Drainage of curd

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Proefschrift
ter verkrijging van de graad van
doctor in de landbouw- en milieuwetenschappen,
op gezag van de rector magnificus,
Dr. H.C. van der Plas,
in het openbaar te verdedigen
op woensdag 29 april 1992
des namiddags te vier uur in de Aula
van de Landbouwuniversiteit te Wageningen

Stellingen

1) Door de resultaten van dit onderzoek toe te passen in de kaasfabrieken zou de aanvoer van grondstoffen voor de bereiding van smeltkaas, na een aanvankelijke stijging in de toevoer, wel eens kunnen stagneren.

Dit proefschrift

2) Onderzoek naar de drainage van wrongel is zowel voor de kwaliteitsborging van kaas als voor de bereiding van weipoeder van belang.

Dit proefschrift

3) Optische sensoren kunnen worden gebruikt om verschillende bestanddelen te onderscheiden in een mengsel. Dit kan op basis van verschil in brekingsindex, zoals Frijlink reeds heeft aangetoond, maar ook op basis van verschil in lichtverstrooiing.

J.J. Frijlink, Physical aspects of gassed suspension reactors. Ph.D. Thesis, TU Delft (1987)

Dit proefschrift

4) De door Rüegg en Moor gegeven verklaring voor de verschillen tussen het gemiddelde oppervlak van sedimenteerde deeltjes in het horizontale vlak en dat in het vertikale vlak is vermoedelijk niet de enige juiste.

M. Rüegg U. Moor, The size distribution and shape of curd granules in traditional Swiss hard and semi-hard cheeses. Food Structure 6 (1987) 35-46

6) Het effect van de wand van het draineersysteem op de drainage kan zeer groot zijn.

Dit proefschrift

7) James Bond heeft nooit kunnen vermoeden dat na zijn film "For your eyes only" de grote vraag naar Maasdammer begonnen is.

Stellingen bij het proefschrift "Drainage of Curd" van Coen Akkerman te verdedigen op 29 april 1992

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Voorwoord

Ofschoon er maar één naam op het kaft van dit boekje staat, is het natuurlijk niet zo, dat dit werkstuk zonder wezenlijke bijdrage van anderen tot stand is gekomen. Zonder volledig te kunnen zijn wil ik hier bij bedanken:

- Mijn beide promotoren, Pieter Walstra en Jaap Schenk, voor de vrijheid, die ze me geboden hebben bij de aanpak van dit onderzoek en de steun bij de realisatie van het proefschrift.
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Abstract

Akkerman, J.C., (1992). Drainage of curd. Ph.D. thesis, Agricultural University, Wageningen. (pp 113, English and Dutch summaries).

Keywords:
curd, whey drainage, syneresis, curd fusion, Gouda cheese, cheesemaking equipment, curd fines

Abstract:

An extensive study was made of the factors governing drainage of curd. A basic feature of this study is the comparison of the behaviour of a single curd grain and the behaviour of batches of uniform curd grains in a drainage column. A detailed study was made of the deformation and whey expulsion from single curd grains, the fusion of curd grains and the sedimentation of curd grains. Furthermore, drainage was studied in small scale drainage equipment. Liquid pressures, wall friction losses and compaction rates were recorded. The porosity was measured using an optical fibre technique. Furthermore the permeability was calculated from experimental results.

1. Introduction

1.1 In general

Cheese is an important food in many countries around the world. Though many different varieties of cheese are produced, the basic principle of the manufacture is always the same. Cheese-making starts with clotting of the milk, i.e. transformation of the liquid milk into a gel. Clotting can be accomplished either by adding rennet to the cheese milk or by acidification of the milk; most cheese is made by renneting. The gel is cut into pieces. Whey, i.e. an aqueous solution of lactose, proteins and salts, is expelled from the pieces; this process is called syneresis (Van Dijk 1982). The process of whey expulsion is usually enhanced by stirring the curd/whey mixture. The temperature is often raised to increase the whey expulsion rate further. Finally, fairly rigid curd grains and a large amount of whey are obtained. The whey and the curd grains are separated. The collected curd grains form a coherent mass that is pressed, salted and ripened. The order of the pressing and salting steps is reversed in the manufacture of some particular cheese types.

Cheese has been known to mankind for many hundreds of years, the product has evolved from rather primitive to (sometimes) a top-ranking delicacy and a wealth of empirical know-how has been gained over these years. Not only the product has evolved, but also the production process. Modern cheese plants nowadays often represent highly automated large scale operations. The large scale of bulk production requires close process control and empirical know-how is becoming inadequate. In the laboratory of Dairy Science and Food Physics of the Agricultural University in Wageningen and at the Netherlands Dairy Research Institute in Ede an extensive study of the fundamentals of some of the key processes in cheese making has been made. Van Hooydonk (1987) focused upon the renneting of milk. Van Dijk (1982) and Van den Bijgaart (1988) performed a detailed study of the syneresis of rennet-induced milk gels. Zoon (1988) investigated the rheological properties of rennet-induced skim milk gels and Roefs (1986) those of acid casein gels. Geurts (1972) studied the salting of Gouda type cheese. Luyten (1988) studied the rheological and fracture properties of Gouda cheese.

The objective of the present research project is to investigate processes occurring during the drainage of a mass of curd grains in whey. It is amazing that up till now this field received little attention in the literature (Walstra et al. 1985) and basic knowledge of the processes is still largely lacking.

1.2 The drainage of curd; an overview

The whey removal is an essential step in cheese making: it concentrates most of the valuable ingredients of the milk into a small volume and it leads to a coherent mass.

During draining four major processes may be distinguished:

1) Additional whey is expelled from the curd grains.
2) Curd grains are deformed.
3) Curd grains partly fuse with each other.
4) Whey flows away through the connected pores between the grains.

The processes occur simultaneously and are interrelated. For instance, the whey expulsion results in a deformation of the curd grains, thereby narrowing the pores between the curd grains through which the whey must flow away. Furthermore, the expulsion of whey contributes to the flow of whey through the channels.

The water content of the cheese is not only determined by the drainage, but it depends also on the curd preparation, shaping and pressing of the curd block, and salting and ripening conditions. Control of the water content during salting (Geurts 1972, Guinee & Fox 1987) and ripening is generally very good, and will not be discussed in this thesis. However, fundamental knowledge about the interactions between the properties of the curd as resulting from its method of preparation, and the processes occurring during drainage (shaping) and pressing is lacking and will be an important topic in this thesis.

1.3 Theoretical aspects of curd preparation

The proteins in milk can be classified into two main groups, caseins and whey proteins. The casein molecules are present in small aggregates (submicelles), which are clustered in approximately spherical aggregates (micelles) (e.g. Walstra & Van Vliet 1986), as depicted in Figure 1.1. Casein micelles in milk mainly consist of α_{s1}, α_{s2}, β and κ-casein, calcium phosphate and water (Walstra & Jenness 1984). According to Van Dijk's model (1990), micellar calcium phosphate consists of complexes of inorganic and organic phosphate and calcium, which link up one by one and bind another limited number of Ca-, Mg- and phosphate-ions. In this way small, partly rigid and more stable ion clusters are formed by which casein molecules are interconnected. There is a dynamic equilibrium between casein and calcium phosphate in micelles and in solution (Walstra 1990), although the equilibrium between casein (and calcium

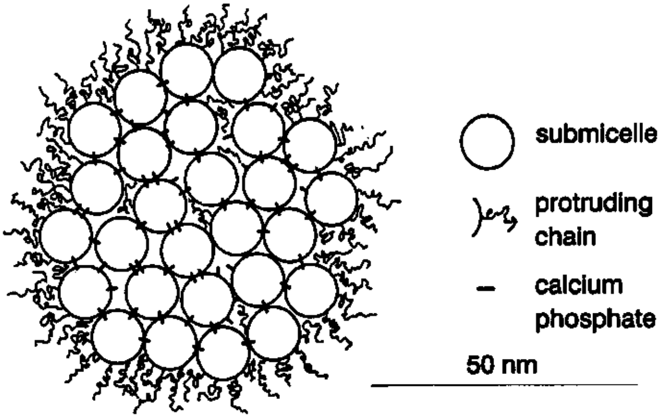


Fig. 1.1 Section through a casein micelle, highly schematic. The protruding chains of mainly κ-casein are clearly visible (Walstra 1990).

phosphate) and the micelles is predominantly to the side of the micelles. Van der Waals attraction would cause the casein micelles to flocculate, if there would be no repulsive interaction energy between them. This repulsion of steric and electrostatic nature is primarily caused by κ-casein. Rennet splits the κ-casein into para-κ-casein and a soluble caseino-macropeptide. Thereby the repulsion between paracasein micelles is greatly diminished. If additional conditions are fulfilled, i.e. temperature not below 10 °C and a sufficient activity of Ca^{++}-ions, the paracasein micelles will flocculate, forming initially irregular aggregates. After a while, the flocculation leads to formation of a gel; a schematic representation of the transformation of single micelles into a gel is given in Figure 1.2.

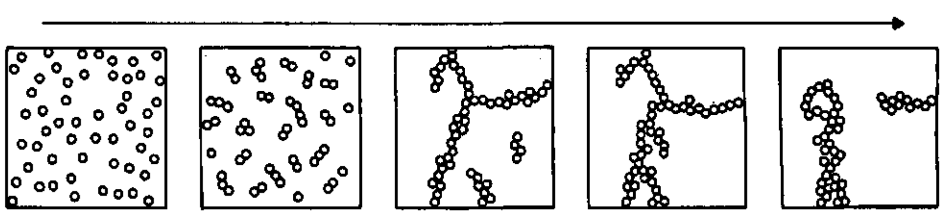


Fig. 1.2 Schematic representation of the change from stable casein micelles to a gel of paracasein micelles during the renneting of milk (Van den Bijgaart 1988).

The gel network consists of strands, that vary in length, thickness and pore size between them (Zoon et al. 1988). The network entraps fat globules.

