectiveness of collisions on the churning times. In view of the previously mentioned approach of trying to derive a formula to describe the relationship between churning times and speed, it would appear that to include an exponent of U would give a better description of this relationship. Thus generally:

$$t = \exp.(-kU^{x})$$

Thus U^{x} could be regarded as proportional to the number of effective collisions. If the value of x is taken as less than one, the fit to the curves of the actual experimental values, improves. In the case of Experiment 2 the value of x is taken as 0.5 and the calculated values using this exponent of x are also shown in Fig. 4. A better fit to the experimental results is obtained than when the exponent of x is taken as equal to one. This then gives some indication that the effectiveness of collisions is less than unity.

As in this investigation only comparative results are of interest, the relationship used was that of the logarithm of the churning times at the different circumferential speeds. This relationship gives a sufficiently good description of the actual trends. In a few statistically worked-out examples, using the formula $t = {}^{1}/_{U^2}$, it was found that the exponent of U varied from 1.5 to 2.2, thus, slight deviations from the formula mentioned above, could naturally be expected for different experiments, whatever formula is being used. This is to be expected as the conditions will vary from one experiment to another.

5.2.2. Efficiency of churning.

A sharp drop in the fat content of the buttermilk occurs approximately in the region of the transition from irregular to uniform aggregation in the case of Experiment 1. At a circumferential speed of 180 cm/sec aggregation was still irregularlydistributed in the cream, but at a speed of 220 cm/sec uniform aggregation occurred. In the region where aggregation occurs uniformly throughout the cream, the decrease in the percentage of fat with subsequent further increases in speed is small in comparison with the large decrease in the fat content over the much narrower transition region. (between 180 and 220 cm/sec).

5.3. THE INFLUENCE OF THE ANNULAR CLEARANCE

By using inner cylinders having different dimensions the effect of the annular clearance on churning could be studied. At a constant speed of the inner cylinder the influence of the annular clearance on the properties of flow were:-

a. As the annular clearance is widened the gradient of velocity decreases proportionally, at least for the conditions used in this investigation. Thus, a proportional decrease in the amount of collisions per unit time could be expected.

b. On widening the annular clearance but with the circumferential speed and kinematic voscosity remaining constant, a higher Reynolds-number is obtained and annular vortices appear at a lower speed.

c. The drag in the case of a cylindrical viscometer with the inner one rotating is proportional to ${R_2}^2{R_1}^2 / {R_2}^2-{R_1}^2$ for laminar flow at constant speed, height of the cylinder and viscosity. Here again, a widening of the annular clearance causes a decrease in the total drag exerted on the outer cylinder.

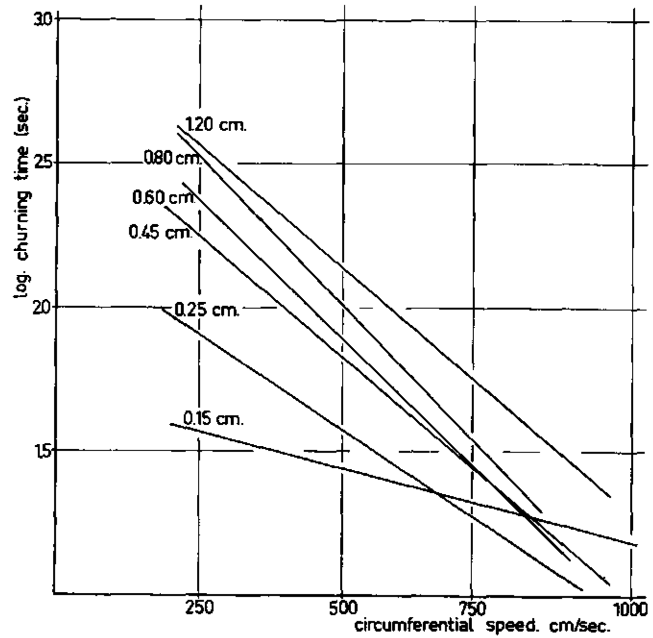


Fig. 5a. The logarithmic relationship of churning time and the circumferential speed.

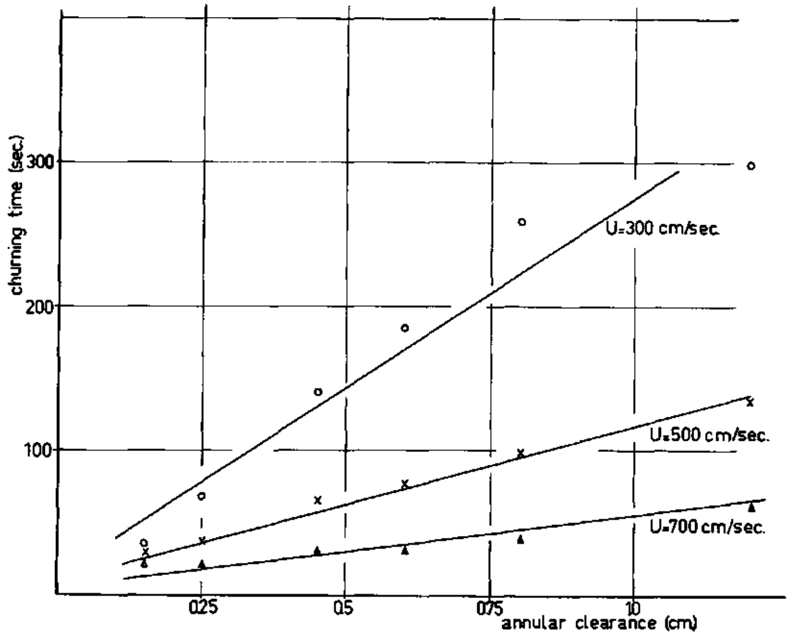


Fig. 5b. The influence of the annular clearance on the duration of churning.

5.3.1. <u>The duration of churning.</u>

To be able to determine the effect of enlarging the annular clearance on churning a series of churns of various speeds for each clearance was carried out. Six different annuli were used. The churning times as well as the fat percentage in the buttermilk for each churn are shown in Table 9.

TABLE 9. The influence of the annular clearance on churning at *different rotational* speeds. (% Fat 39.7; Temperature 18°C; Nd = 41.7)

Rev.	0.15		0.25		0.45		0.60		0.80		1.20	
min.	CT	%B	CT	%B	CT	%B	CT	%B	CT	%B	CT	%B
750	65	11.2	180	14.7	360	23.7	600	6.0	480	2.4		
1000	50	15.3	95	16.2	180	5.7	255	4.7	495	2.5		
1500	35	17.2	55	6.5	105	3.9	135	2.6	300	2.7		
2000	25	19.4	35	7.1	65	3.5	90	2.5	180	2.3	360	3.0
2480	15	5.0	25	2.3	35	1.1	55	1.9	100	2.3	240	2.1
2890	20	5.2	18	2.6	45	3.0	40	1.3	70	2.3	150	1.2
3850	17	3.9	11	2.0	20	1.4	23	0.9	35	1.1	95	2.0
4350	13	1.3					15	1.1	25	1.2		
5900											36	1.8

CT = Churning time in seconds. %B = Percentage fat in the buttermilk.

The logarithmic relationship of churning times to the circumferential speed of the inner cylinder is shown graphically in Fig. 5.a. Except for the one exceptional case of the 0.15 cm annulus, the regression lines for the other annuli are more or less parallel to one another. This indicates that the rate of decrease in the churning tends to be the same irrespective of the size of the annulus. The lower rate of decrease in the case of the 0.15 cm annulus can possibly be ascribed to the flow pattern changing due to aggregates obstructing the smooth flow pattern in the small space.

In Fig. 5.b. is shown the influence of the annuli on the churning times using the same circumferential speed. The churning times were calculated from the regression equations, but could also have been obtained from the regression lines shown in Fig. 5.a.

A direct relationship exists between the churning times and the annular clearance. By doubling this clearance (and thus diminishing the gradient of velocity), the duration of churning is also doubled. The combination of this factor and the speed of the inner cylinder, would give:-

$$t = (R_2 - R_1)\ \exp.(-kU)$$

or

$$\mathrm{Log.}\left[{}^{t}/(R_2 - R_1)\right] = -kU.$$

In Fig. 6, the values of $\mathrm{Log.}\left[{}^{t}/(R_2 - R_1)\right]$ have been plotted against the circumferential speed using the results given in Table 9. Again the divergent values for the 0.15 annulus are observed, but for the other annuli a common straight line is found, thus ${}^{1}/_{U.}\ \mathrm{Log.}\left[{}^{t}/(R_2 - R_1)\right]$, could be considered a rate constant of butter formation.

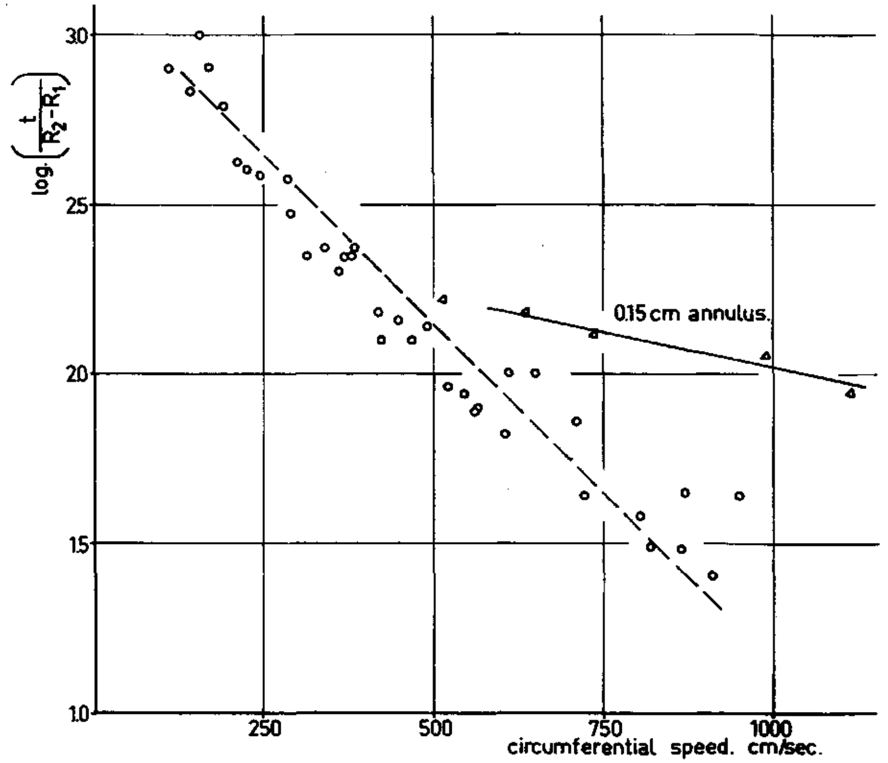


Fig. 6. The relationship between the logarithm of the ratio - churning time to annular clearance - and circumferential speed.

5.3.2. Efficiency of churning.

In the course of these experiments it became obvious that the size of the annular clearance influenced not only the churning times, but also the efficiency of churning as well, as shown in Table 10.

TABLE 10. The influence of the size of the annular clearance on the efficiency of churning.
(% Fat 39.6; Temperature 18°C; Nd = 43.5)

Annulus cm	Rev/min.	Circ. speed cm/sec	Churning time (min)	% Fat in buttermilk	Remarks
0.15	1420	364	3	13.5	Irregular aggregation
0.25	"	350	5½	13.5	" "
0.45	"	316	13½	3.3	Uniform aggregation
0.60	"	295	19½	3.0	" "

In Table 10 it will be seen that at a constant rate of revolutions the efficiency of churning, judging by the percentage fat in the buttermilk, improves as the annular clearance is enlarged. As the Reynolds-number increases when the clearance is enlarged, the possibility exists that some correlation between this number and the efficiency could be found.

Effective aggregation will also, amongst other factors, depend on the force of impact between globules and on the shear stresses. The forces acting on such a globule can conveniently be expressed by means of the Reynolds-number. In Table 11 are given the values of $U(R_2-R_1)$ at the zone of transition from irregular to uniform aggregation, for different annular sizes. The $U(R_2-R_1)$-values are directly proportional to the Reynolds-number for fluid contained between two concentric cylinders

TABLE 11. The circumferential speeds and the $U(R_2-R_1)$-values of the transition from irregular to uniform aggregation for different annular clearances.
(% Fat ± 40; Temperature 18°C)

Exp.	Annulus (cm)	Speed cm/sec	$U(R_2-R_1)$
1/8	0.15	680	120
	0.25	463	116
	0.45	316	144
	0.60	205	123
9/1/2	0.15	637	96
	0.25	369	92
	0.45	225	101
	0.60	157	94

The larger the annular clearance the lower is the circumferential speed of the inner cylinder required to obtain efficient churning. At the transition from irregular to uniform aggregation the values of $U(R_2-R_1)$ seem to be approximately the same irrespective of the annular clearance being used. The kinematic viscosity (v) which is also necessary to express the Reynolds-number, was taken as a contant.

In Fig. 7 the fat percentages in the buttermilk are plotted against values of $U(R_2-R_1)$ for all the individual churns of the results given in Table 9. The vertical lines A and B respectively represent the average value of $U(R_2-R_1)$ where irregular aggregation was last encountered and where uniform aggregation was for the first time observed. Between the two vertical lines would be the region of the transition from irregular to uniform aggregation. A large fall in the fat content of the buttermilk occurs over this transition region and is followed by a further slight decrease with subsequent increase in the circumferential speed i.e. beyond line B. It does seem that the efficiency of churning could be expressed by means of the Reynolds-number. This gives an indication that a certain ratio of the inertial to viscous forces is required in order to obtain uniform aggregation of practically all globules.

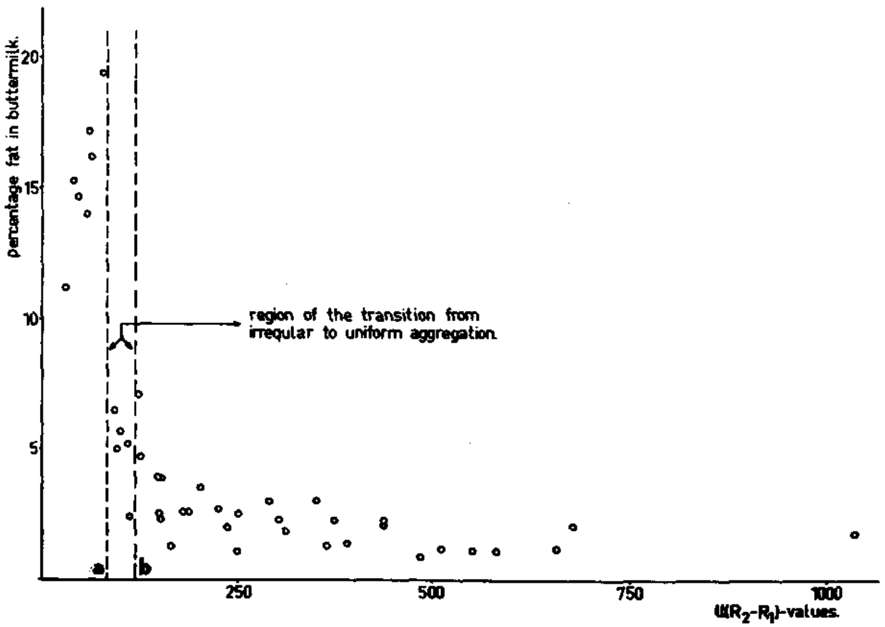


Fig. 7. The efficiency of churning for the different annuli as related to the Reynolds-number. (Constant kinematic viscosity).

5.4. THE INFLUENCE OF VISCOSITY

McDOWALL (1953) ascribed less efficient churning as being due to high viscosity in a case when lime was used as a neutralizer in cream. MULDER (1947) showed that by increasing the viscosity of the cream serum by adding sugar (glucose), the efficiency of churning improved and a moderate increase in the duration of churning occurred. In a system where cream is contained between two concentric cylinders, viscosity will undoubtedly have a great influence on the general properties of flow. By increasing the viscosity, higher shear stresses will be obtained, accompanied by a lowering of the Reynolds-number. It is thus obvious that this will have some influence on churning.

In the present experiments the viscosity of the cream was increased by adding carboxyl methyl cellulose (CMC). Different amounts were added to separated milk in concentrations varying from 0.05 to 0.50 per cent, in order to get a wide range of viscosities. The CMC was well mixed first with skimmilk with the aid of a Waring Blender and then used to standardize the cream. The treatment of the standardized cream was then carried out in the usual way although a longer time for de-aeration was allowed for the very viscous creams. A Hoepler viscometer was used in determining the viscosity and measurements were done at the churning temperature of the cream.

In Fig. 8 are illustrated the trends in the churning times and the butterfat content in the buttermilk with increasing viscosities for different fat percentages of the cream. In general, a decrease occurs in the duration of churning as the viscosity increases, becoming more pronounced as the fat percentage is lowered. A very small decrease is observed in the case of the high fat creams (45 and 50 per cent).

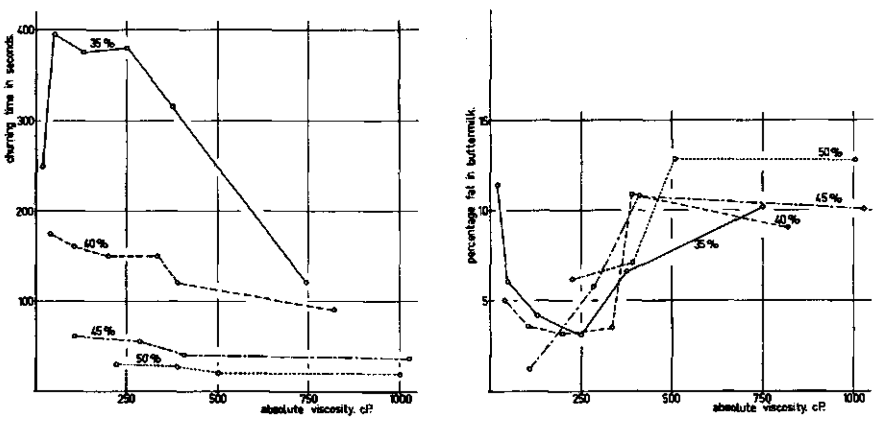


Fig. 8. The effect of viscosity on churning for different fat percentages in the cream.
(Temp. 18°C; Annulus 0.45 cm; Speed 450 cm/sec.)

It appears that at a certain viscosity value the fat in the buttermilk starts increasing irrespective of the butterfat content of the cream. This rise occurs over the range of Reynolds-numbers 98 to 62 which will be a region of true laminar flow. In the case of the 35 per cent cream a higher viscosity improved the efficiency of churning even when at a low viscosity - i.e. when no CMC was added - irregular aggregate formation was encountered. Churning again became less efficient at a viscosity value of approximately 300 cP (Re = $\pm$ 82). When churning low fat creams it was noticed that at first an increase in the churning times occurred before the final decrease, as indicated in Table 12.

TABLE 12. The effect of viscosity on the churnability of low-fat creams. (Exp. I. 29.5% fat; Exp. II. 30.0% fat; Annulus 0.45 cm; Churning temperature 18°C)

	Exp. I				Exp. II		
cP	450 cm/sec		651 cm/sec		651 cm/sec		
	CT	%B	CT	%B	cP	CT	%B
9	420	11.8	220	8.8	9	280	5.4
19	390	10.1	290	3.7	19	330	3.1
33	510	9.7	330	2.6	27	305	3.4
82	450	8.6	380	4.9	34	314	3.7
183	290	3.5	100	5.0	60	175	4.1
436	160	3.5	75	5.0	93	155	5.7
1166	86	9.1	45	8.2	350	65	3.9
					746	45	5.8

CT = Churning time in seconds. %B = Percentage fat in buttermilk.

The churning efficiency improves in the case of low-fat creams which seem to indicate that uniform aggregation was encountered which is, however, not the case. Irregular aggregation was still encountered, but apparantly a large number of globules have participated in aggregation in contrast to the situation when normal cream is churned. The increase in the churning times of the low-fat creams (35% and lower) could probably be ascribed to the effect of the viscous cream plasma dispersing the effect of the force of collision.

5.5. DISCUSSION

Churning is dependent on the collision chances of the particles and whether or not the intensity of such collisions is adequate to ensure a stable aggregate. Many contributory factors are involved, but in order to obtain some insight into the process certain assumptions have to be made. For convenience therefore, the process of aggregation can be divided into two aspects. These are, firstly, the collision chances and, secondly, the effectiveness of such collisions. The collision chances according to VON SMOLUCHOWSKI (1917) are directly proportional to the gradient of velocity. By assuming that the effectiveness of aggregation is unity i.e. at every collision an irreversible aggregate is formed, a formula can be derived, based on the gradient of velocity, relating the duration of churning to the circumferential speed. Under these conditions the course of the decrease in the churning times with increasing speeds of the inner cylinder should be of the first order, thus

$$- \text{Log (churning time)} = kU.$$

This equation does not quite describe the general trends in churning times at increasing speeds and it is thus obvious that the effectiveness of collisions cannot be ignored nor be taken as unity. The fact that the conditions originally laid down by VON SMOLUCHOWSKI are not applicable in the case of cream or in this investigation is a reason for these deviations. The main factors contributing to this deviation can be ascribed to:

a. Every collision will not necessarily result in an irreversible aggregate.

b. A certain degree of disruption which varies inconsistently at the different speeds.

c. Possible changes in the flow pattern due to aggregates causing a disturbance in the smooth pattern of the cream.

The general formula for describing the decrease in the churning times as the circumferential speed is increased will probably have the form:

$$\text{churning-time} = \exp.(-kU^x).$$

It appears that the value of x will be less than one which indicates the influence of the lower effectiveness of collisions on the churning times. This value of x, will vary depending on the circumstances of churning. The logarithm of the churning time, speed relationship, gives a good description of the trends in the duration of churning with the circumferential speed and this equation was used for comparative purposes in this investigation.

Using various annular clearances at increasing circumferential speeds, the rate of decrease in the churning times remains the same, except in the case of a small annulus. At constant circumferential speed an alteration in the annular clearance caused a proportional change in the churning time. The general formula to include the width of the annulus will then be:

$$\text{churning-time} = (R_2-R_1)\ \exp.(-kU^x).$$

The divergent results observed for small annuli are possibly due to aggregates causing a disturbance in the flow pattern in such a small space.

The wider the annulus the lower the speed that is required for effective aggregation, i.e. the speed necessary for the transition from a condition of irregular aggregation to a condition where aggregation is uniformly distributed throughout the cream. A sharp fall in the butterfat content of the buttermilk over this transition region is observed and further increases in the speed produce only a small additional improvement. The efficiency of churning is related to the Reynolds-number and for the different annuli the transition from irregular to uniform aggregation takes place at approximately the same Reynolds-number. This seems to indicate that effective aggregation is dependent on the ratio of the inertial to the viscous forces, and in order to obtain the same aggregation characteristics, the ratio of the forces acting on the globules should be similar.

Viscosity generally has a tendency at first of improving the efficiency of churning, but beyond a certain stage increasing viscosity causes a lessening of efficiency. As the Reynolds-number also diminishes less efficient churning is to be expected. However, due to the high shear stresses caused by the viscosity more rapid churning is obtained, but the higher the fat content of the cream the smaller the influence of the viscosity of the plasma.The further apart the globules are the greater the influence of viscosity in dispersing the effect of the force of collision. This will tend to prolong the churning time at first, but possibly as a result of the high shear stresses of the serum, aggregation is more easily obtainable. At high viscosities a large gradient of velocity is localized immediately around the inner cylinder; the result being that irregular aggregation takes place.

6. THE INFLUENCE OF TEMPERATURE

The influence of temperature on the conventional churning process has already been extensively studied. The temperature used for the conventional churning process generally lies within a narrow range, since factors such as the duration of churning, fat loss in the buttermilk and especially the consistency of the butter have to be taken into consideration. The churning temperature will be determined by factors such as the crystallized condition of the fat, the season, the influence of temperature on viscosity and on the properties of foaming, etc. Generally, it is found that at low temperatures, within certain limits, longer churning but less fat loss is found, and vice versa at high temperatures. In this investigation only the overall influence of temperature on churning is considered.

a. At low temperatures only a small amount of liquid fat is present, and due to the crystallized condition of the fat, deformation of the globule is difficult. The area of contact between globules will be small with the result that the effectiveness of collisions will be low. In these cases the angle of collision will become more important. Direct collisions between globules will have a better chance of producing aggregates than when globules collide at an angle. The efficiency of churning could be improved by increasing the speed, but on the other hand, owing to the weak adhesion of globules, disruption will then be higher.

b. At higher temperatures the globules are easily deformed and sufficient liquid fat is present for a bigger area of contact between globules. Aggregation will naturally occur more easily and even coalescence is possible. A lower speed would now be adequate to furnish the required collision chances to ensure efficient churning. The fat on the other hand becomes softer as the temperature is increased and the chances of disruption will also increase and even homogenization is possible if too high speeds are employed.