The network shows an inclination to contract. It is caused by a tendency to rearrange the strands that make up the network. This causes a spontaneous pressure, exerted by the gel network on the whey enclosed; this endogenous syneresis pressure is, in a non-syneresed skim milk gel, some 1 to 10 Pa (Van Dijk 1982). In the early stages of the gelation process the build-up of pressure by the formation of new contacts is only partly counteracted by relaxation due to breaking of strands and strengthening of the strands (Van den Bijgaart 1988). If the gel is geometrically constrained, the rearranging will cause local condensation of strands, leaving larger pores elsewhere. This phenomenon is called microsyneresis (Van Dijk 1982). It results in an increase of the permeability of the gel with time (Van Dijk 1982, Van den Bijgaart 1988). It can be concluded that the properties of the milk gel, and thereby those of the curd grains, will be affected by the time elapsed after renneting. The effect of ageing may be enhanced by the decreasing pH due to the formation of lactic acid by starter bacteria. The lowering of the pH increases the permeability of the network and initially also the endogenous syneresis pressure (Van den Bijgaart 1988), and also affects the rheological behaviour (Zoon et al. I 1989). If the gel is not constrained, expulsion of whey (syneresis) will lead to shrinkage of the gel and thereby to concentration of the matrix. It will make new contacts between the strands feasible, regenerating endogenous syneresis pressure. Shrinkage can locally promote the formation of thicker strands and thus a stiffening of the casein matrix (Van den Bijgaart 1988). The concentration distribution of paracasein in the gel at various stages has not yet been precisely determined, but Van den Bijgaart (1988) calculated concentration profiles for the case of one-dimensional syneresis, as illustrated in Figure 1.3. The permeability of concentrated skim milk gels is decreased (Van den Bijgaart 1988). Concentration by means of syneresis always results in inhomogeneous gels, therefore the experiments were conducted with gels preconcentrated by means of ultrafiltration. These gels contain a substantial amount of whey proteins in addition to paracasein and have a slightly lower permeability than those preconcentrated by syneresis (Van den Bijgaart 1988). Permeability and endogenous syneresis pressure of the paracasein network increase considerably with temperature (Van den Bijgaart 1988). Fat globules impede the shrinkage of the gel, probably due to the higher particle volume fraction of the gel and a lower permeability of the matrix (Van den Bijgaart 1988). Addition of $CaCl_2$

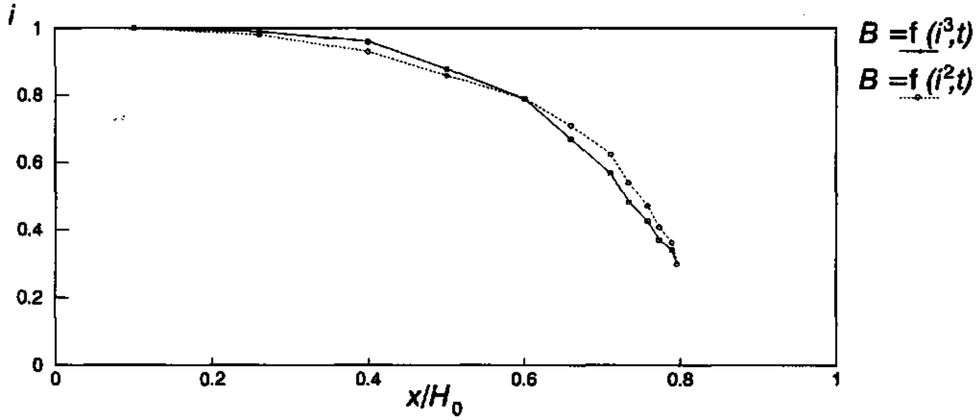


Fig. 1.3 Calculated concentration profile of paracasein as function of the relative distance towards the bottom of a rennet skim milk gel, after 20 % shrinkage, where i is concentration with regard to the original milk. Two functions of permeability are taken: $B = f(i^3,t)$ and $B = f(i^2,t)$, original height of the gel = 5 mm. Although the permeability clearly differs the resulting concentration profile is almost the same (Van den Bijgaart 1988).

causes a pH drop. After the compensation of the pH, the $CaCl_2$ addition appeared to have only limited effect on the syneresis rate and permeability (Van den Bijgaart 1988).

Mechanical stress results in a greatly enhanced shrinkage of the gel (Van den Bijgaart 1988). The deformation induced by external stress results in an increased permeability of the network (Van Dijk 1982). Zoon et al. (II 1989) assumed that at large deformations whole strands will be broken at several places in the network. This microscopic fracturing thereby causes large pores in the gel. Furthermore, the deformation will certainly facilitate formation of new contacts, and thus increase the pressure upon the whey. After small and rapid deformations the original shape of the gel is largely recovered, but after longer lasting stresses or greater deformations it is not recovered. Hence, the gel has both elastic and viscous properties and therefore rheological behaviour of the gel is time-dependent (Zoon et al. 1988). The network consists of strands of varying thickness and size (Zoon et al. 1988). Long lasting stresses or greater deformations will cause breaking of some of the strands, so the broken ends will not reform in a random way, but in such a way that they are stress-free. This process will lead to a slow yielding of the strands, after which the loose ends may form new junctions elsewhere (Van Vliet et al. 1991). Rapid and small deformations may also break the strands, but the yielding will not take place and the bonds will immediately be restored as the stress is released. As the network consists of strands of various sizes and thickness, the relaxation times of the strands in network will vary: consequently the network has a wide spectrum of relaxation times.

1.4 Practical aspects of curd preparation

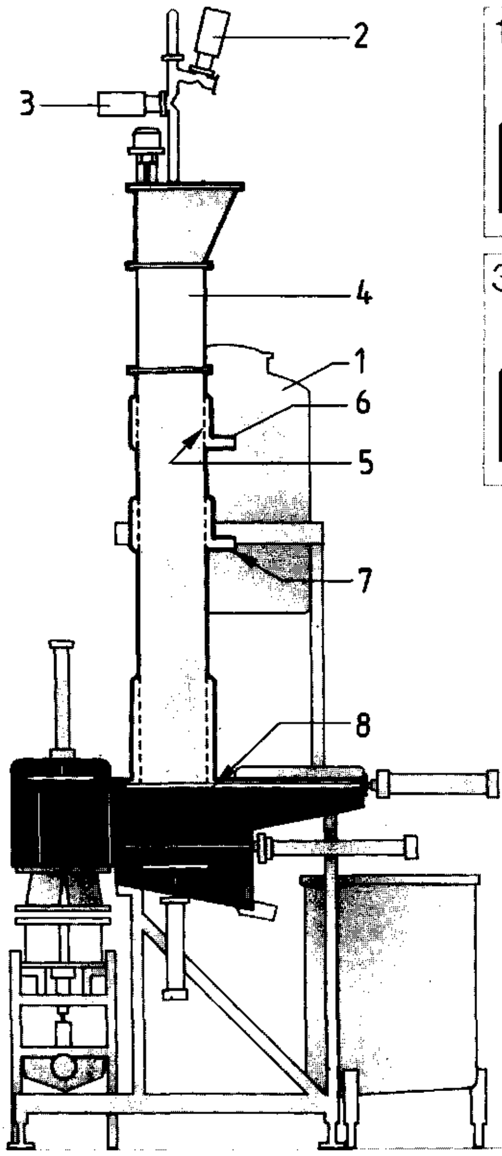
In cheesemaking the clotting of milk is followed by cutting the gel into pieces. The cutting induces syneresis, which starts at the outer layers. Hence, in the outer layer the concentration of paracasein will soon be higher than in the inner part of the curd grain. As syneresis proceeds, the outer layer becomes more concentrated and is sometimes referred to as a skin. The syneresis rate, defined as volume of whey expelled per volume of original gel, will depend on the size and the surface area of the curd grains (Walstra et al. 1985). The firmness of the gel at the moment of cutting and the way of cutting/stirring determine the size distribution of the curd grains (Straatsma & Heijnekamp 1988) and thus affect the syneresis rate. Van den Bijgaart (1988) attributed the permeability of syneresed curd mainly to the permeability of the outer layers. Walstra et al. (1985) suggested that the skin may also decrease deformability, and thereby retard shrinkage. Other important variables that affect the syneresis rate of rennet induced gels are pH, temperature and pressure applied upon the curd grains (Walstra et al. 1985). The applied pressure will depend on the process conditions in the cheese vat: the mixture of curd grains and whey is commonly stirred to prevent sedimentation of the grains and to promote syneresis. Stirring intensity and volume fraction of the curd grains during stirring determine the pressure on the grains and thereby syneresis rate (Van den Bijgaart 1988). The pH, in the case of Gouda cheese manufacture, will mainly be determined by the amount of starter culture and $CaCl_2$ added. The starter will probably not produce sufficient lactic acid before molding to accomplish a significant drop in pH, but the starter contains a small amount of lactic acid, that will, together with the added $CaCl_2$ solution, instantaneously decrease the pH by approximately 0.2 units (Walstra et al. 1987). The clotting temperature is usually around 30 °C, but often the temperature is raised when the curd is cut and stirred for a while. In Gouda type cheese manufacture, usually a part of the whey is removed before hot water is added to the remaining curd-whey mixture. The extent of syneresis will not only be determined by the syneresis rate, but also by the time during which syneresis can take place. The end point of syneresis, probably at a curd volume less than 0.3 times of the original volume (Van den Bijgaart 1988), is generally not reached. Minor variations in curd preparation of Gouda cheese among various manufacturers are common and among different cheese types larger variations exist. For instance, studies on the curd grain size distribution in a cheese, i.e. the most studied parameter relevant to curd grains, revealed wide variation between various Swiss semi-hard and hard cheese types (Rüegg & Moor 1987). Heerink (1981) found an effect of curd grain size distribution upon the drainage behaviour. The water content of the cheese is also affected by the curd grain size (Straatsma & Heijnekamp 1988). The curd grain size may have an effect upon the drainage behaviour, but the water content of curd grains will vary with size as well, thereby affecting the water content of the cheese.

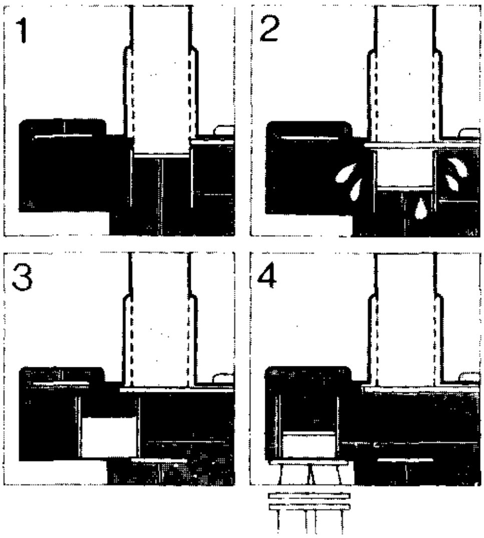
The drainage behaviour of curd may depend on (some of) the parameters given above. Various empirical methods have been proposed to determine the proper time to start drainage of the curd. Scott Blair & Coppen (1940) introduced the so called pitching point technique. A cylindrical sieve was filled with curd grains and inverted after 50 seconds. Then the height of the curd cylinder was measured. Because the observed height appeared to depend on the consistency of the curd grains and on the filling level of the sieve, the column was reinverted and after 7 seconds it was weighted. By taking the weight/height ratio, the effect of filling level could be eliminated and now the ratio appeared to be an adequate measure of the time to start pitching. An empirical relation between drainage behaviour and consistency of the curd grains is used in the following test. The cheesemaker squeezes a handful of curd grains and the curd is considered "ripe" if the grains are readily transformed into a coherent mass that can easily be divided into the original curd grains again. Sometimes, the colour of the grains is used as an indication of ripeness (Van der Haven & Oosterhuis 1986). The yellow colour reflects to a certain extent (depending on the feed of the cows) the concentration of the fat phase. Alternatively, the appearance (gloss) of the curd grains may be used. A handful of curd grains is taken and if too many of the curd grains are shiny, the curd is not considered ripe (Van der Haven & Oosterhuis 1986). The shiny appearance is probably caused by a fast syneresis due to the pressure increase when curd is lifted out of the whey. In later stages of the curd preparation the effect of the increased pressure on syneresis will be less, resulting in a less shiny surface. Replacing such more or less intangible methods by more reliable and universally applicable tests could be useful. The results of this thesis may provide relevant information to achieve that.

1.5 Practical aspects of the draining of curd

Various types of drainage equipment are used to perform drainage, depending on the scale of production, variety of cheese produced, and cost/benefit ratio. Sometimes, draining is performed in the cheese vat itself. This is particularly done in small scale production units like cheese farms. After stirring of the curd-whey mixture, the curd grains are allowed to pitch. The grains are collected by means of a perforated stainless steel strip. Subsequently, the curd grains are left for a certain time. Direct application of a high stress causes "jamming"; a very rapid decrease of the permeability, causing poor drainage behaviour. The waiting period seems to be important to create fusion between the grains (Kerkhof 1979). After a while, a pressure is often exerted upon the collected grains by putting a perforated stainless steel plate on top and/or by removing the whey (leading to decreased buoyancy, hence increased pressure). The curd mass is cut into blocks and put into cheese molds. At some farms the curd is stirred/scalded very intensively, by which the water content will become low; immediately after stirring the curd grains are put into molds.

In factories two types of draining equipment are used: batch and continuous. In the case of batch-wise drainage the curd-whey mixture is pumped into a shallow vessel, the so called "strainer". The curd grains are evenly distributed in the vessel, and left for a while. Then the whey is removed through the perforated bottom. The curd bed is cut in blocks and put into molds. Various types of continuous drainage machines have been constructed, but the basic feature is mostly the same. Vertical pipes are filled with a curd-whey mixture, this may either be done from the top or from the bottom of the pipe. The whey is removed through (sections with) perforations in the cylinder wall, i.e. in horizontal direction. The whey outlet is in most machines restricted by a back pressure. The use of continuous draining equipment requires (due to the curd preparation being batch-wise) a buffer tank. Sometimes a part of the whey in the buffer tank is removed before draining. A schematic drawing of a continuous drainage machine is given in Figure 1.4. Curd grains will sediment if the curd-whey is not stirred. The stirring and ageing of the curd grains in the buffer tank changes the properties of the curd grains as time goes on. The changed properties of the curd grains induce a variation in the water content among the cheeses after drainage. This variation can be reduced by slow cooling of the curd/whey mixture in the buffer tank, thereby reducing syneresis (De Vries & Staal 1974). Smart timing of the cheese presses further reduces the variation in water content (De Vries & Staal 1974): Pressing of





The Casomatic drainage system: The curd/whey mixture is temporarily stored in a buffertank (1). At (2) it is pumped into the drainage pipe. A whey inlet (3) is used to fill the pipe at the beginning and to supplement whey. The level of the whey and the curd grains can be monitored in a view glass (4). The whey is removed through sieves (5) at three subsequent whey outlets (6), (7) and near the bottom. The curd column is cut at (8). An stepwise view of the cutting is given in the adjacent figure. At (1) the curd column makes a downward movement. At (2) the cutting is made and the block is shortly pressed between bottom of the knife and the piston. At (3) the curd block is moved and at (4) the mold is filled.

moist curd blocks effectively stops drainage by the formation of a well-closed rind. All curd blocks of a batch are pressed at the same time. Hence, the interval between drainage and pressing is longer for the first molded curd blocks. Continuous drainage equipment is generally used in large scale bulk production, because it is more efficient than a strainer. However, continuous drainage equipment limits the flexibility in the size and shape of the cheese. In plants, which produce many different varieties of cheeses, strainers are preferred.

1.6 Theoretical aspects of drainage of curd

In the draining equipment the packing of curd grains will initially be very loose and the packing will become more compact as draining proceeds. The compaction of the curd block is directly linked to the flow of whey out of the curd block. In principle, the whey can flow through the curd grains as well as through the openings between them. Although only a few experimental results have been published (Heerink 1981, Kerkhof 1979), it is known that a curd column compacts very rapidly. The compaction will probably vary with the properties of the curd grains and the process conditions during the drainage. Darcy's law can be applied to a vertical column with drainage in axial direction:

$$\langle v \rangle = -\frac{1}{A}\frac{dV}{dt} = -\frac{B}{\eta}\frac{\Delta p_f}{x} \tag{1.1}$$

where

$\langle v \rangle$ = superficial velocity (m/s)
A = cross-sectional area (m^2)
V = volume (m^3)
t = time (s)
B = permeability (m^2)
η = dynamic viscosity (Pa.s)
p_f = liquid pressure (Pa)
x = axial distance (m)

The following process parameters are taken: Δp_f = 1000 Pa, x = 0.1 m, η = 10^{-3} Pa.s. If B would be determined by the permeability of the syneresed gel, estimated to amount at the very most to 10^{-13} m^2 (Van den Bijgaart (1988) obtained this figure for a skim milk gel, its relative remaining volume being 0.2), the superficial velocity, i.e. flow rate/cross-sectional area, would be 10^{-6} $m.s^{-1}$. The compaction during 1000 seconds would be only 1 mm, i.e. orders of magnitude smaller than observed. Obviously, the permeability of a draining curd block is determined by the flow through the connected pores between the curd grains and not by the permeability of syneresed curd grains. The flow through the curd blocks will be determined by size, shape and number of the interconnected pores, any of which will change during drainage.

The compaction of a curd column may result from altered packing of the curd grains (reorientation) and from deformation of the curd grains. Probably, the compaction is initially caused more by changes in the packing than by deformation of the curd grains (Kerkhof 1979). The size and shape of the pores presumably change slower in the case of deformation than in the case of reorientation. The reorientation is probably restrained by fusion between the curd grains, because it would require the breakage of some of the bonds between the curd grains (Kerkhof 1979).

The deformation of a curd grain will probably be determined by its surroundings, its compliance and the exerted stress. Deformation will increase the contact area between the curd grains and thereby extend the area over which fusion can take place.

The fusion of curd grains is considered to result from the formation of bonds between the grains. The formation of bonds will probably be determined by the reactivity of surfaces of the curd grains and the distance between the reactive sites involved. The reactive sites will often not exactly match to one another, but Brownian motion will cause movement of the sites, thereby increasing the number of bonds formed. The process is likely analogous to the processes inside the curd grains (Green & Grandison 1987). However, it should be noted, that the outer layer of the curd grain will be almost devoid of fat globules, because the globules are lost in the whey during cutting/stirring of the gel (Mulder et al. 1966). Hence, the formation of bonds between the surfaces of curd grains will not be hampered by fat globules, which do normally not contribute to the network.

Curd grains tend also to adhere to many materials, including those commonly used in the cheese industry (Hostettler & Stein 1954). Emch et al. (1967) found a considerable effect of the wall upon the flow of curd grains in certain types of cheese presses.

During compaction of the bed some bonds between curd grains will break. This may ultimately lead to breaking of the junctions, i.e. all the bonds between two curd grains together. The extent of breaking of bonds will probably depend upon the area over which fusion has taken place, the number and type of the bonds, the exerted mechanical stress and the packing of the bed.

In addition to the drainage of curd, the preparation of curd and the pressing of the curd blocks are among the factors affecting the water content of cheese before brining. Moreover it has to be taken into account that the water content of a curd block is an average, because the water will be unevenly distributed throughout the loaf (Geurts 1978) and in a different pattern at the various stages (Straatsma & Heijnekamp 1988). The moisture in a curd block is composed of whey between curd grains and whey inside the grains, while the proportion will probably vary at the various stages. Obviously, the determination of merely the water content is of limited value when studying drainage. Kerkhof (1979) already indicated the need to measure the porosity; however up till now no one has developed a method to do so.

In order to study the drainage one certainly has to control the curd preparation strictly. The water content, the deformability, the shape and size (distribution) of the curd grains and the reactivity of the surface of the curd grains may affect drainage behaviour. Investigators often try to perform the curd making in a more or less reproducible way by taking "standardized conditions" (Heerink 1981, Straatsma & Heijnekamp 1988). A major problem in this approach is that the results are only to a limited extent applicable to other conditions. Moreover, the characterization of the curd by meaningful parameters is hampered by the lack of suitable standard procedures.

Although draining is an essential step in cheesemaking, only a few publications on this subject exist (Walstra et al. 1985). Certain improvements are desirable, but the lack of understanding of the fundamentals of drainage hampers these developments. Current problems are: 1) Controlling the standard deviation of the water content of the cheese requires an extensive trial and error procedure when new drainage equipment is being put into use. 2) Today, the standard deviation of the water content in Gouda cheese manufacture is approximately 0.6% (Straatsma et al. 1984). A reduction of this figure would increase the yield. 3) The production of whey powder is hampered by the presence of curd fines, a considerable reduction of the amount of curd fines in the second whey may be accomplished by appropriate drainage (De Vries & Van Ginkel 1985). An additional advantage hereby is the slight increased yield. 4) The leakage of whey out of the curd blocks before, during and after pressing results in fouling, thereby causing a build-up of unwanted micro-organisms and phages, and a decrease of the quality of the whey. Whey of satisfactory microbial quality has become a valuable product and the costs of the sanitation and the waste water treatment have risen dramatically over last years. Hence, reduction of the amount of leaked whey is attractive. In Gouda cheese approximately 25% of the weight of the curd block obtained after draining is lost by whey leakage before brining. 5) The use of the current continuous drainage equipment restricts the flexibility as to shape and size of curd blocks. 6) Certain quality defects of cheese are linked to drainage, especially the growth of molds just below the rind of cheeses made in continuous drainage equipment occurs frequently. Other quality defects attributed to draining and/or pressing include increased firmness near the rinds and cracks (Schaller 1991).

The improved process would ideally produce identical curd blocks, that do not leak whey anymore, with a water content of about 47% (in the case of Gouda cheese, 12 kg). Subsequently the block should be pressed, without getting a substantial moisture loss, to obtain a well-closed rind.

1.7 Theoretical modelling of drainage of curd

The draining of curd can be characterized as a particular type of expression, and in this section it will be considered as such. Expression means the expelling of liquid from a solid-liquid mixture by squeezing or compaction (e.g. Shirato et al. 1986, Schwartzberg 1983); mostly the solid consists of discrete particles. The main factors governing expression are the interaction between speed and extent of compaction, the amount of liquid that can be expressed, and the forces needed to achieve compaction (Schwartzberg 1983).