It thus becomes clear that a proper amount of liquid fat must be present and consistency must be optimal. The conditions at the different temperatures are so completely different that direct comparison is not justified.

The following aspects were investigated:

a. Aggregation characteristics.

b. Relative position of similar aggregation characteristics with respect of the speed.

c. The duration of churning, and fat content in the buttermilk.

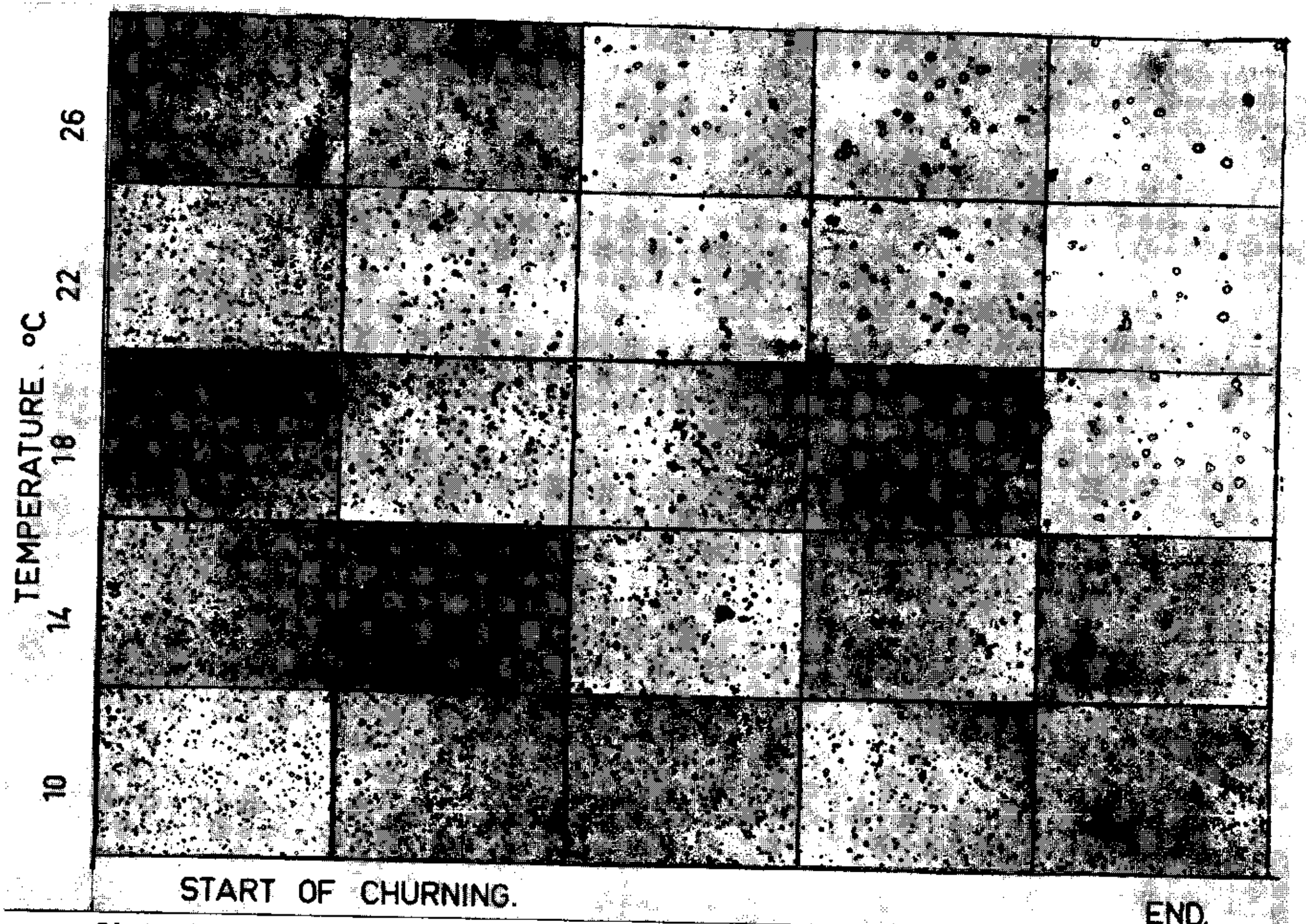


Plate 4. Aggregation characteristics at different temperatures.
(Speed 450 cm/sec; Magnification 100x)

6.1. AGGREGATION CHARACTERISTICS.

In the previous paragraphs it was shown that with increasing speeds of the inner cylinder the manner and extent of aggregation differ considerable and that only in a relatively narrow range of speeds, efficient churning was encountered. When using the same speed, but varying the temperature, a similar phenomenon is experienced as will be seen in Table 13.

TABLE 13. Aggregation characteristics at different temperatures when the speed is kept constant. (U = 473 cm/sec; Annulus - 0.45 cm; 40.5% cream; Nd = 43.7)

Churning temp.	Churning time (min.)	% Fat in buttermilk	Remarks
8	11	14.0	Irregular aggregation
10	9½	15.0	" "
14	9½	10.2	" "
18	6	2.9	Uniform aggregation
22	14	0.9	"Mechanical" emulsion tendency
26	21	0.6	" " "
32	(11)	0.9	Water-in-fat emulsions
38	-	-	"Free fat" separating

Three different aggregation characteristics could definitely be distinguished, simply by varying the temperature. The values for the churning times and fat content in the buttermilk given in Table 13, therefore, give a completely wrong impression of the effect of temperature on churning, since the aggregation characteristics are so completely different at the different temperatures. At temperatures of 32° and 38°C melted fat separated (oiling off), but formed an emulsion as soon as churning was recommenced. In these cases, i.e. at the high temperatures, the end of churning is impossible to determine. The low fat percentage in the buttermilk indicates the greater initial efficiency of aggregation, but after a certain stage the further growth of aggregates is retarded.

In Plate 4 are shown micro-photographs of samples taken during the process of churning at different temperatures at a constant speed (450 cm/sec). Differences in the type and eveness of size of the aggregates, as well as the degree of participation of globules in aggregation, can be noticed. At 10° and 14°C, irregular aggregation occurs, and at 18°C aggregation is uniformly distributed throughout the cream. At 22° and 26°C there is a tendency towards a stationary state of dispersion. At 10° and 14°C, aggregates are uneven in size and a large proportion of globules have not participated in aggregation. A tendency towards coalescence, is observed at the higher temperatures while at 10° and 14°C, and to a certain extent at 18°C, the original globules can still be recognized in such an aggregate.

6.2. THE RELATIVE POSITION OF SIMILAR AGGREGATION CHARACTERISTICS WITH RESPECT TO SPEED.

An attempt to establish a speed where the aggregation characteristics would be the same over a reasonably wide range of temperatures, did not succeed. This can, however, be expected as the changes in the aggregation properties of fat at different temperatures are considerable. In this connection, MULDER and KLOMP (1955) have estimated the fat present in the solid state at different temperatures, and have shown, for instance, that for winter-cream that has previously been cooled to $0^{o}C$, the percentage at $10^{o}C$ was 81 per cent, and at $26^{o}C$ only 16 per cent. The effect of this can be seen quite clearly in observing the trends in the churning times at different speeds and at different temperatures shown in Fig. 9. With increasing temperatures the same aggregation characteristics appear at relatively lower speeds. The higher the churning temperature the narrower the range of speeds at which efficient or normal churning can still be obtained.

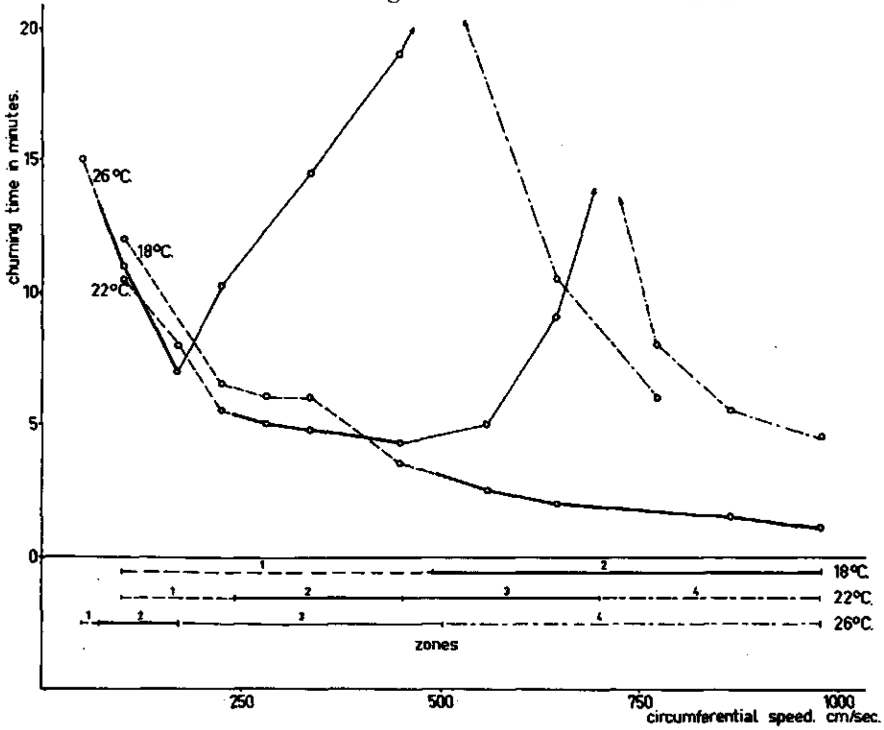


Fig. 9. The influence of the temperature on the relative position of similar aggregation characteristics with respect to the speed. (1) Irregular aggregation. (2) Uniform aggregation. (3) Tendency of "mechanical" emulsion. (4) "True" water-in-fat-emulsion. (Fat 39.8%; Annulus 0.45 cm; Nd = 42.1)

In experiments, at 30° and 34°C the different churning characteristics could not be distinguished properly, although at 30°C irregular aggregation did occur in a water-in-fat-emulsion. The results of experiments at these two temperatures are shown in Table 14. Experiment II in Table 14 is of the same series as given in Fig. 9.

TABLE 14. Effect of high temperatures (30° and 34°C) on churning time and fat content in the buttermilk.
(% Fat ± 40; Annulus - 0.45 cm)

Circ. speed cm/sec.	Exp. I		Exp. II		
	30°C		30°C		34°C
	C.T.	% B	C.T.	% B	C.T.
104	34	(11.9)	90	(13.90)	
156	24	7.8	72	2.6	
225	24	4.3	63	2.5	120 ?
338	19	3.4	16	2.7	
646	-	-	12	-[x]	

C.T. - Churning time in minutes.
% B - Fat in buttermilk.
( ) - Irregular aggregation
x - Water-in-fat-emulsion.

At a circumferential speed of 646 cm/sec, water-in-fat-emulsion was definitely obtained and also when a condition of irregular aggregation was encountered. In both experiments it seemed that there is a tendency towards obtaining a "mechanical" emulsion as it is noticed that, during churning, destabilization occurred reasonably fast. The rate of the absorption of Sudan III is taken as an indication of the level of destabilization of the globules. Much longer churning times are obtained in these cases when compared with lower temperatures (Table 15), whilst with increasing speed the churning times decrease continually until a water-in-fat-emulsion is obtained. This is in contrast to what is found when churning at lower temperatures, where, with increasing speeds, first a decrease is obtained, then an increase, and finally a decrease again. In view of the fact that with increasing temperature there is a narrowing of the range of speeds at which progressive aggregation occurs, it is doubtful whether at 30°C this particular condition could still be obtained. Either this range where normal churning is possible becomes so narrow that, in view of the limited possibilities of varying the speeds on the churning apparatus, proper differentiation between the different characteristics of aggregation at these high temperatures could not be made, or progressive aggregation is no longer possible. It appears that a stable aggregate is not so easily obtainable, although there is some indication in Table 14 that some stable aggregates do form at a speed of 104 cm/sec and probably at lower speeds also. At this speed efficient butter formation should be possible, since at 26°C (See Fig. 9) efficient butter formation could still be obtained. It would seem at 30°C and higher, aggregates of globules are thus not stable, and they now coalesce.