Most common theoretical approaches are (modified) Terzaghi models (Leclerc & Rebouillat 1985) as shown in Figure 1.5.

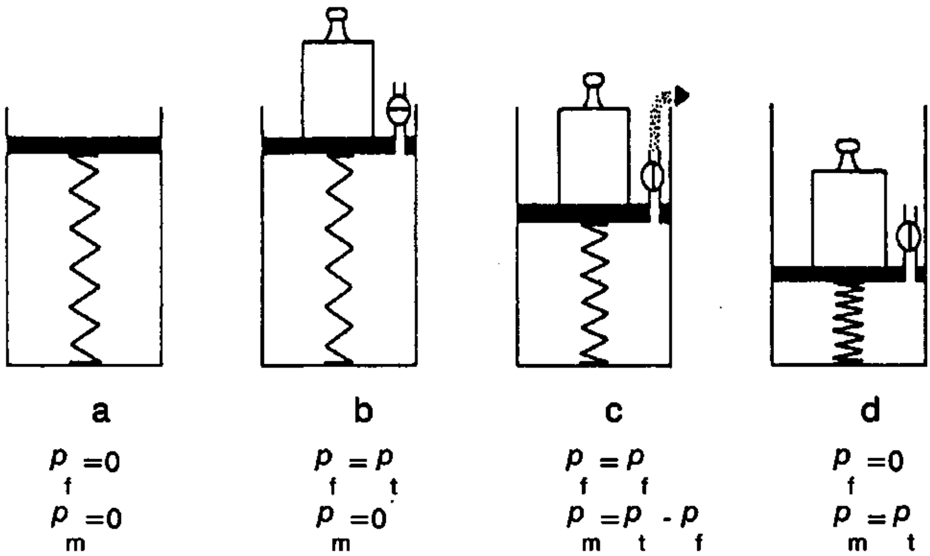


Fig. 1.5 The Terzaghi model, explained by a frictionless piston in a cylinder filled with an incompressible liquid, a spring, a stopcock and a load. In (a) a spring is immersed in a cylinder filled with water. In (b) a load is applied. The piston cannot descend and the liquid pressure is equal to the applied pressure. In (c) the stopcock is opened, water escapes and the piston sinks. At (d) the spring carries the total load (Van den Bijgaart 1988).

One of the basic presumptions in these models is that any element under stress is instantaneously deformed. Time dependent behaviour of the solid-liquid mixture is caused by restricted liquid flow. Furthermore, the expulsion of liquid from the solid is assumed to be zero. Kerkhof (1979) applied this theory to the drainage of curd. He concluded from comparison between his experiments and his model calculations, that instantaneous deformation of the curd grains did not take place and that the time-dependent deformation of the curd grains is an essential step in drainage behaviour.

Therefore Kerkhof (1979) formulated a new model. In this model, called the relaxation and expression of particles (R.E.P.), the time-dependent behaviour of curd is taken into account. It was used to predict uni-axial drainage behaviour of thin layers of curd from results obtained from compression experiments. Schematic drawings of Kerkhof's compression experiments and drainage experiments are given in Figures 1.6 and 1.7, successively.

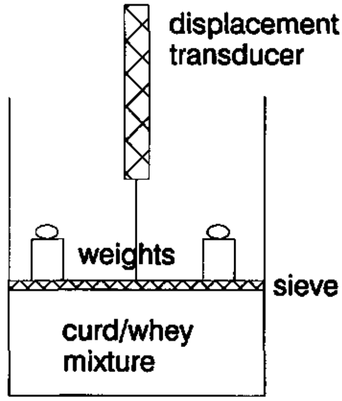


Fig. 1.6 Schematic representation of the compression tests as performed by Kerkhof (1979). A fairly thin layer of curd is compressed by means of a weight on top. The compaction is measured by means of a displacement transducer.

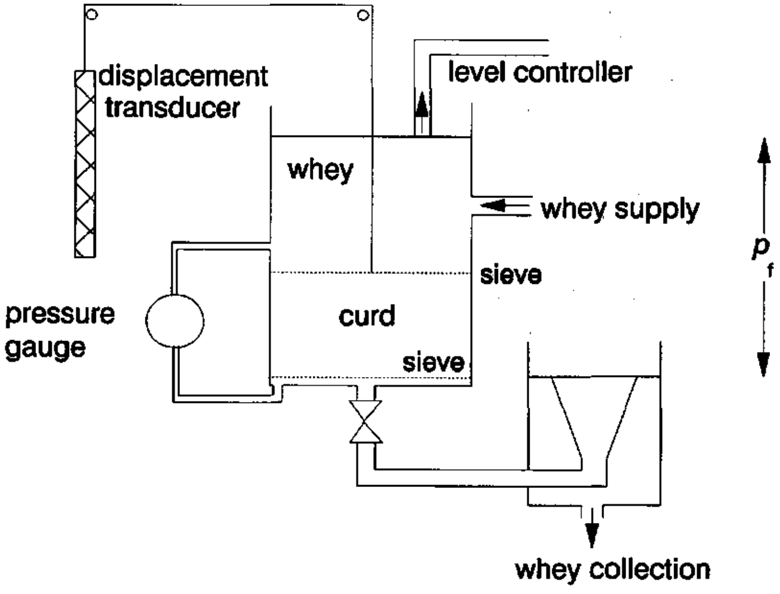


Fig. 1.7 Schematic representation of the drainage experiments as performed by Kerkhof (1979). A fairly thin layer of curd is put in a vessel. The bottom of the vessel is covered by a sieve. The compaction of the curd layer is measured by a displacement transducer that is mounted to a sieve on top. Whey flows through the curd layer, while its level is kept constant by the level controller. The liquid pressure difference can be measured by a pressure gauge. The amount of whey that flows through the curd layer is registered.

He based his model on the following presumptions:

1) The void ratio (= free whey volume per unit volume curd grains) (e) changes when a stress (p_m) is exerted on the packed curd grains; the final void ratio (e^*) depends on the exerted stress.

2) The volume of the whey in the curd grains per unit volume dry matter (Ω) changes due to the exerted stress; the final whey volume fraction (Ω^*) will depend on the exerted stress.

3) The rates of change in free whey content and whey content of the curd grains are proportional to the difference between actual value and final value of these quantities. These quantities are thus represented in the equations (1.2) and (1.3) respectively:

$$\frac{de}{dt} = -k_e\,(e - e^*) \qquad (1.2)$$

where

e = void ratio (m^3/m^3)

t = time (s)

k_e = first order rate constant (1/s)

e^* = final void ratio (m^3/m^3)

and

$$\frac{d\Omega}{dt} = -k_\Omega\,(\Omega - \Omega^*) \qquad (1.3)$$

where

Ω = volume of whey in the curd per unit volume of dry matter (m^3/m^3)

t = time (s)

k_Ω = first order rate constant (1/s)

Ω^* = final volume of whey in the curd per unit volume of dry matter (m^3/m^3)

4) In the drainage experiments (Figure 1.7) the contribution of the expelled whey to the total whey flow across the curd bed was neglected, because relatively thin curd layers were used. Therefore the superficial velocity of the whey at any time was uniform throughout the curd bed, although it decreased with time.

5) The compaction rate at the top of the curd bed is higher than the compaction rate near the bottom of the curd bed. However, compared to the superficial velocity of the whey across the bed the difference in compaction rate throughout the curd bed was

very small, because thin curd layers were used. Therefore this difference was neglected.

In Kerkhof's model, compaction due to decreasing porosity and to decreasing curd volume are distinguished. Relations for the decrease in free whey volume and in curd volume were derived from compression experiments. The compaction of the curd bed in the compression experiments was assumed to result solely from whey expulsion from the curd grains after a certain arbitrarily chosen time, i.e. the change in free whey content was then assumed to be zero. In other words, the first order rate constant k_e was far larger than k_Ω. As a result of this, a great part of the initial compaction was attributed to the decrease of the void ratio, and also the equilibrium void ratio e^* was reached in an early stage. The now remaining part of the compaction curve was used to fit a function of curd volume versus time, according to the assumptions 2 and 3 given above: see equation (1.3). This function is extrapolated to zero time. The difference in compaction height between total compaction and the function that describes the compaction due to decreasing curd volume, is caused by the reduction of the free whey content. Subsequently, a function of the decreasing free whey content is fitted according to the assumptions 1 and 3: see equation (1.2). Figure 1.8 depicts

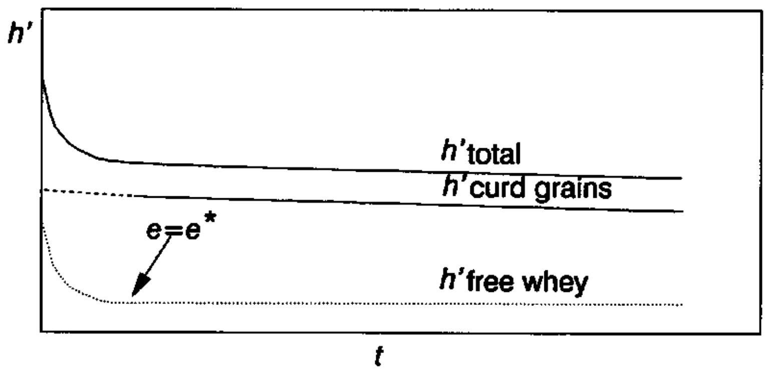


Fig. 1.8 An example of the calculation of the contribution of the volume of the curd grains (φ) to the total compaction of draining curd, according to Kerkhof (1979). After a certain time, the contribution to the change in dimensionless height (h') of the curd bed due to decreased free whey volume (e) is assumed to be negligible ($e = e^*$). Now, the compaction due to change in height of the curd grains can be derived by curve fitting the remainder of the total compaction graph. The obtained function is extrapolated to time $t = 0$ (dashed line). The compaction due to change in curd volume is subtracted of the total compaction, this results in the change in free whey volume.

the above relations graphically. This technique, although probably subject to a non-negligible error, results in a final value for both free whey volume and curd volume and in proportionality constants for both variables. By conducting compression tests at various pressure levels, several values are obtained of e^*, k_e, Ω^* and k_Ω, and plotted versus the exerted stress. The obtained values are used in equations (1.2) and (1.3), to calculate the change in curd volume and free whey at any stress.

In Kerkhof's experimental setup the liquid pressure (p_l) was kept constant. The superficial flow was calculated by Darcy's law from the liquid pressure and the total permeability, where the latter was obtained by integrating the local permeability over the height of the column. Darcy's law could be used to calculate the liquid pressure at any place from the local permeability and the superficial flow. The latter was constant throughout the curd bed (assumption 4). Kerkhof modified the distances into distances relative to the solids in the curd, whereby assumption (5) resulted in constant (relative) superficial flow. The stress upon the curd grains was calculated from shear stress due to liquid flow and the pressure exerted by curd upon underlying layers due the density difference between curd and whey. The equations (1.2) and (1.3) were used to calculate the void ratio (e) and the whey content of the curd grains (Ω).

Finally the model needed a relationship to calculate the local permeability, Kerkhof used a relationship between permeability and porosity. This relationship has been sought much after, but a universal solution does not exist (Scheidegger 1960). Kerkhof divided the relation more or less arbitrarily into 3 periods, depending on void ratio. In the beginning the packing of the curd is loose, and the curd column can be compacted without altering the surface area of the curd grains, the Blake-Kozeny relation was used:

$$B = \frac{\varepsilon^3 d_p^2}{150 (1 - \varepsilon)^2} \tag{1.4}$$

where

B = permeability (m^2)

ε = porosity (-)

d_p = diameter of the spherical curd grains (m)

In the second period the decreasing porosity is accompanied by a fast decrease in surface area of the curd grains, therefore the Blake-Kozeny equation (eq. 1.4) was modified. In the third phase the compaction results in blocking of some of the interconnected openings, resulting in a fast decline of permeability. In neither of the above periods the permeability, as derived from theory values, exactly matched the experimental ones. To achieve this, Kerkhof needed the experimental results of the permeability test itself.

If the starting conditions are known, the calculation of the next time step can be executed, et cetera. The scheme is displayed in Figure 1.9.

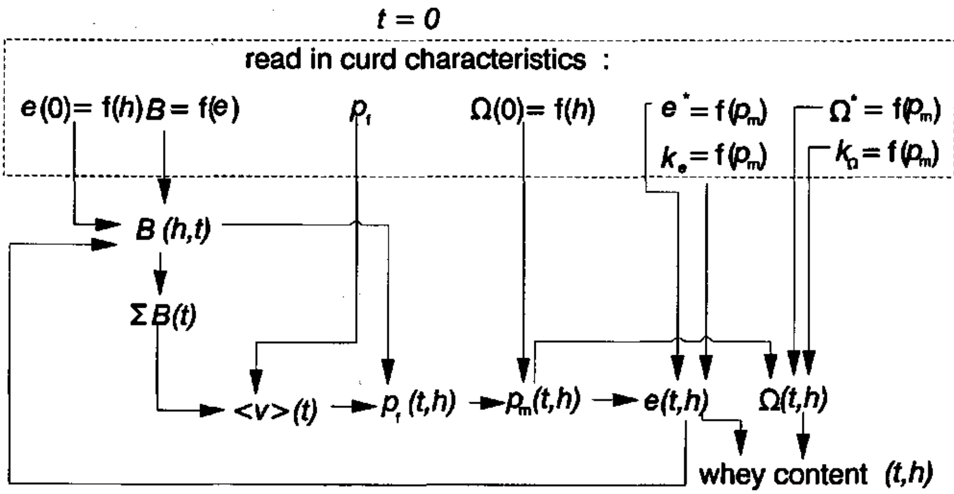


Fig. 1.9 Computer flow chart of the calculations of the drainage through a thin layer of curd according to the R.E.P. model (Kerkhof 1979). The input parameters are in the box. The void ratio at start is used to calculate the local permeability of the infinite small layers of curd. The local permeability is integrated to obtain the total permeability of the curd bed. In combination with the constant liquid pressure (p_t) the superficial velocity ($<v>$) is calculated. The latter is constant throughout the bed and combination with the Darcy equation yields the local liquid pressure drop (p_l). Combination with the mechanical pressure due to weight of the curd layer above, yields the total stress upon the curd. The latter is used to calculate the void ratio (e), the volume of whey content per volume unit of dry matter (Ω) and the whey content of the curd block at the subsequent time step, et cetera.

Kerkhof compared his model calculations with results of drainage experiments and concluded that the model was in harmony with his experimental results, therefore it could be concluded that the time needed to deform curd grains is essential in the process of draining curd. Kerkhof considered his approach as a tentative pilot study, i.e. application of the model to factory conditions, e.g. thicker layers of curd, was not possible in its current form. Furthermore, relationships on the particle level, e.g. fusion and whey expulsion, were only empirically described. His experimental setup had also certain "hidden" imperfections leading to wrong results, as will be discussed in section 4.1.

1.8 Scope of the present work

In spite of the fact that drainage is an essential step in cheesemaking, the fundamental knowledge about it is rather limited. It is stated earlier that four processes can be distinguished in drainage:

1) Additional whey is expelled from the curd grains.
2) Curd grains are deformed.
3) Curd grains partly fuse.
4) Whey flows through the connected pores between the curd grains.

However, quantification of the role of each of these processes is lacking and their mutual interactions are virtually unknown.

In order to study the fundamentals of drainage several obstacles must be taken:

1) The properties of curd grains affect the drainage, therefore the curd preparation has to be closely controlled.
2) Characterization of the obtained curd was difficult, because it was not known beforehand which parameters are relevant. Moreover, standard procedures to perform such characterizations were generally not available, although this has recently become feasible for certain major parameters like size and shape distribution (Noel et al. 1990). Consequently, adequate control of the curd preparation is difficult to perform.
3) Small-scale curd preparation results in curd grains that may bear little resemblance to those produced on factory scale. In our conditions large-scale curd production was mostly not possible.

A new method of curd preparation was therefore developed. It enabled the production of almost identical cube shaped curd grains. Thereby, we were able to negotiate the first two obstacles, and an additional advantage is that curd grains of the same batch could be used to study processes like deformation and expression as well as the overall drainage behaviour. However, our curd grains were not identical to those produced on factory scale; therefore, experiments were also conducted in

NIZO's experimental plant, where samples of curd grains were taken from conventional cheese vats.

The cube shaped curd and the curd obtained at NIZO's experimental plant were used in various experiments. The main objectives were:

1) Characterization of the curd grains. Our method of curd preparation made it possible to introduce controlled variation in the curd properties. The development of relevant, measurable characteristics is thereby feasible.

2) Determination of the role of the drainage vessel. To that end, the close control of the properties of the curd was indispensable, because the (variation in) construction and mode of operation of the drainage vessel and the (variation in) curd properties are mutually dependent.

3) The distinction of the four processes involved (see above). The cube shaped curd grains proved to be highly suitable to study expression and deformation. Curd fusion and properties determining transport phenomena, e.g. the distribution and size of the pores between the curd grains, could also be studied independently.

Reliable methods to determine the above mentioned variables, e.g. extent of fusion among the curd grains, were generally not available. Therefore, a great part of our effort was concentrated on the development of appropriate methods. The results of the experiments were partly used to make a computer model of the drainage. The aim of the model was to improve the understanding of the drainage process; it may also be instrumental in saving on costly factory scale experiments.

2. Materials & methods

2.1 Curd preparation

2.1.1 Curd made in a small cheese vat

A 40 liter cylindrical cheese vat with one rotating knife was used to make curd. The milk was pasteurized at 72 °C for 15 s and the fat/protein ratio has been standardized to make full-cream Gouda cheese, so called "48+" milk. The milk was clotted at 30 °C with 40 ml $CaCl_2$ solution (397 g/l) per 100 kg (≈ 1,4 mM) and 20 ml rennet (Rademaker, 10800 Soxhlet units). No starter was used. The curd was cut after approximately 30 minutes and scalded at 35 °C after 30 minutes of stirring. Subsequently, the curd-whey mixture was stirred for about 30 minutes. On average the curd grains were much smaller than those made in conventional cheese vats, because the cutting/stirring intensity in small cheese vats has to be higher than in larger cheese vats to prevent excessive sedimentation of the curd grains. Excessive sedimentation of the curd grains will enhance fusion between them, resulting in undesired aggregates. Furthermore, the reproducibility of the properties of the curd grains, e.g. the size distribution of the curd grains, was unsatisfactorily.

2.1.2 Cube shaped curd grains obtained in a new type of cheese vat

Control of the curd preparation is essential to study drainage behaviour. Furthermore, the costs of the experiments had to be limited and thus the preparation of small batches of curd was necessary. However, curd preparation on a small scale often induces "scaling down" effects (see above), unless special (and expensive) precautions are taken, such as in the cheese process simulator of NIZO (Straatsma & Heijnekamp 1988). Curd grain size and shape will affect other properties of the grains as well. Ideally, curd grains of constant shape, size and composition should be available in drainage experiments. Therefore, it was tried to develop an alternative method of curd preparation to achieve this aim.

A double walled rectangular perspex box (20 l) with external thermostat, was used to clot the milk. A grid of stainless steel wires in a frame was placed at the bottom of the vat, and another frame of horizontal wires was placed alongside of a wall. The gel was cut in horizontal slabs by moving the latter frame towards the opposite wall. Subsequently, the slabs were cut into cube shaped curd grains by moving the bottom frame upwards. The curd grains were stirred by pumping four liters of whey into the cheese vat and subsequently supplying large air bubbles through the bottom of the vat. The air flow was interrupted by a pause pulse switch (24 seconds pulse, 20 seconds pause) to avoid breaking of the curd grains, while mixing satisfactorily. The entire setup is displayed in Figure 2.1.

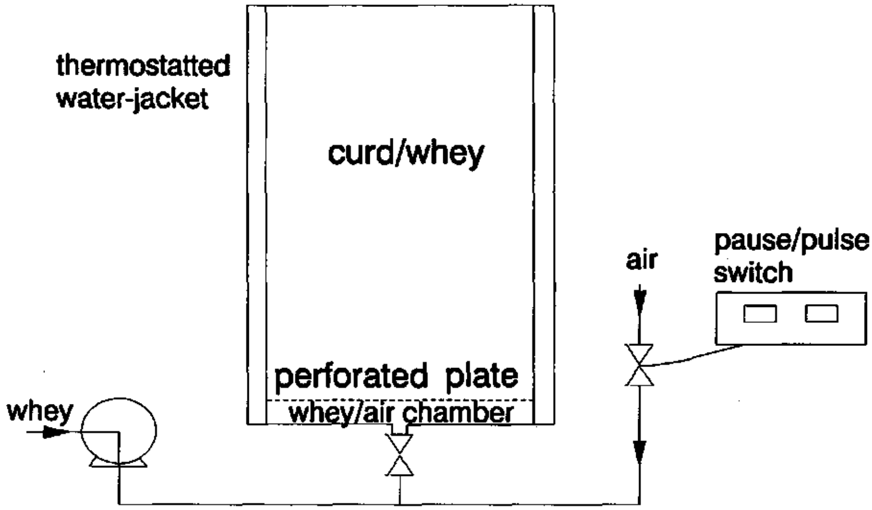


Fig. 2.1 A schematic drawing of the cheese vat used to prepare cube sized curd grains. The curd was clotted in the vat and cut into cube shaped particles; the latter were stirred by pumping whey and subsequently air through the bottom of the vat. The openings at the top of the whey/air distribution chamber were temporarily closed during clotting to avoid mixing of whey and milk.