6.3. DURATION OF CHURNING

The only remaining alternative for studying the effect of temperature on the duration of churning, was to conduct a series of churns at various speeds for each temperature in a region where normal churning is encountered. In doing this it became possible to compare the trends, obtained at the different temperatures, on the basis of the speeds employed, rather than the actual churning times. These experiments, covering the whole range of temperatures, were divided into two groups, namely: A series covering temperatures from 6° to 22°C, and another covering temperatures from 18° to 38°C. At each temperature a number of churns was made using different circumferential speeds of the inner cylinder. This was done at four-degree temperature intervals. A further experimental series covered the temperature range from 10° to 34°C, but with bigger intervals. The same batch of cream was used for all churns within one series, but creams different to that, were used for the other. Slight differences between the series due to variation between creams could be expected, but the general influence of temperature on the trends would not greatly be affected, especially since the experiments were conducted within a period of one month and the pre-treatment of all the cream was the same. In Figures 9 and 10 the results of these experiments are illustrated, showing the influence of the temperature on churning at different circumferential speeds.

Generally, it is found that with an increase in temperature a lower speed is required to obtain efficient churning. When churning at low temperatures (14°C and lower), a high fat content of the buttermilk is found, although the transition from cream to butter is "instantaneous". In contrast to those experiments conducted at 18°C and higher, where there is a relatively large decrease in the fat content of the buttermilk in the region of the transition from irregular to uniform aggregation, the decrease is not so distinct at churning temperatures of 6° and 10°C. At these low temperatures it is noticed that in a region where irregular aggregation is encountered, "loose" aggregates would from at a very early stage in the churning process, which did not occur at the same stage at higher temperatures. At a churning temperature of 14°C the same tendendies were observed as for the higher temperatures, but the fat content in the buttermilk is still

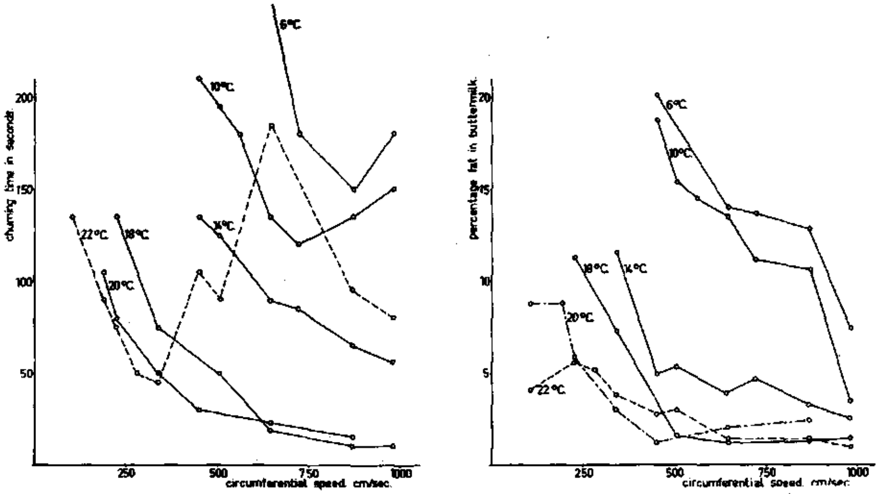


Fig. 10. The influence of the churning temperature at different circimferential speeds, on churning.

relatively high in this region, even when aggregation was uniformly distributed throughout the cream.

Buttermilk samples of these experiments conducted at low temperatures showed excessive oiling-off when heated, in contrast to those at the higher temperatures. Although a certain amount did oil-off from samples from churns conducted at high temperatures, the ratio of oiled-off fat to the total fat of the buttermilk is far less than for experiments conducted at low temperatures. This gives the impression that at low temperatures the membrane is damaged, but that since the amount of liquid fat is small the area of contact is also small, with the result that disruption occurs more easily.

A tendency for an increase in the churning times at temperatures of 6° and 10°C is observed at the higher speeds. It seems that at these low temperatures (6° and 10°C), some disruption might occur, causing an increase again in the churning times. The stability of the aggregates is probably not of such an order to withstand the hydrodynamic forces, which is to be expected owing to the small amount of liquid fat present. Furthermore, adhesion is weak due to the small area of contact between hard globules.

In order to find some common basis on which to evaluate the influence of temperature on churning a comparison was made of the "transition points" and the rate of butter formation at various temperatures. In Table 15 the results of four experiments are given, showing the approximate circumferential speeds when the transition from irregular to uniform aggregation occurs, and the regression coefficients of the relationship - logarithm of the duration of churning against circumferential speed - for each temperature series.

As the temperature is increased the lowest speed required to obtain efficient churning, i.e. the transition from irregular to uniform aggregation, decreases until a minimum is reached in the region of 22° - 26°C. A further increase in the temperature does not necessarily mean a further decrease in the speeds required to bring about this transition. Although the speeds at which transition occurs could be established reasonable accurately, churning times were difficult to determine exactly. Some tendency for a decrease might be present up to a certain temperature. At the transition from irregular to uniform aggregation, variations in the churning times could be considerable, and thus not much value could be attached to them. However, the lowest times are obtained in the region 22° - 26°C after which a definite sharp increase is noticed. This is probably due to an equilibrium tendency in the state of dispersion.

TABLE 15. Minimum circumferential speed (transition from irregular to uniform aggregation) required to obtain efficient churning and the regression coefficients at different temperatures. (Annulus - 0.45 cm; Fat - ± 40%)

Exp.	Temp. °C	Transition point			Neg. Coef. of regression (x10⁴).
		Speed cm/sec	C.T.	% B	
11/7	10	586	570	8.3	12.9
	14	473	570	5.1	13.4
	18	320	660	3.1	12.1
	22	99	300	4.7	39.0
7/11	6	645	315	14.0	6.9
	10	559	180	14.5	3.2
	14	451	135	5.0	7.3
	18	338	75	7.3	15.8
	20	225	80	5.9	15.6
	22	104	135	4.1	21.5
28/11	18	451	330	6.4	7.0
	22	282	300	2.1	9.6
	26	156	300	4.2	25.9
	30	156	1440	7.8	9.8
5/12	10	773	210	4.3	3.3
	18	559	180	6.6	9.3
	22	338	285	4.3	15.3
	26	169	420	2.3	28.4
	30	169	4320	2.6	42.2
	34	-	-	-	-

C.T. - Churning time. %B - % Fat in buttermilk.

Generally, an increase in the coefficient of regression, although not so obvious for some of the experiments (Table 15), is noticed as the temperature is increased. This seem to indicate that at the higher temperatures, the decrease in the duration of churning per unit change in speed, is more rapid than at the lower temperatures.

6.4. DISCUSSION

Churning will be dependent on firstly, the collision chances and secondly, the effectiveness of such collisions in forming a stable aggregate. If, in a number of churns, the same speed is used, then since the collision chances are practically the same at the different temperatures, variations in the churning can be attributed to differences in the effectiveness of collisions. The effectiveness of collisions will in this case be dependent on the amount of liquid fat present and the consistency of the fat.

At low temperatures the globule membrane is firmly held to the globules and the fat so completely crystallized that sufficient adhesion of globules cannot readily occur. At temperatures where there is a small amount of liquid fat present, the area of contact between globules is small, with the result that an unstable aggregate is formed which can easily be disrupted again. At these low temperatures the angle of collision will be a relatively more important factor in obtaining effective adhesion between globules than at the high temperatures. In order to obtain efficient churning, higher speeds have to be employed to improve the collision chances and collision intensity. However, by increasing the speeds still further, the possibility of disruption increases to such an extent that the duration of churning starts increasing again, as experienced at the temperatures 6^{0} and 10^{0}C. A tendency for an equilibrium in the state of dispersion is thus also possible at these low temperatures, even at speeds lower than those applicable for instance at 14^{0} and 18^{0}C.

The higher the temperature becomes the more liquid fat is present. Easier aggregation will occur and the aggregates will be more stable, but on the other hand the fat becomes softer. At high temperatures more rapid aggregation occurs, but there is also increased disruption of the aggregates so that a tendency towards an equilibrium in the state of dispersion is more easily obtainable. The temperature for optimum conditions will thus be dependent on a sufficient amount of liquid fat present and optimum consistency. This will in turn be determined by the composition of the fat, pre-treatment of the cream, etc.

At increasingly high temperatures the range of speeds, over which uniform and progressive aggregation occurs, narrows until a stage is reached where it can no longer be obtained.

It appears that a stable aggregate at these high temperatures (30°C) is not possible and that complete coalescence of globules is the only alternative. This then results in increasing churning times. With further increase, disruption predominates completely, but destabilization does occur and on stopping the churn "free fat" separates.

Employing a constant circumferential speed to determine the effect of an increase in temperature, increased efficiency is obtained, but the aggregation characteristics differed over the whole range of temperatures used in the investigation. Proper comparisons can thus not be made as regards the duration of churning, since the aggregation characteristics are so different. Within certain limits of variation this is still possible, but over a wide range other means for comparison have to be found.

The minimum circumferential speed required to obtain efficient churning decreases as the temperature is raised. The lowest speed for efficient churning, in this investigation, was obtained in the region of 26°C after which, with a further increase in temperature the speed remained the same. It appears that a more rapid rate of decrease in the duration of churning per unit change in the circumferential speed occurs at higher temperatures than at lower temperatures. Not much can be deduced from the churning times, and in addition fluctuating values are to be expected because of the different aggregation conditions, degree of disruption, etc., at the various temperatures.

7. THE INFLUENCE OF THE FAT CONTENT OF THE CREAM

7.1. THEORETICAL CONSIDERATIONS

For the conventional method of churning the fat content of the cream is in the range of 20 to 40 per cent. MULDER (1946) found much shorter churning times when, for instance, 25 per cent cream was churned than in the case of a 9 per cent cream. The percentage loss of fat, i.e. the fat content of the buttermilk expressed as a percentage of the quantity of fat present in the cream, was higher for the low-fat cream. COMBS and COULTER (1930) have shown that the minimum percentage fat loss was obtained when the fat content of the cream was in the range 35 to 40 per cent. LYONS and O'SHEA (1936), in their experiments with a small churn, found minimum fat losses at about 35 per cent, beyond which fat losses increased again, as the fat percentage in the cream was increased. An increase in the churning times was also reported by the latter workers.

Marked differences in the conditions of aggregation over a wide range of percentages are to be expected, especially when taking into consideration the fact that in high-fat cream globules touch each other, whereas at lower percentages they are more apart. At high fat percentages, as a result of globules rubbing against each other, rapid and effective aggregation would be expected. In the case of the low-fat creams, however, the globules have some freedom of movement. The collision chances as well as the effectiveness of aggregation will thus improve with increasing fat content of the cream.

On the other hand, however, an increase in the fat content of the cream is coupled with an increase in viscosity. The flow properties at the different fat percentages will thus not be similar, and may even take on such proportions that a high gradient of velocity will be localized only in the immediate vicinity of the rotating inner cylinder. This will also lead to a badly distributed collision frequency accross the annular clearance. At high viscosities no vortices will appear, thus completely altering the flow pattern from that pertaining in all the other experiments conducted at lower fat levels. Another phenomenon of interest here is that, due to the centrifugal properties of the vortices, some separation of the serum and the fat will occur, and probably the fat will concentrate towards the centre of such a vortice.

According to VON SMOLUCHOWSKI (1917), a direct relationship exists between the collision chances and the number of particles. But here again, as has been pointed out before in Chapter 5 and in the preceding paragraphs, the conditions differ completely to those laid down by VON SMOLUCHOWSKI. In order to derive a formula to describe the relationship between the churning times and the fat content of the cream, a similar approach can be made as that given in Chapter 5, thus:

$$\text{Log.(churning time)} = -kF^x$$

where F is equal to the percentage of fat in the cream.

7.2. DURATION OF CHURNING

Cream separated to a fat percentage of approximately 60 per cent, was standardized with skimmilk to the desired fat percentage. Heat treatment, de-aeration and cooling was the same for all the creams, and was done after standardization.

In Fig. 11 is shown the decreasing trend in the churning times as the fat percentage of the cream is raised. For purposes of comparison a calculated curve having the exponent of x (in the formula log. $t = -kF^x$) equal to one, is included. It appears that in this case the value of x is higher than one, and if this value is taken as equal to two, a much better fit to the actual experimental curve is obtained.