Mixed milk was used pasteurized and standardized to full-cream Gouda cheese. The milk was clotted by adding 40 ml $CaCl_2$ solution (397 g/l) and 20 ml rennet (10800 Soxhlet units) per 100 kg cheese milk. No starter was used.

The firmness of the gel was checked by testing the cohesion by slowly lifting a finger out of the gel. The height of the bump which rises above of the flat surface of the gel before fracture occurred and the plane of fracture were judged. The clotting time was usually taken around 35 minutes, the clotting temperature was 30 °C. The mesh size of the cutting grids was either 8 mm or 10 mm. The curd grains were stirred for approximately 30 minutes. As much whey as possible (usually approximately 5 kg) was removed and curd was scalded by adding approximately 3 kg wash water to reach a final temperature of 35 °C. Due to the lower stirring intensity and the unfavorable size and shape of the curd grains the syneresis was slower than in conventional cheese vats. After adding the wash water, the curd-whey mixture was stirred for three to six hours until the curd grains had reached a certain density. In spite of the prolonged stirring, the density of the cube shaped curd grains was less than the average density of curd grains in conventional cheese vats just before draining.

2.1.3 Curd made at NIZO

Curd in factories differs from the cube shaped curd obtained. Therefore, some experiments were conducted with curd grains taken from a conventional cheese vat. At NIZO's experimental factory, curd grains were prepared in both Tebel and Ost IV cheese vats. A small portion of the curd grains were used in various experiments.

2.2 Density of curd grains

Direct estimation of the water content of curd grains has been performed by various workers (e.g. Kerkhof 1979). This water content will vary with the size of the grains; therefore, it will be an average value. The common technique of determining the water content of a product is by weighing the product before and after drying. However, a certain quantity of whey inevitably adheres to the curd grains. A thin layer of whey on the outside of the curd grains increases the apparent water content substantially (Kwant 1980). "Drying" the outside of the grains by wiping (Kerkhof 1979) or suction may induce considerable syneresis. An additional complication is that whey contains a small amount of dry matter, so the whey content of the curd grains is slightly higher than the water content. Accurate calculation of the whey content from the water content is not as simple as expected, because of the steric exclusion of serum proteins (see below).

The whey content can also be estimated indirectly by density measurements. The density of curd grains was determined by various authors in order to estimate the extent of syneresis (e.g. Stoll 1966). Whereas a wide range of liquids was used in these studies, we estimated the density of curd grains by dropping curd grains into thermostatted (35 °C) sodium chloride solutions of various densities. In case of the cube shaped curd the test was confined to a screening, because the density of the curd grains hardly varied. In other cases the percentage of floating curd grains was determined by weighing the floating and sinking fractions. Walstra et al. (1985) indicated the possibility to calculate the loss of whey from density measurements. A basic presumption hereby is that the sum of the volumes of the curd grains and the expelled whey is equal to the volume of the former non-syneresed gel. A curd grain consists of three components, whey, paracasein matrix plus micellar calcium phosphate (="paracaseinate") and fat globules. The amount of fat and paracaseinate in a curd grain hardly changes after scalding in case of Gouda cheese. Obviously, the ratio fat/paracaseinate can be considered constant.

All experiments were conducted with standardized milk, the amounts of paracaseinate and fat per 100 kg of cheese milk that are recovered in the curd grains were estimated successively at 2.7 and 3.0 kg. The loss of paracaseinate and fat to the whey are estimated at 0.1 and 0.2 kg/100 kg cheese milk, respectively.

The density of a curd grain can be recalculated to the fraction of paracaseinate or whey, if the densities of the three main fractions are known.

$$\rho_g = \alpha\rho_m + \beta\rho_f + \gamma\rho_w \tag{2.1}$$

where

ρ_g = density of the curd grain (kg/m^3)

ρ_m = density of paracaseinate (kg/m^3)

ρ_f = density of fat (kg/m^3)

ρ_w = density of (diluted) whey (kg/m^3)

α = volume fraction of paracaseinate (m^3/m^3)

β = volume fraction of fat (m^3/m^3)

γ = volume fraction of (diluted) whey (m^3/m^3)

The sum of the volume fractions will be 1:

$$\alpha + \beta + \gamma = 1 \tag{2.2}$$

We further put:

$$\theta = \frac{\beta}{\alpha} \tag{2.3}$$

where

θ = fat/paracaseinate ratio (m^3/m^3)

Combining (2.1),(2.2) and (2.3) yields:

$$\alpha = \frac{\rho_g - \rho_w}{\theta\,(\rho_f - \rho_w) + (\rho_m - \rho_w)} \tag{2.4}$$

The densities of the fat and whey in the grains at 35 °C were taken from Walstra &

Jenness (1984); fat: 905 kg/m^3 ; whey: 1020.8 kg/m^3. The whey in the curd grain will be diluted by wash water. The remaining volume of whey is diluted to 85% of its original concentration and the equilibrium between whey in the curd grains and the whey around the curd grains is reached (90% after 25 minutes (Van den Berg & De Vries 1976)). Then the density of the diluted whey can be estimated at 1017 kg/m^3. The density of paracaseinate was calculated from an equation given by Munro (1980): 1438 kg/m^3. The volume ratio fat/paracaseinate then is 1.77.

Some difficulties in the use of this method are:

1) In the determination of the fraction of the floating curd grains, it takes approximately 30 seconds before the last floating curd grain is taken out of the beaker. During the experiment the sodium chloride penetrates into the grains, resulting in an increased density. If the replacement of whey by salt solution is solely caused by diffusion, the mass transfer to a spherical curd grain can be calculated, assuming negligible surface resistance (Heldring & Singh 1981):

$$\frac{C - C_s}{C_0 - C_s} = \frac{2}{\pi} \frac{R}{r} \sum_{n=1}^{\infty} \frac{(-1)^{n+1}}{n} \sin\frac{n \pi r}{R} \exp\frac{-n^2 \pi^2 D t}{R^2} \qquad (2.5)$$

where

C = concentration as a function of r and t (kg/m^3)

C_s = constant concentration at the surface (kg/m^3)

C_0 = initial uniform concentration (kg/m^3)

R = radius of particle (m)

r = radial variable (m)

D = diffusion coefficient (m^2/s)

t = time (s)

The following data were used: an effective diffusion coefficient of NaCl of approximately 10^{-9} m^2/s and penetration during 30 seconds in a spherical curd grain (R = 0.003 m). In these circumstances approximately 15% of the whey is replaced by NaCl solution. The density increase would then be approximately 2 kg/m^3. The result is likely an overestimate, because the contact time is probably shorter and the outer layer of the curd grain has a relatively low whey content. It is thus likely that the density of the curd grains is slightly overestimated as the curd grains with a density slightly lower than the density of the salt solution will sink. The density difference between two subsequent solutions is 7 kg/m^3 (in the case of factory curd we used only five solutions ranging from 5 to 9% NaCl). Consequently only small shifts in the classification of the curd grains are expected.

2) Steric exclusion of serum proteins with respect to the casein micelles occurs (Van Boekel & Walstra 1989) and it should be taken into account in a paracaseinate matrix. Whey proteins are concentrated in domains without paracasein strands, leading locally to a slightly higher density of the "whey". It will partly compensate for the areas devoid of serum protein in close environment of the strands. However, as the curd preparation proceeds, the number and size of the domains without paracaseinate strands are likely to decrease, leading to a slightly lower density of the "whey". In the extreme case of "whey" totally devoid of serum proteins, its can be calculated by considering the density of whey proteins (≈ 1350 kg/m^3) (Buma 1965) and the concentration of serum proteins in diluted whey; the latter is estimated at 0.5 wt.%. The density of the remaining liquid is then estimated 1012.8 kg/m^3. The lower density of the whey would cause an overestimation of the whey content by at most of 5 percent, but this only happens when the whey content is already quite low.

3) Adherence of salt solution to the outside of the curd grains will be relatively larger for smaller curd grains and therefore slightly overestimate the amount of sinking curd grains, because smaller grains have usually a higher density. This is because syneresis proceeds relatively fast and the loss of fat at the outer layer is relatively large in small curd grains. For spherical curd grains, the surface area, and thus the volume of adherent salt solution, increases with the reciprocal of the radius of the curd grain. The resulting error is small, even if as much as 20 percent of the weight would result from adherent salt solution, if the radii of the curd grains differ by a factor 2 and if the true sinking/floating ratio is 1:1, the error is estimated at 2 percent.

4) The paracaseinate content of curd grains with a decreased fat content, i.e. very small particles, may be considerably overestimated. Moreover, the salt uptake of these small particles is not negligible. Therefore, the whey content can not be estimated accurately from density measurements in this case.

If future research leads to altered figures for the densities of the fat, paracaseinate or whey inside the curd grain, the results can be easily recalculated from the densities of the used sodium chloride solutions (Wolf et al. 1974, Beattie 1928). Notwithstanding the difficulties mentioned above, the method was found to be satisfactorily reproducible. The classification in percentages of floating grains in five salt solutions, 5, 6, 7, 8, 9% NaCl, respectively, in case of factory curd proved to be useful and was convenient as the results were known immediately.

The paracaseinate concentration is directly related to the whey content (both as volume fractions), the latter is given as the factor γ. Authors, like van den Bijgaart (1988), used the term relative remaining volume (i), i.e. the volume of a syneresed slab of curd expressed as fraction of the volume of the clotted cheese milk. The composition of milk changes slightly during the season, hence, we estimated the density of the cheese milk at 1024 kg/m³. The amount of reclaimable paracaseinate in milk was estimated at 2.7 kg per 100 kg, corresponding to 0.019 m³ paracaseinate/m³. The relative remaining volume is then:

$$i = \frac{\alpha_0}{\alpha_t} \tag{2.6}$$

where

α_0 = volume fraction reclaimable paracaseinate in milk

α_t = volume fraction paracaseinate in the curd

Table 2.1: The densities of the used sodium chloride solutions (ρ), the corresponding volume fraction paracaseinate in the curd (α), the volume fraction whey in the curd (γ) and the relative remaining volume (i).

[NaCl] wt.%	ρ kg/m³	α m³/m³	γ m³/m³	i m³/m³
5.0	1028.8	$5.4\ 10^{-2}$	0.85	0.36
5.4	1031.7	$6.7\ 10^{-2}$	0.82	0.29
5.6	1033.1	$7.3\ 10^{-2}$	0.80	0.26
5.8	1034.5	$7.9\ 10^{-2}$	0.78	0.24
6.0	1035.9	$8.5\ 10^{-2}$	0.76	0.23
7.0	1043.0	$1.2\ 10^{-1}$	0.68	0.16
8.0	1050.2	$1.5\ 10^{-1}$	0.59	0.13
9.0	1057.3	$1.8\ 10^{-1}$	0.50	0.11

The relation between density and remaining volume is given in Table 2.1.
Note: If *i* is calculated on a mass base, the relative remaining volume is slightly lower, because the density of the curd grain increases with the whey expulsion.