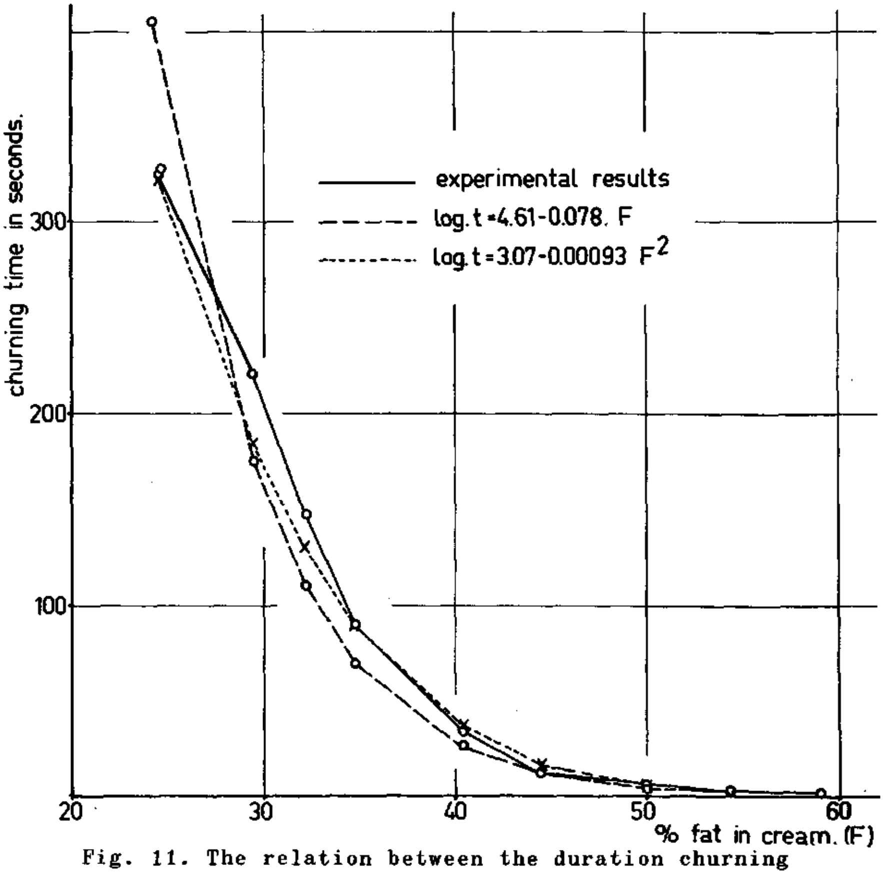


Fig. 11. The relation between the duration churning and the percentage fat in the cream. (Temp. 18°C; Annulus 0.45 cm; Speed 651 cm/sec.)

From four experiments conducted at different periods and at different circumferential speeds it appears that the rate of decrease in the churning times as the percentage of fat increases is approximately constant, as will be seen in the following regression equations.

Experiment	Speed cm/sec	Regression equation
27/2/2	650	Log.t = 4.61 - 0.078 Fat %
"	450	Log.t = 5.10 - 0.082 Fat %
17/10	504	Log.t = 5.98 - 0.098 Fat %
24/10	504	Log.t = 6.12 - 0.091 Fat %

As the regression equations were used only for comparative purposes, the general formula to describe the relationship between churning times and fat percentage was taken for the sake of simplicity as: Log.t = -kF. This gives a reasonably good description of the experimental curves actually obtained. Using covariance analysis no significant difference was obtained between the rates of decrease (regression coefficients or slopes), but a significant difference was found between the experimental means (elevation).

7.3. THE EFFICIENCY OF CHURNING

The speed at which the transition from irregular to uniform aggregation occurs, differs according to the fat percentages of the cream, as can be seen in Table 16.

TABLE 16. The effect of fat percentage on the transition from irregular to uniform aggregation at different circumferential speeds. (Temperature - 18°C; Annulus - 0.45 cm)

Circ. speed cm/sec	Churning time (min)				% Fat in buttermilk				% Fat in buttermilk as % of fat in cream			
	40%	30%	20%	10%	40%	30%	20%	10%	40%	30%	20%	10%
225	$5\frac{1}{2}$				8.9				22.3			
338	$2\frac{1}{2}$				3.8				10.5			
450	2	9			2.1	16.1			5.2	53.7		
504	$1\frac{1}{2}$	$6\frac{1}{2}$	20		1.9	15.6			4.8	52.0		
651	$\frac{1}{2}$	$3\frac{3}{4}$	9		1.1	11.1	10.8		2.8	37.0	54.0	
770		$2\frac{1}{2}$	9			6.3	9.2			21.0	46.0	
867		$2\frac{1}{4}$	7	26		3.3	4.5	4.5		11.0	22.5	45.0
980			$4\frac{3}{4}$	12			1.9	2.6			9.5	26.0

The transition from irregular to uniform aggregation for a 40, 30 and 20 per cent cream occurs at circumferential speeds of approximately 338, 770 and 980 cm/sec, respectively. For a 10 per cent cream this transition could not be established, as high enough speeds could not be risked with the apparatus.

In Fig. 12 are shown the trends in the churning times as well as the percentage of fat in the buttermilk with increasing fat percentages of the cream, at two different circumferential speeds. In the case of the lower fat percentages, irregular aggregation is encountered, (Shown by dotted lines in the figure.). Higher values for the fat in the buttermilk are observed for the low- and high-fat creams, the lowest values being in the region of 35 to 50 per cent. It appears, therefore, that the range of fat percentages where efficient churning will be obtained i.e. where there is a low fat content in the buttermilk, will vary, depending on the circumferential speed.

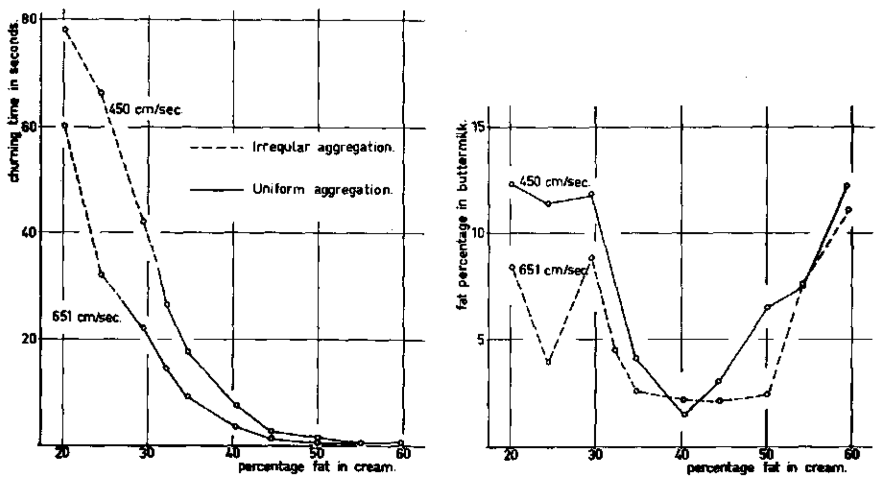


Fig. 12. The influence of the percentage fat in the cream on churning at two different circumferential speeds. (Temp. 18°C; Annulus 0.45 cm.)

The higher the speed the wider the range, and vice versa. The higher losses in the buttermilk of the low-fat creams are attributable to irregular aggregation.

The higher fat losses in the case of the high-fat creams (>55%) are ascribed to the poorly distributed gradient of velocity in the annular clearance due to the high viscosity of the cream. Applying higher speeds to such cream does not improve this condition as significantly as it does in cases when cream of lower fat percentages are churned, as indicated in Table 17.

TABLE 17. The influence of different speeds on the churning of creams having high fat percentages, in comparison with those having lower fat percentages.

Exp.	Circ. speed cm/sec	59.6% Cream		49.6% Cream			
		C.T.	%B	C.T.	%B		
I	104	6	12.8				
	225	2	6.7	(50)	16.2		
	338	2	13.6	30	14.1		
	504	1	14.1	15	4.3		
	660	1	11.2	7	3.8		
		59.2% Cream		49.5% Cream		39.4% Cream	
						C.T.	%B
II	52	(90)	22.0				
	104	75	30.1	(1140)	21.0		
	221	10	18.6	900	13.2	(1140)	13.1
	320	5	15.0	450	5.5	780	4.6
	473	6	12.1	285	3.6	690	1.0
	603	6	11.4	255	1.4	570	1.4

C.T. = Churning time in seconds.
( ) = Irregular aggregation.
%B = Percentage fat in buttermilk.

When churning cream having a high percentage of fat (55% and higher) it was often noticed that butter forms round the revolving inner cylinder first (sticking to it), and then gradually spreads outwards until butter has formed throughout the whole annular clearance. In these cases, annular vortices are seldom seen and then only for brief intervals, which indicates that two types of flow can exist under these circumstances.

In a region where the degree of disruption has taken such proportions that there is a tendency for a "mechanical" emulsion to develop, it is found that in cases of low-fat creams (30% and lower, generally) the duration of churning is indefinitely prolonged. Instead of obtaining a gradual increase in the churning times as the speed is increased in this region, a large jump is observed. This is in contrast to those cases i.e. when such a condition exists, but, when cream of a higher fat percentage is churned. These differences are illustrated in Table 18.

TABLE 18. Disruption tendencies in creams of different fat percentages. (Annular clearance - 0.45 cm).

Exp. I 50% Cream					Exp. II 30.4% Cream				
Speed cm/sec	18°C		22°C		Speed cm/sec	18°C		22°C	
	C.T.	%B	C.T.	%B		C.T.	%B	C.T.	%B
99	210	(25.1)	95	(14.4)	99			( )	-
221	180	(18.3)	65	4.3	223			3480	3.8
270	70	8.9	50	1.6	320	2580	(13.5)	>2	1.3
320	55	5.4	130	1.6	427	1080	(11.3)	>2	1.0
421	45	2.6	195	1.1	603	660	2.8	>2	0.9
465	25	3.1	480	0.9	744	540	2.2	>2	1.3
586	15	2.8	285	2.7	860	600	1.4	>2	1.0

( ) - Irregular aggregation. C.T. - Churning time in seconds
>2 - No butter formation after 2 hours. %B-% Fat in buttermilk.

At a churning temperature of 22°C the same tendencies, with regard to churning times, are found with both 50 and 40 per cent creams (Chapter 4), but the trend differed significantly when a 30 per cent cream was churned. After two hours of churning no butter was formed in the case of a 30 per cent cream i.e. at a temperature of 22°C, although granules did form at an early stage during the churning process. Apart from these disruptive tendencies it appears that granules have more space to move in, and that this is also a factor contributing to the much longer churning times. Stopping the churn, or, sometimes, when disturbing the general even flow, would cause butter to form immediately.

7.4. DISCUSSION

Similar to those cases in which the temperature or the annular clearance was varied, the transition from irregular to uniform churning is also affected by the percentage of fat in the cream. To obtain effective churning, a higher speed of the inner cylinder is necessary if the fat content of the cream is low, but apparently churning is also not satisfactory in the case of high-fat creams (55% and higher) irrespective of the speed applied. At the same speed, minimum fat losses are obtained in the range of about 35 to 50 per cent fat. The actual extent of this range will depend on the speed which is being used.

The collision chances, as well as the effectiveness of such collisions, improve as the fat percentage of the cream is increased, and both have an important influence on the duration of churning. In addition, it is also realized that the conditions of aggregation over a wide range of percentages differ considerably as regards the sphere of attraction between globules, the flow pattern, the viscosity, etc. However, it appears that some of these factors contribute to more effective collisions, when the percentage of fat is raised. Approaching the problem of deriving a formula in the same manner as that described in Chapter 5, to reflect the relationship between the duration of churning and the fat percentage (F) of the cream, the following equation appeared suitable:

$$\text{Log.}(\text{churning-time}) = -kF^x$$

x apparently having a value higher than one. By taking x as equal to two, a good fit to the actual experimentally obtained curves was obtained.

As the viscosity of the cream increases, the flow behaviour changes in that the Reynolds-number decreases and there is a tendency towards laminar flow. In the case of very viscous creams a large gradient of velocity is confined to the rotating inner cylinder which means that sufficiently high collision chances between globules will occur only at the surface of the rotating inner cylinder. It might be reasoned that layer after layer of butter would be formed and that eventually the cream at the outer cylinder would also be subjected to the same, or nearly the same, conditions as the cream at the inner cylinder at the start of churning, but this, however, does not occur in reality. Usually lumps of butter become stuck to the annular clearance and "slipping" of the inner cylinder occurs, with the result that a big percentage of the cream remains unchurned.