2.3 Size distribution of curd grains

Various methods exist to determine the "size distribution" of curd grains, e.g. Niederauer (1976) and Schaap (1970). Both methods use sieves to classify the curd grains in various groups. Curd grains do not have a spherical shape, therefore the results of each sieve method will be influenced by the orientation of the curd grains in the sieve. Recently a method based upon image analysis that could be used to determine size as well as shape distributions was developed (Noel et al. 1990)

Schaap's (1970) method to determine the size distribution of curd particles has become a standard method in the Dutch cheese industry. A sample of approximately 150 g of curd grains in whey is passed successively through five sieves of decreasing mesh sizes (11 mm, 7.5 mm, 5.5 mm, 3.5 mm and 1 mm). The sieves are held partly in the whey, and the finer particles are sieved out by gentle stirring. The curd grains are dried by gentle dabbing with filter paper and weighed.

2.4 The curd flattener

The deformation and the syneresis due to stress of syneresed curd grains is a relatively unexplored topic. The deformation, due to external stresses, of non-syneresed curd slabs under the whey was studied by Van Dijk (1982). The results obtained with his apparatus were found to be not very reproducible. Van den Bijgaart (1988) studied the shrinkage of curd slabs with the so-called microscope method. A porous glass filter is placed under water on top of a curd slab, the resulting compaction of the slab is followed by focusing at certain intervals at the filter. The change in height can be read of a micrometer knob of the microscope. The expulsion of whey occurs only at the top of the curd layer. In draining curd the sideways expulsion is probably more important. Therefore we developed a new method that had closer resemblance to the drainage of curd grains in a curd bed.

The deformation of cube shaped curd grains was studied in uni-axial compression. A single curd grain was placed underneath a cover glass, fixed to a stainless steel bascule. The force acting upon a curd grain could be easily changed by means of adding weights or counterweights. The dimensions of the bascule were taken such that the beam stood almost completely parallel to the plane of the bottom. The bascule was placed inside a perspex tank filled with a 0.9% sodium chloride solution (having the same osmolality as milk serum). A certain exchange between whey and salt solution will occur, but this does likely not affect the compaction behaviour. The tank was thermostatted at 35 °C. Before the measurement started, the exerted force was measured by a HBM Q11 force transducer connected to a HBM MC2 amplifier. A photograph of the horizontal cross section of the curd grain was taken at start, 30 s and at 900 s. The exerted force on the cross section is the exerted stress. The height of the curd grain was measured by a cathetometer at the following times: 0 , 30, 90, 150, 300, 450, 600, 900 s. Three curd grains were studied simultaneously. A fourth curd grain was placed without any pressure upon it, next to the other grains and served as blank. The entire set-up is displayed in Figure 2.2.

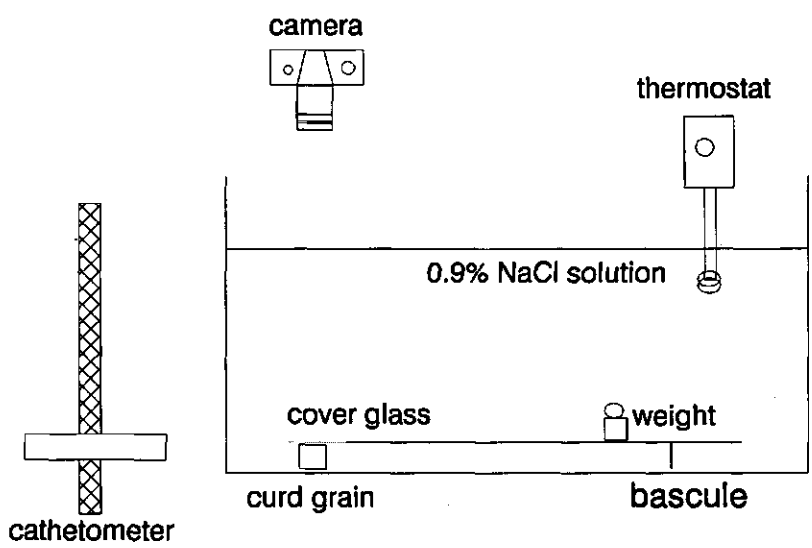


Fig. 2.2 A schematic drawing of the curd flattener.

The force applied was constant during each experiment, thus the increase in horizontal cross section led to a decreasing stress. The area was linearly interpolated between the values at 30 s and 900 s to calculate the average stress. The volume reduction of the curd grain could be roughly estimated by taking the (interpolated) cross-sectional area and the height at each time. The volume corresponds to the concentration of paracasein.

2.5 Drainage columns

2.5.1 Compaction and liquid pressure measurements in radial drainage vessels

All continuous drainage machines are equipped with one or more radial whey outlet(s). To simulate drainage behaviour therein two radial drainage vessels were constructed. The batch-wise operated drainage columns consisted of a vertical perforated stainless steel cylinder (diameter 12 or 20 cm, 20.7% openings, pore size 4 mm high and 0.35 mm width) inside a perspex cylinder. The inner cylinder was partly filled with curd, the outer cylinder was filled with whey, sometimes hot water was added to the whey to increase the temperature to approximately 35 °C. A small spherical porous glass filter was mounted in the middle of the curd column a few cm above the bottom of the column, an altered packing of the curd grains in its direct environment was hereby unavoidable. The liquid pressure difference between the glass filter and the outer ring was measured by a Validyne DP45 pressure transducer, with a Dash 6-18 membrane mounted inside, connected to a Validyne CD15 carrier modulator. If the liquid pressure was lower than 5 Pa it could not be measured. The liquid pressure transducer had an upper limit of 500 Pa, in that case the liquid pressure could be measured from the difference in the water level in two capillaries (not shown). The compaction of the curd column was followed by a HBM W50 displacement transducer connected to a HBM MC2 amplifier. Both transducers were connected to a Kipp BD41 *X-t* recorder. The setup is displayed in Figure 2.3.

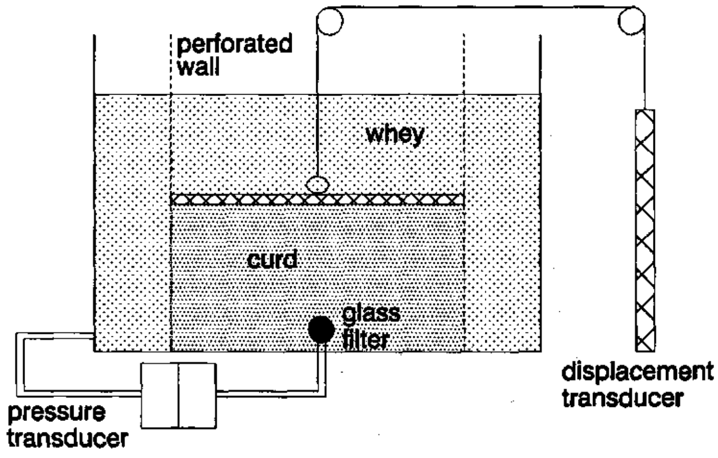


Fig. 2.3 A schematic drawing of the measurement of the liquid pressure and compaction of a curd-whey mixture in a cylindrical drainage column. The external pressure was exerted by applying a weight.

2.5.2 Permeability tests in a radial drainage column

The geometry consisted of three concentric cylinders, at which a liquid pressure gradient was installed between the outermost and the innermost cylinder. The middle cylinder was filled with curd grains and a mechanical pressure was exerted at the top (see Fig 2.4). The whey flowed from the outermost cylinder, wherein the level of the liquid was highest, to the innermost.

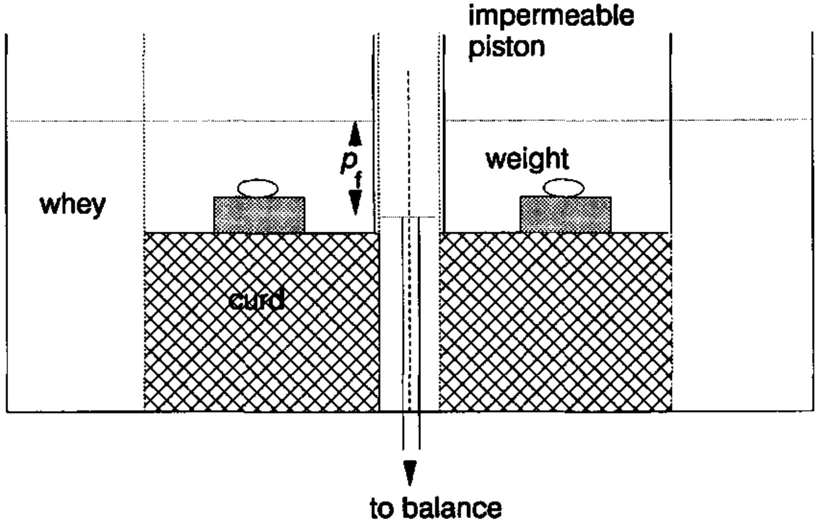


Fig. 2.4 The experimental setup of the radial permeability test.

2.5.3 Compression and permeability experiments in an axial drainage column

Kerkhof (1979) used the setup displayed in Figures 1.6 and 1.7. The setup of our compression test was similar to the one used by Kerkhof. A perspex cylinder (diameter 11.5 cm) was filled with a thin layer of curd under the whey. On top of the curd a disc (25% openings, pore diameter 1.5 mm) with a weight on top was placed. The compaction could be followed by means of a cathetometer.

The permeability tests were conducted in a perspex cylinder (diameter 11.5 cm) with a perforated stainless steel bottom (25% openings, 1.5 mm diameter pores). A weighted perforated disc was placed on top. The cylinder was placed in a vessel filled with water, a liquid pressure gradient was installed by keeping the level of the whey in the perspex cylinder above that of the water in the vessel. The whey level and the level of the curd layer could be measured by means of a cathetometer.

2.5.4 Pressure loss measurement in a curd column

The pressure loss during compaction in a column due to adherence to the wall was measured by Schwartzberg et al. (1985). Their set up consisted of a cylinder wall mounted on top of a load cell, during compaction and relaxation experiments the stress on the load cell was recorded.

We developed an alternative approach. The pressure (or actually force) exerted upon the bottom of the cylinder was measured. The difference between pressure on the top plus the pressure due to weight of the curd and pressure on the bottom of the cylinder is the pressure loss due to adherence to the wall. A perspex disc was mounted to a load cell by means of a 15 cm steel rod. The disc was placed in the inner cylinder of one of the above described drainage columns. A layer of curd grains was put upon the disc. Another disc was placed on top. Weights were placed upon this disc. The outer cylinder of the curd column was filled with whey. The load cell was connected to a *X-t* recorder (Kipp). The setup is schematically displayed in Figure 2.5. Measurements were conducted during at least 15 minutes.