It can be accepted that the same effect of disruption on the duration of churning will be obtained as that described in a previous chapter i.e. for a 40 per cent cream, but apparently this disruption effect takes a completely different form in the case of low-fat creams. The inability of low-fat creams to form butter at higher than normal temperatures, cannot be attributed to disruption alone. As the aggregates form the distance between aggregates increases. This will also have an important influence in retarding the formation of butter, as the aggregates have now more freedom of movement, and the chances of avoiding each other are bigger.

8. THE INFLUENCE OF THE ACIDITY OF THE CREAM

The influence of the acidity on churning is strongly coupled with the condition of the casein at that particular acidity. GUTHRIE and SHARP (1931) showed that churning could be possible over practically the whole range of pH-values. In their experiments the shortest times were found in a region where the casein was in a precipitated form, whereas in a range where the casein is "dissolved", the longest churning times were obtained. MULDER (1947) found that the general trend in the churning times and the efficiency of churning with increasing acidities will also be dependent on the churning temperature. At low temperatures (10^{o}-12^{o}C), MULDER (1947) found first a rise in the duration of churning coupled with a lowering of the efficiency with an increase in the acidity, but then, in the region where the casein starts precipitating, a sharp decrease in the duration of churning, as well as an improvement in the efficiency of churning, occurred. In contrast to this, at higher temperatures (18^{o}-20^{o}C), a gradual decrease in the churning times as well as an improvement in the efficiency was noticed with increasing acidities.

MULDER (1947) found that washed cream does not exhibit the same phenomenon, but by adding small hard particles to fresh cream the same effect was obtained than in the case when precipitated casein was present. More rapid and efficient churning was obtained due to the precipitated casein particles, now having greater shearing properties and also as a result of a weakening of the membrane of the globules.

In experiments carried out in this investigation the cream was treated in the same way as described previously and a lactic acid solution was added after the cream was cooled. After the addition of lactic acid a crystallization time of at least 20 hours was allowed before churning. Different amounts of a 10 per cent lactic acid solution were added to portions of cream to give pH-values ranging between 4.0 and the pH of fresh cream. Final pH-measurements were done at the time of churning.

The effect of increasing the acidity of the cream on the duration of churning, and on the percentage of fat in the buttermilk is clearly reflected in Table 19.

A drop, both in the churning times and the percentage of fat in the buttermilk, is noticed between pH-values 5.5 and 4.6 and apparently a minimum is reached at the iso-electric point of the casein. A sharper drop is particularly observed in the case of a 30 per cent cream between pH-values of 5.0 and 4.60. Efficient churning, in the case of a 30 per cent cream, is obtained at a pH-value of 4.63, whilst at higher pH-values irregular aggregation is encountered. In the case of a 40 per cent cream efficient churning is obtained at all the pH-values, even for fresh cream, but the efficiency improves, as the acidity is raised. Acidity has a much greater effect in

TABLE 19. The influence of acidity on churning. (Circ. speed = 450 cm/sec Annulus 0.45 cm; Temperature 18°C)

40% Cream			29.7% Cream		
pH	C.T.	%B	pH	C.T.	%B
6.72	90	4.4	6.71	310	14.3
6.20	60	3.2	6.18	300	17.6
5.70	85	5.2	5.71	280	19.0
5.12	32	2.3	5.01	210	14.4
4.90	15	1.5	4.87	110	4.4
4.62	7	1.6	4.63	20	0.9
4.16	6	2.2	4.10	23	1.0

C.T. - Churning time in seconds.
%B - % Fat in the buttermilk.

the case of a 30 per cent cream than for a 40 per cent cream, and in both instances the effect becomes noticeable at pH-values lower than 5.5.

Figure 13 illustrates the influence of different circumferential speeds on the churning of acidified cream (pH in the region of the iso-electric point of casein). Besides a decrease in the churning times, a much lower speed is sufficient to be able to get a relatively low butterfat content of the buttermilk than in the case of fresh cream. Again is noticed the greater affect of acidity on the churning of a low-fat cream than in the case of a high-fat cream.

Judging by the tendencies in the fat percentage of the buttermilk, it would appear that the transition from irregular to uniform aggregation for a 30 per cent cream, shifts from a speed of 651 cm/sec for fresh cream, to 225 cm/sec for acidified cream and, for a 40 per cent cream, from 225 cm/sec to 100 cm/sec. By visual means it is found that for a 30 per cent cream the transition point shifts from 651 cm/sec for fresh cream, to 450 cm/sec for acidified cream, and for a 40 per cent cream no visual difference could be detected. Apparently it can be deduced that when acidifying the cream the transition from irregular to uniform aggregation occurs at a lower speed, but certainly not as pronounced as the graphs indicate.

It is found that even when irregular aggregation is encountered a low fat content was obtained in contrast to that when the same aggregation condition existed in fresh cream. The difference, however, is that in the case of acidified cream, practically all globules take part in aggregation whilst in fresh cream a great majority of globules are still unaltered. Aggregates are thus in a more advanced stage of development than in the case of fresh cream, but irregular aggregation is still predominant. Filtering through a 50 μ

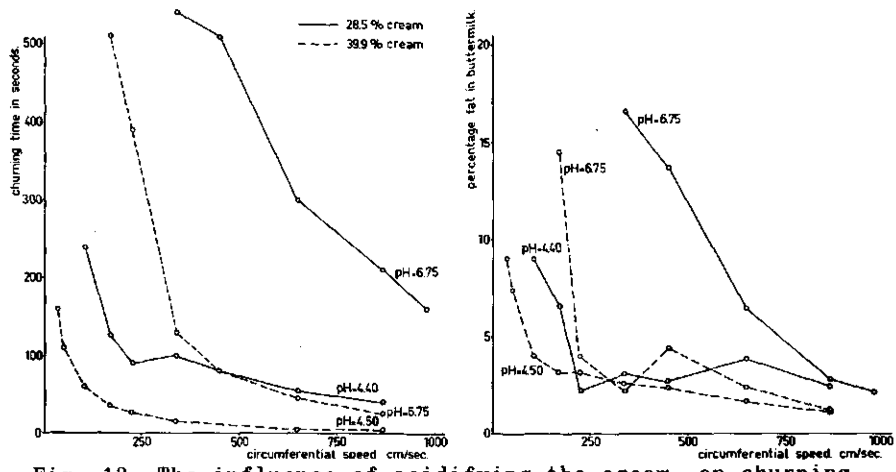


Fig. 13. The influence of acidifying the cream, on churning at different speeds, for two levels of fat percentage in cream.

filter apparently removes all aggregates and thus this is the reason for the lower fat content in the buttermilk.

Similating the experiments made by MULDER (1947) and by GUTHRIE and SHARP (1931), with "washed" 40 per cent cream at a churning temperature of 18^{0}C, and in this investigation the same results were obtained as will be noticed in Table 20.

TABLE 20. Churning washed cream at different pH-values. (Temp. 18^{0}C. Annulus 0.45 cm. Speed 450 cm/sec.)

Normal cream			Washed cream		
pH	Churning time	% Fat in buttermilk	pH	Churning time	% Fat in buttermilk
6.75	245	8.6	6.7	297	3.5
			5.4	270	5.5
4.5	105	2.9	4.4	370	7.6

The cream was "washed" three times. The influence of the casein particles is thus apparent. Adding solid particles to the fresh cream should have the same effect and a few experiments were carried out, to see whether the same would be obtained in this case.

	Churning time (sec)	% Fat in buttermilk
Normal cream	420	10.1
5% finely ground glasswool	125	5.0
5% Amberlite (± 40 μ size)	240	2.3
5% Milk solids-not-fat	500	8.1
20% Milk solids-not-fat	∞	-

Again the same effect is obtained. The addition of milk solids-not-fat retarded butter formation due to the "cushioning" effect of the solids-not-fat thus causing a decrease in the collision intensity.

From all these experiments, the importance of the precipitated casein particles on the process of churning becomes obvious. Much lower speeds are sufficient to cause effective aggregation, mainly due to the shearing properties of the casein particles and also as a result of a weakening of the membrane of the globule. Uneven-sized aggregates and disproportionate growth of aggregates was still predominant at these lower speeds, but it appears as if this aspect of aggregation is not significantly affected. At these lower speeds the disruptive forces are not so great as to limit the size of the aggregates. The high viscosity of acidified cream is also a factor that has to be considered, mainly concerning its effect on the flow properties of the cream.

9. THE EFFECT OF THE SIZE OF THE GLOBULES

The reason why cream from cows that produce large fat globules, e.g. the Channel breeds, churns more rapidly than cream from the Ayrshire and Holstein breeds, which produce smaller globules, is usually ascribed to the size of the globules. The same reason is given to explain why cream obtained during early lactation, churns better than cream obtained during late lactation. There is, however, not sufficient proof that the differences in churning obtained in these cases are solely attributed to the size of the globules.

HUNZIKER, MILLS and SPITZER (1912) found that churning was twice as long for creams containing small globules (average diameter 3.4 μ) than for creams containing larger globules (average diameter 4.7 μ). They separated the small-globule cream from large-globule cream of the same milk and churned under similar conditions. By fractional centrifugation of milk, SIRKS (1935) separated the bigger globules (average 3μ) from the smaller globules (average 2μ). He found churning times of 31 and 80 minutes and a fat content in the buttermilk of 0.34 and 0.53 per cent, respectively. Using approximately the same methods, to obtain creams containing globules of different average diameters, TVERDOKHLEB (1957) also obtained longer churning times for cream having smaller globules.

In order to obtain creams containing globules having different average diameters, mixed herd milk was centrifuged in the following manner:-

a. Normal speed at 40°C.

b. Separating at 20°C at half normal speed and thus selectively transfering large globules only in the cream. Re-separating the cream at 40°C in order to obtain a cream with approximately 40 per cent fat.

c. Re-separating the skimmilk of (b) at 40°C, at higher than normal speed.

These creams were then standardized to 35 per cent fat and the treatment of the cream was carried out in the same manner as described previously. The size frequency distribution of the globules was determined as follows:

Two to three drops of cream were diluted with a 50 per cent glycerol solution and gently mixed. A suitable quantity of this diluted sample was placed in a haemacytometer cell (depth of cell 100 μ), and at least 30 minutes was allowed for the globules to rise to the top. By means of a ocular micrometer scale and using a magnification of approximately 970x, the sizes were determined. All globules in the field for the full depth of the cell were measured. The sizes of approximately 500 globules were determined in class intervals of 1.2 μ. The fields were randomly taken over the haemacytometer cell. A fourth sample, being a mixture of creams obtained from treatments (b) and (c), was also included in these experiments.

The size distribution of the globules in 1.2 μ class intervals is given in histogram form in Fig. 14.

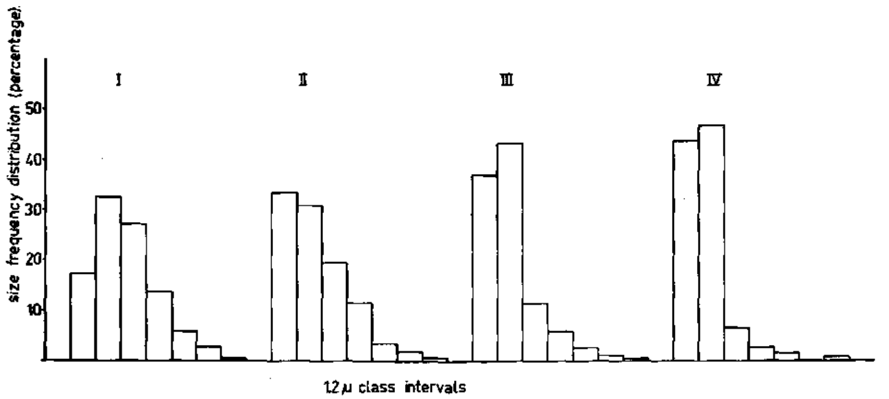


Fig. 14. The size distribution of fat globules. I. Separating at 20°C at half normal speed. II. Normal separating. III. Mixture of I and IV. IV. Separating "skimmilk" of I at 40°C at higher than normal speed.

The results of churning experiments are shown in Table 21, using an annular clearance of 0.45 cm and a churning temperature of 18°C.

TABLE 21. The influence of the size-distribution of fat globules on churning. (Temp. - 18°C. Annulus - 0.45 cm).

Speed cm/sec	I (2.6 μ)		II (2.1 μ)		III (1.8 μ)		IV (1.5 μ)	
	C.T.	%B	C.T.	%B	C.T.	%B	C.T.	%B
450	210	12.0	225	11.0				
650	120	5.1	130	3.7	180	5.3	270	7.5
770	95	4.2	105	4.1				
860	70	3.1	80	3.3			225	3.5

C.T. = Churning time in seconds.
%B = Percentage fat in buttermilk.

According to VON SMOLUCHOWSKI the collision chances increases to the third power of the diameter of the globule. These results show clearly the influence of the globule size on churning. As the relative number of small globules increases an increase in the churning times occurs. The churning also becomes less efficient.

10. SUMMARY AND CONCLUSION

It has only recently been proved without any doubt to be possible, to churn cream of a moderate fat content cream in the absence of air. In this laboratory, in preliminary experiments, successful and encouraging results were obtained by MULDER and SCHOLS (1953) and MULDER and HAANS (1953), and as a continuation of their work this investigation was commenced. The aim of this study was mainly to investigate, firstly, the phenomenon of aggregation and disruption and secondly, the establishment of the relationship between - the duration and efficiency of churning - and various conditions, in the absence of air.

An essential requirement for the object of this investigation was to have a simple or at least a systematic flow pattern of the cream. This was done by means of the rotational movement of cream contained between two coaxially arranged concentric smooth cylinders of stainless steel, with the inner one able to rotate. The circulation of water through the double-walled outer cylinder permitted effective control of the churning temperature during the churning process. Two "observation windows" made it possible to follow the churning process in the annular clearance. Vacuum de-aerated cream was churned after an adequate crystallization time, and, before churning commenced, a period of warming-up to its churning temperature of at least one hour was allowed. Proper precautions were taken to ensure that no air was incorporated in the churn during the churning process. All experiments were conducted in a region of speeds where the flow pattern of the cream was characterized by the presence of annular vortices. (Taylor vortices).

The characteristics of churning at different circumferential speeds of the inner cylinder can be distinguished mainly on the following aspects:-

a. Homogeneity of aggregation.

b. Aggregation and disruption phenomena.

Aggregation can either be irregularly or uniformly distributed throughout the cream. When the growth of aggregates occurred irregularly or disproportionately, butter formation was gradual. Although, in this case, practically all globules will eventually participate in aggregation, the stage where the first aggregates became visible, was considered as the end of churning. This was done because of experimental difficulties as a result of lumps of butter getting stuck in the annular clearance. When aggregate formation was uniformly distributed, butter formation was "instantaneous", and the termination of the churning process left no doubt when butter was formed. The number of collisions per unit time and the collision effectiveness was adequate to induce aggregation of practically all globules the moment churning commenced, whereas when irregular aggregation existed, aggregates formed at various stages during the churning process. The rate of aggregation was more rapid than that advanced by VON SMOLUCHOWSKI (1916) for the coagulation of colloids, probably due, amongst other factors, to the poly-dispersed globule sizes and the concentration of the dispersed phase. The transition from irregular to uniform aggregation occurred over a narrow range of speeds and a large drop in the fat content of the buttermilk occurred over this transition region.

As the circumferential speed was increased, a more stable aggregate was obtained. The stability also improved during the course of churning. With increasing speeds a greater tendency of disruption of aggregates existed, which had the effect of limiting the size of the aggregate. The higher the speed, the smaller the aggregate and the more even-sized the aggregate, that was obtained. Eventually, disruption developed to such an extent, that an increase in the duration of churning was found. At such high speeds, there was a tendency towards a stationary state of dispersion, but aggregation finally predominated, due to aggregates eventually acquiring a stable form. A complete equilibrium between aggregation and disruption was obtained in certain instances. The persistency of a stationary state of dispersion was particularly noticed when low-fat creams were churned. At still a further stage, usually at high speeds and at high temperatures (22 $^{\circ}$C and higher), "true" phase inversion occurred.

The transition from irregular to uniform aggregation was found at lower circumferential speeds of the inner cylinder as the temperature was increased, but on the other hand, disruption of aggregates also occurred more easily. Also, the range of speeds narrowed where uniform aggregation was obtained until a stage was eventually reached where complete coalescence of globules occurred. This was usually accompanied by much longer churning times.

At low temperatures the area of contact between globules is small, due to the limited amount of liquid fat present. This necessitated higher speeds to obtain effective aggregation; on the other hand, higher speeds will cause easier disruption.

In establishing the relationship between the duration of churning and the circumferential speed on the inner cylinder, only those results when uniform aggregation existed, were used. Churning could be looked upon as inversely proportional to the collision chances and the effectiveness of such a collision in forming an irreversible aggregate. Assuming the conditions in this investigation were the same as those laid down by VON SMOLUCHOWSKI (1917) for the coagulation of colloids in a locally laminar current, then the collision chances between globules will be directly proportional to the gradient of velocity. These considerations lead to the formula:

$$\text{churning time}(t) = \exp.(-\ kU).$$

However, due to disruption, and the fact that an irreversible aggregate does not necessarily form, and furthermore, that the conditions laid down by VON SMOLUCHOWSKI are not applicable, (e.g. the diameter of the globules in respect to the distance between globules cannot be ignored in the case of cream), a better formula to describe this relationship is:

$$t = \exp.(-kU^x).$$

In a few cases the formula was applied to the actually obtained results. It was found that the value of x was smaller than one. This then gave quite a good fit to the experimentally obtained curves.

The velocity gradient decreases with increasing clearance between the cylinders. By experiment it was found that the duration of churning was directly proportional to the annular clearance. Thus, the general formula when combining the effect of the annular clearance (R_2-R_1) and the circumferential speed (U), should be:

$$t = (R_2-R_1) \exp.(-kU^x).$$

Apparently for the smaller annular clearances - 0.15 cm in this investigation - the formula was not applicable, probably due to aggregates causing disturbance in the flow pattern in the small space. For the different annular clearances and different speeds, uniform aggregation was related to the Reynolds-number.

With increasing fat percentages(F), both the collision chances and the effectiveness of collisions will improve. The formula

$$t = \exp.(-kF^x),$$

derived in the same manner as in the case when the circumferential speed was varied, gave a good discription of the relationship between the duration of churning and the fat percentage(F). In this case the value of x was higher than one. When x was taken as equal to two, a better fit to the experimentally found curves was obtained. For lower fat percentages, a higher speed was necessary to obtain uniform aggregation,but apparently, when the fat content was high (55% and higher), no marked improvement in the churning efficiency occurred. This can be ascribed to the high viscosity, as a high gradient of velocity is only confined to the area immediately around the rotating inner cylinder, thus, irregular distributed aggregation takes place. Also must be taken into consideration the fact that butter granules were formed practically instantaneously on the surface of the cylinder due to the close packing of the globules. Irregular aggregation thus resulted.

Increasing the viscosity, generally had a tendency of initially improving the churning efficiency, but beyond a certain stage the efficiency lessened. The effect of viscosity had a distinct effect on diminishing the duration of churning in the case of low-fat creams, whilst its effect was not great for fat percentages higher than 40. At certain viscosity values, however, and in the case of low-fat creams (30% and lower) the duration of churning was prolonged, which can possibly be ascribed to the effect of viscosity in dispersing the force of collisions between globules.

Acidified cream (pH 4.6) churned more rapidly and some improvement in the efficiency of churning was found in comparison to that when fresh cream was churned under similar conditions. This must be due to the precipitated casein particles, as this effect could be similated by adding solid particles, such as finely ground glasswool, etc., to "washed" cream.

It was found that as the relative number of big globules increased in the cream, much shorter churning times were obtained and churning became more efficient.

In this investigation it was shown that:

a. Efficient churning is possible provided that favourable conditions existed, in order that - (i) Aggregation of globules occurred uniformly throughout the cream; and (ii) Excessive disruption of aggregates did not occur.

b. A possibility existed in establishing, formulae describing the general trend in the relationship between the duration of churning and various conditions that are known to influence churning.

S A M E N V A T T I N G.

"Karnen bij afwezigheid van lucht".

Nog slechts betrekkelijk kort geleden werd onomstotelijk bewezen, dat het karnen van room met een matig hoog vetgehalte onder geschikte omstandigheden plaats kan vinden bij afwezigheid van lucht. In dit laboratorium werden succesvolle en stimulerende ervaringen opgedaan, tijdens voorlopige proefnemingen van MULDER en SCHOLS (1953) en van MULDER en HAANS (1953). Dit onderzoek werd dan ook aangevat als een voortzetting van het hunne. Het doel was hierbij voornamelijk om de verschijnselen van aggregatie en disruptie te onderzoeken, en bovendien de afhankelijkheid van karnduur en karnrendement van allerlei uitwendige omstandigheden op te sporen, dit alles bij het karnen zonder lucht.

Een essentiële voorwaarde was hierbij de mogelijkheid de room in een eenvoudige, of tenminste een geordende stromingstoestand te brengen. Dit werd bereikt door de room tussen twee gladde, roestvrijstalen, concentrische cylinders te brengen, waarbij de binnenste om zijn as kon draaien. Circulatie van water om de buitenste cylinder maakte het mogelijk de temperatuur tijdens het karnen constant te houden. Het karnproces kon geobserveerd worden door twee "venstertjes". Alvorens tot karnen werd overgegaan, werd de room ontlucht, gekoeld bewaard om het vet te laten kristalliseren, en voor het gebruik geleidelijk gedurende ten minste één uur op karntemperatuur gebracht. De nodige voorzorgen werden genomen om toetreden van lucht voor of tijdens het karnen te voorkomen. Alle proeven werden uitgevoerd onder omstandigheden waarbij de stroming van de room was gekarakteriseerd door z.g. Taylor-wervels.

Om onderscheid te maken in de kenmerkende eigenschappen van het karnproces bij verschillende omtreksnelheden van de binnenste cylinder, zijn voornamelijk de volgende aspecten van belang:

a. De homogeniteit van de aggregatie door de hele vloeistof.

b. Het belang van disruptie ten opzichte van aggregatie.

De aggregatie kan onregelmatig zijn, dan wel gelijkmatig verdeeld door de gehele hoeveelheid room. Als de groei van de aggregaten ongelijkmatig of onregelmatig was, dan werd geleidelijk boter gevormd. Hoewel in dit geval vrijwel alle vetbolletjes ten slotte aan de aggregatie deel zullen nemen, werd toch het moment waarop de eerste boterkorrels zichtbaar werden als het eindpunt van het karnproces beschouwd. De reden hiervoor was het optreden van experimentele moeilijkheden, zoals het vast gaan zitten van boterkorrels. Bij gelijkmatig door de room verdeelde vorming van aggregaten, was de botervorming "momentaan", zodat het eindpunt ondubbelzinnig vastgesteld kon worden. In dit geval waren het aantal botsingen per tijdseenheid en de effectiviteit van de botsingen voldoende groot om de aggregatie van bijna alle bolletjes te doen plaats vinden vanaf het begin van het karnen. De aggregaten werden daarentegen in het geval van onregelmatige aggregatie gevormd tijdens verschillende stadia van het karnproces. De aggregatie verliep sneller dan overeenkwam met de theorie van VON SMOLUCHOWSKI (1916) betreffende de uitvlokking van solen, waarschijnlijk tengevolge van o.a. de spreiding in de grootte van de vetbolletjes en de hoge concentratie van de disperse fase. De overgang van onregelmatige naar regelmatige aggregatie vond plaats tussen nauwe grenzen voor wat betreft de omtreksnelheid, waarbij een sterke afneming van het vetgehalte van de karnemelk in dit overgangsgebied werd waargenomen.

Bij toenemende omtreksnelheid, werden stabielere aggregaten verkregen. De stabiliteit nam tevens toe tijdens het karnen. Toenemende snelheid gaf echter ook een grotere neiging tot disruptie, hetgeen resulteerde in een beperking van de grootte van de aggregaten. Hoe groter de snelheid was, des te kleiner en uniformer waren de gevormde aggregaten. Uiteindelijk werd de disruptie zo belangrijk, dat een toeneming van de karnduur plaatsvond. Bij zulke grote snelheden bestond er een neiging tot het ontstaan van een evenwicht tussen aggregatie en disruptie, maar uiteindelijk bleek de aggregatie overwegend, tengevolge van de stabiele vorm die de aggregaten tenslotte verkregen. In sommige gevallen kon echter een echt evenwicht worden verkregen. Deze neiging tot evenwicht tussen beide verschijnselen handhaafde zich vooral bij het karnen van room met een laag vetgehalte. In een nog verder stadium, doorgaans bij een hoge snelheid en een hoge temperatuur (22^{0}C en hoger), vond een fasenomkering plaats (vorming van een "water-in-vet-emulsie").

De overgang van onregelmatige naar regelmatige aggregatie werd bij lagere omtreksnelheid gevonden, indien de karntemperatuur werd verhoogd, maar dan vond ook de disruptie van aggregaten gemakkelijker plaats. Tevens werd het gebied van snelheden waarbij regelmatige aggregatie plaatsvond nauwer bij toenemende temperatuur, en tenslotte werd dan een stadium bereikt waarbij volledige samenvloeiïng van vetbolletjes optrad. Dit ging doorgaans samen met een veel langere karnduur.

Bij lagere temperaturen is het aanrakingsoppervlak van twee bolletjes kleiner, tengevolge van de dan beperkte hoeveelheid vloeibaar vet. Daardoor waren hogere snelheden nodig om een effectieve aggregatie te verkrijgen. Anderzijds vindt bij grotere snelheden gemakkelijker disruptie plaats.

Bij het onderzoeken van het verband tussen karnduur en omtreksnelheid werden alleen resultaten gebruikt, die waren verkregen bij regelmatige aggregatie. De effectiviteit van het karnen werd evenredig geacht aan de botsingskans en aan de effectiviteit van de botsingen voor wat betreft de vorming van een stabiel aggregaat. Indien men veronderstelt dat de omstandigheden bij dit onderzoek gelijk waren aan die waaraan VON SMOLUCHOWSKI (1917) uitgaat bij de coagulatie van solen in een (plaatselijk) laminaire stroom, dan zal de botsingskans omgekeerd evenredig zijn aan de snelheidsgradiënt. Deze overwegingen leiden tot de vergelijking: karnduur = exp.(- kU).

Aangezien evenwel disruptie optreedt, de gevormde aggregaten niet noodzakelijkerwijs onveranderlijk zijn, en bovendien de omstandigheden die VON SMOLUCHOWSKI aanwezig veronderstelde niet overeenkomen met de onderhavige (zo is b.v. de diameter van de vetbolletjes in room niet verwaarloosbaar klein t.o.v. hun afstand), wordt het verband beter beschreven door de formule

$$\text{karnduur}(t) = \exp.(-\ kU^{x}).$$

Bij enige experimenten werd deze formule toegepast op de gevonden uitkomsten. Voor x werden waarden gevonden kleiner dan 1. De formule gaf een tamelijk nauwkeurige beschrijving van het gevondene.

De snelheidsgradiënt neemt af met toenemende afstand tussen de cylinders. Uit de proefnemingen bleek dat de karnduur recht evenredig was aan deze afstand. Zo zou dan de algemene vergelijking die de invloed van deze afstand (R_2-R_1) en de omtreksnelheid (U) beschrijft als volgt worden:

$$t = (R_2-R_1)\ \exp.(-\ kU^{x}).$$

Klaarblijkelijk kon de formule voor de kleinste spleetwijdten (hier 0,15 cm) niet worden toegepast, waarschijnlijk omdat de gevormde aggregaten in de kleine ruimte het stromingspatroon verstoorden. Voor wat betreft verschillen in spleetwijdte en snelheid, was het gebied waarin regelmatige aggregatie optrad, afhankelijk van het getal van Reynolds.

Bij toenemende vetgehalte (F), zullen zowel de kans op als de effectiviteit van botsing groter worden. De vergelijking

$$t = \exp.(- kF^{x}),$$

afgeleid op dezelfde wijze als in het geval van veranderde omtreksnelheid, gaf een goede beschrijving van het verband tussen karnduur en vetgehalte. Hierbij bleek de waarde van x groter dan 1 te zijn. Voor x = 2 werd een goede overeenstemming met de experimenteel bepaalde curven verkregen. Bij karnen van room met een lager vetgehalte waren hogere snelheden nodig om regelmatige aggregatie te verkrijgen, maar bij zeer hoge vetgehalten (55% en hoger) bleek geen duidelijke toeneming van de uitkarningsgraad. Dit kan toegeschreven worden aan de hoge viscositeit, tengevolge waarvan een grote snelheidsgradiënt alleen dicht bij de draaiende cylinders optreedt. Ook moet in het oog worden gehouden dat op deze plaatsen vrijwel onmiddellijk boterkorrels worden gevormd, doordat de vetbolletjes dicht tegen elkaar liggen. Ongelijkmatig over de vloeistof verdeelde aggregatie is het gevolg.

Verhoging van de viscositeit had doorgaans aanvankelijk de neiging de uitkarningsgraad te verbeteren, maar bij verdere verhoging nam de effectiviteit weer af. De afneming van de karnduur tengevolge van toenemende viscositeit was groot bij room met een laag vetgehalte, en klein bij room met meer dan 40% vet. Bij bepaalde viscositeitswaarden en lage vetgehalten (30% en minder) werd de karnduur evenwel verlengd; dit moet waarschijnlijk toegeschreven worden aan verkleining van de heviqheid van de botsingen tussen de bolletjes.

Aanzuren van de room (pH 4,6) resulteerde in sneller karnen en toegenomen karnrendement, vergeleken met het karnen van zoete room onder gelijke omstandigheden. Dit moet toegeschreven worden aan de aanwezigheid van neergeslagen caseïnedeeltjes, daar het effect ook verkregen kon worden door vaste deeltjes, zoals glaspoeder, aan "gewassen" room toe te voegen.

Het bleek dat een veel kortere karnduur en een hoger rendement werden verkregen, indien de room een relatief groot aantal grote vetbolletjes bevatte.

Uit dit onderzoek bleek:

a. Doelmatig karnen is mogelijk indien gunstige omstandigheden worden gekozen opdat (1e) aggregatie gelijkelijk in de gehele hoeveelheid room plaats vindt en (2e) overmatige disruptie van aggregaten achterwege blijft.

b. Het is mogelijk formules op te stellen die de algemene lijn beschrijven van het verband tussen karnduur en diverse omstandigheden die het karnproces beïnvloeden.

ACKNOWLEDGEMENTS

This investigation was carried out at the Laboratory of Dairying, The Agricultural University, Wageningen, The Netherlands, to whom the author is indebted for this privilege.

Sincere thanks are due to Prof. Dr. H. MULDER for his stimulating guidance, interest and criticism during the course of this investigation.

The author is grateful for the help and constructive criticism by Dr. Ir. P. WALSTRA and Dr. Ir. C.J. SCHIPPER.

Thanks are due to Prof. Dr. G. VOSSERS for his explanation of the hydrodynamic aspects encountered in this investigation.

Appreciation is expressed to members of the Staff of the Laboratory of Dairying for their help and co-operation.

Special thanks are due to Mr. M. MARTIN for the correction of parts of the English text and to Dr. Ir. P. WALSTRA in helping with the Dutch Summary.

The author wishes to thank the South African Department of Agricultural Technical Services for the opportunity of studying in The Netherlands, as well as the South African Dairy Industry Control Board for the bursary granted.

REFERENCES

BARTOK, W. & MASON, S.G., (1959). J. Coll. Sci. 14, 13.

CLAY, P.H., (1940). Proc. Ned. Akad. van Wet. 43, No. 6-10. Part I, 852. Part II, 979.

CLOWES, (1916). J. Phys. Chem. 20, 407. Quoted by SUMNER. (1954).

COMBS, W.B. & COULTER, S.T., (1930). Minn. Exp. Sta. Bull. 273. Quoted by McDOWALL. (1953).

DAM, W. VAN & HOLWERDA, B.J., (1934). Versl. Landb. Onderz., Dept. of Agric., The Hague. 40, 175.

FASTOVA, N. & VLODAVETS, I., (1956). Mol. Prom. 17,(8), 29. Quoted in Dairy Sci. Abs. 19, 343.

FREUNDLICH, H., (1922). "Kapillarchemie". Publ. by Akad. Verlagsgesellschaft. Leipzig.

GORBATSCHEW, S.W., (1935). Koll. Z. 73, 14 & 21.

GRISCHENKO, A.D., (1950). Mol. Prom. 6. Quoted by VLODAVETS. (1952).

GRISCHENKO, A.D., (1953). Mol. Prom. 14,(4), 28. Quoted in Dairy Sci. Abs., 17, 337.

GRISCHENKO, A.D., (1959). Proc. XVth Int. Dairy Congr., London. 2, 1030.

GUTHRIE, E.S. & SHARP, P.F., (1931). J. Dairy Sci. 14, 1.

HUNZIKER, O.F., MILLS, H.C. & SPITZER, G., (1912). Purdue Agric. Sta. Bull. 159. Quoted by McDOWALL. (1953).

KING, N., (1931). Milch. Forsch. 12, 500.

KING, N., (1932). Milch. Forsch. 14, 114.

LYONS, & O'SHEA., (1936). Econ. Proc. Roy. Dub. Soc. 3,(10), 119. Quoted by McDOWALL. (1953).

McDOWALL, F.H., (1953). "The Buttermaker's manual". Publ. by New Zealand Univ. Press. Wellington.

MOHR, W. & BROCKMANN, C., (1930). Milchw. Forsch. 10, 173.

MULDER, H., (1946). Versl. Landb. Onderz. 52, 269.

MULDER, H., (1947). "Problemen en Resultaten bij Wetenschappelijk Zuivelonderzoek". Part II. Publ. by "Alegemene Nederlandsche Zuivelbond. (F.N.Z.)", The Hague.

MULDER, H. & SCHOLS, J.J.G., (1953). Proc. XIIIth Int. Dairy Congr., The Hague. 2, 706.

MULDER, H. & HAANS, N.G.M., (1953). Unpubl. Results. Laboratory of Dairying. Univ. Wageningen. The Netherlands.

MULDER, H. & KLOMP, R., (1955). Neth. Milk & Dairy J. 10, 123.

MÜLLER, H., (1926). Kolloid. Z. 38, 1. & Kolloidchem. Beihefte. 26, (1928), 257. Quoted by OVERBEEK. (1960).

MÜLLER, H., (1928). Kolloidchem. Beihefte. 27, 223. Quoted by OVERBEEK. (1960).

OVERBEEK, J. Th. G., (1960). "Kinetics of flocculation" in "Colloid Science" I. Editor KRUYT, H.R., Publ. by Elsevier Publ. Co., Amsterdam.

PALMER, L.S. & WIESE, H.F., (1933). J. Dairy Sci. 16, 41.

PRANDTL, L., (1956). "Strömungslehre". Publ. by Fiedr. Vieweg & Sohn. Braunsweg.

RAHN, O. &. SHARP, P.F., (1928). "Physik der Milchwirtschaft". Publ. by P. Parey. Berlin.

ROUSE, H., (1959). "Advanced Mechanix of Fluids". Publ. by J. Wiley & Sons. Inc. N.Y.

SCHLICHTING, H., (1955). "Boundary Layer Theory". Publ. by McCraw-Hill. N.Y.

SHUVALOV, V.N. & VLODAVETS, I.N., (1954). Kolloid Zh. 16,(5), 396. Quoted in Dairy Sci. Abs. 17, 337.

SIRKS, H.A., (1935). "Jaarversl. Rijkslandb. Proefst." Hoorn. Quoted by MULDER. (1947).

SMOLUCHOWSKI, M. VON, (1916). Physik. Z. 17, 557 & 585. and Z. Physik. Chem., (1917). 92, 129. Quoted by OVERBEEK. (1960). Also quoted by TENDELOO. (1931, 1932).

SMOLUCHOWSKI, M. VON, (1917). Z. Physik. Chem. 92, 155. Quoted by OVERBEEK, (1960), and also quoted by FREUNDLICH. (1922).

SNEDECOR, G.W., (1956). "Statistical Methods". 5th Ed. Publ. by Iowa State Coll. Press. Ames. U.S.A.

SUMNER, C.G., (1954). "Clayton's Emulsions and their Treatment". 5th Ed. Publ. by Churchill. London.

TAYLOR, G.I., (1923). Phill. Trans. Roy. Soc. 223, 289.

TAYLOR, G.I., (1935). Proc. Roy. Soc. London. Serie A, 151, 494.

TAYLOR, G.I., (1936). Proc. Roy. Soc. London. Serie A, 157, 546.

TENDELOO, H.J.C., (1931). Chemisch Weekblad, 28, 634. Part I.

TENDELOO, H.J.C., (1932). Chemisch Weekblad, 29, 151. Part II.

TVERDOKHLEB, G.V., (1957). L.L.A. Raksti. 6, 485. Quoted in Dairy Sci. Abs. 22, 531.

VLODAVETS, I., (1952). Mol. Prom. 13,(12), 30.

WIEGNER, G., (1911). Kolloid Z. 8, 227. Quoted by OVERBEEK. (1960).