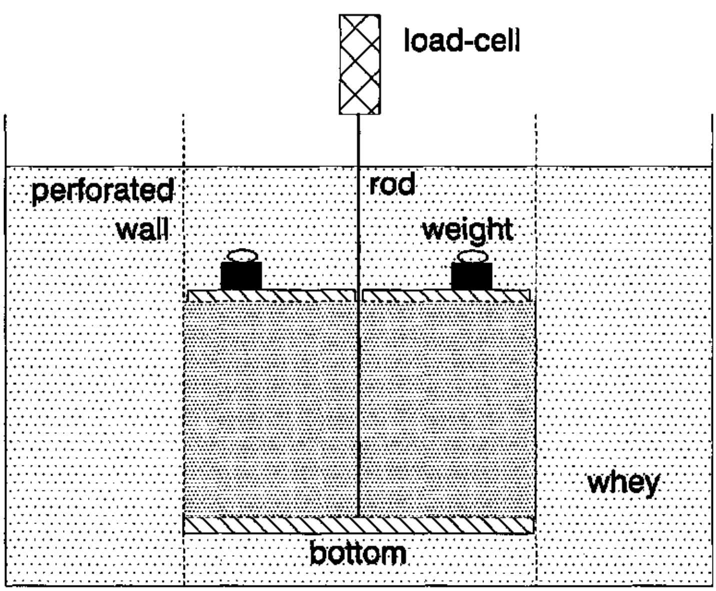


Fig. 2.5 A schematic drawing of the indirect measurement of the pressure loss in cylindrical drainage column. The load-cell has been mounted by means of a rod to the bottom of the curd bed. The exerted force on the bottom is less than the sum of the forces exerted due the weights and the curd layer. Its difference is due to adherence of curd to the wall.

2.6 Fusion of curd grains under the whey

The fusion of curd grains was studied by Ilyushkin et al. (1980). They developed a device consisting of two cups. The bottom of the upper cup and the top of the lower cup were equipped with a gauze. Both cups were filled with curd grains and stacked. A load was placed on top of the upper cup, and after 2 minutes of compression the cups were separated and the separation force was recorded on a rheo-consistometer. It is likely that the method has several disadvantages, e.g. the curd grains adhere to the gauze, the gauze bends and the gauze cuts into the upper curd layer.

We tried to circumvent these disadvantages. The force needed to break the bonds between curd grains was studied by placing a stainless steel piston with a thin perforated bottom (9.5 cm diameter, 100 holes of 6 mm diameter, thickness of the bottom 1 mm) upon a layer of curd grains under the whey in a 1 liter beaker. The piston was filled with curd grains from the same batch and a disc loaded with a weight was placed on top. The piston was mounted to a stainless steel rod. The beaker was placed in a thermostatted bath. The curd grains in the upper layer fused in the open spaces in the piston with the curd grains in the lower layer during a certain time. To avoid the adhesion of curd grains of the lower layer to the stainless steel piston, a filter paper with perforations congruent and coinciding to those in the piston was attached to its bottom by two sided adhesive tape. In the wet environment the tape lost its adherence to the paper. The beaker was placed in an Overload Dynamics Material Testing Instrument, table model S 100, fitted with a 200 N load-cell. The rod of the piston was attached to the load-cell, which subsequently moved upwards with a speed of 100 mm/min. The force needed to break the bonds was registered by a Kipp *X-t* recorder. The fracture stress was calculated from the contact area between the curd grains, i.e. the sum of the cross-sectional area of all perforations in the piston, and the maximum required force. The results of three or four measurements were averaged to account for the deviations (approximately 10 percent of the average value). The setup is schematically displayed in Figure 2.6.

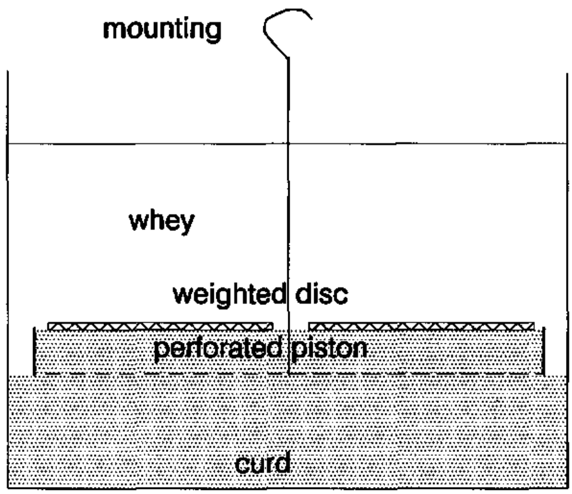


Fig. 2.6 A drawing of the apparatus to measure the stress needed to break the bonds between curd grains. The curd grains in the top layer fuse with the curd in the bottom layer at the openings in the perforated piston. The force needed to separate both layers is recalculated to a fracture stress. A filter paper, with holes congruent to those in the piston, was glued to the bottom of the piston to avoid adherence of curd to it. The glue becomes unstuck in the wet environment.

2.7 Pore size distribution and porosity measurement

Porosity, i.e. the volume fraction of (liquid filled) openings in a solid, has been estimated in a wide range of products by various authors (e.g. Scheidegger 1960), but methods to determine the porosity of draining curd or similar materials could not be found in literature. The porosity itself is an important parameter, but the pore size distribution throughout the curd bed may be even more important.

We developed a new method to estimate the apparent pore size distribution throughout the curd bed. Due to the characteristics of the curd bed some prerequisites had to be considered. The soft and highly deformable material urges a rapid and gentle method. The pores in the curd bed are generally small, therefore the resolution of the method should be high. Non-destructive methods are to be preferred, because they allow the changes in one curd bed to be measured.

The method is based upon an application of optical fibres. Optical fibres enjoy a wide range of applications, e.g. in telecommunications and in surgery. The basic feature of all optical fibres is that light is harnessed in the fiber. The extremely pure glass in a cladding ensuring total reflection, hardly reduces the intensity of a beam of light. The use of fibres as an optical probe was described by Frijlink (1987). With this equipment he measured the bubble size and speed in air lift loop reactors. Ronteltap and Prins (1989) introduced the idea of a moving optical sensor to measure the bubble size distribution in foams. Our estimation of the pore sizes is based on a variant of this method.

An optical fibre (PCS200, diameter of the core = 200 μm, diameter including the cladding = 380 μm) is connected to a light source at one end, whereas the other end has been conically shaped, ending in a nearly hemispherical tip. Light of wavelengths in the near infra-red region, is emitted through the tip into the surrounding medium. Some light is reflected into the fibre depending on the conditions in the surrounding of the tip. The reflected light is projected by means of a Y-splitter (GTE-Atea type Lan-Tap OCL 0102-Y) on a silicon photo-electric cell. The resulting voltage will therefore depend on the medium surrounding the tip.

In Frijlink's (1987) setup, water and air could be distinguished by differences in refractive indices between air (n = 1) and water (n = 1.33). Differences in refractive index between whey in curd grains and in expelled whey are, however, unlikely. Nevertheless, the intensity of the reflected light was clearly higher inside curd grains than in whey. This is presumably caused by the increased light scattering in curd grains.

The glass fibre is held in a capillary, its tip protruding by approximately 5 mm. The capillary is attached to a pneumatic cylinder. By sliding the piston, the capillary can be moved up and down, its stroke being 10 cm. The position of the capillary is recorded by means of linear potentiometer (Elap pls 100), mounted alongside of the piston. The speed of the capillary is controlled by a reducing valve. A cylinder of perforated stainless steel (diameter 12 or 20 cm, 20.7 % openings, pore size 4 mm high and 0.35 mm width) was filled with curd grains and whey. The column was placed in a plastic vessel, that had been filled with whey. Drainage was enhanced by putting a weight on a perspex disc on top of the curd. The capillary could be put either vertically, through holes in the disc, or horizontally, through holes in the cylinder, into the curd column. The latter option was hardly ever used, as the positioning caused experimental problems. Initially the compression of the curd column was performed with the perforated disc on top of the curd column, but it appeared later on that the flow of whey was influenced by the holes, so later on a solid disc was used to compact the column, and was replaced by the perforated one before the measurement started. The position of the fibre tip and the voltage of the photo-electric cell are both registered in a computer (HP Vectra ES 12) with the aid of a Metrabyte DAS-16 data-acquisition board. The entire setup is graphically displayed in Figure 2.7.

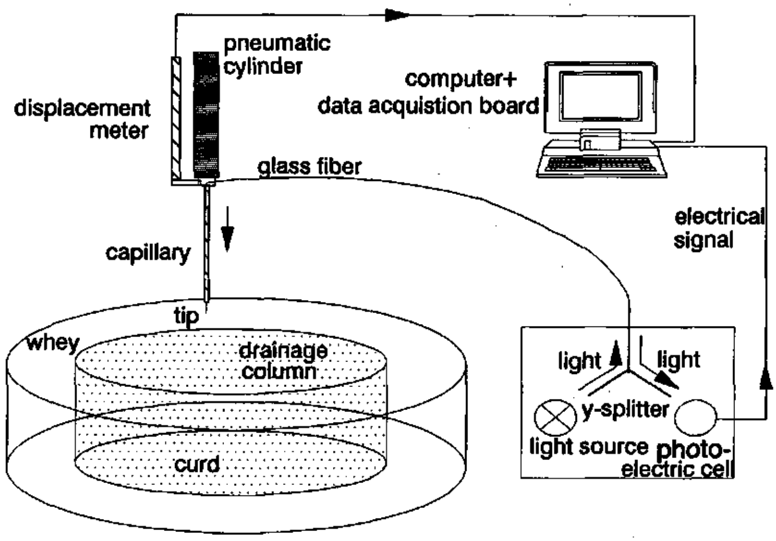


Fig. 2.7 A schematic drawing of the porosity meter.

The signals of the photo-electric cell and the linear potentiometer were sampled at a frequency of 7 kHz and 64 kbytes were taken at a time. This corresponds to one sample per 6 μm and a probe speed of 2 cm/s. The signals were sent directly to a hard disk under the so called DMA mode (direct memory access) and converted afterwards. External triggering was used. The programming language was Asyst 3.10. Continuous sampling of both position and voltage of the photo-electric cell results in a voltage versus position pattern (Figure 2.8). The circuitry of the photo-electric cell was such that the smallest reflection corresponds to the highest voltage. The signal showed a small dent followed by a sharp rise at curd-whey transitions and a peak followed by rapid decrease at the whey-curd transitions. The signal was converted into chord lengths of whey by determining the subsequent positions of the largest positive and largest negative slope. The interpretation of the signal was hampered by the occurrence of shoulders and rider peaks, therefore we assumed that peaks within 0.3 mm of each other belonged to the same pore. The chord length of whey is usually not identical to the true dimensions of a pore, as piercing of a horizontal cylindrical pore

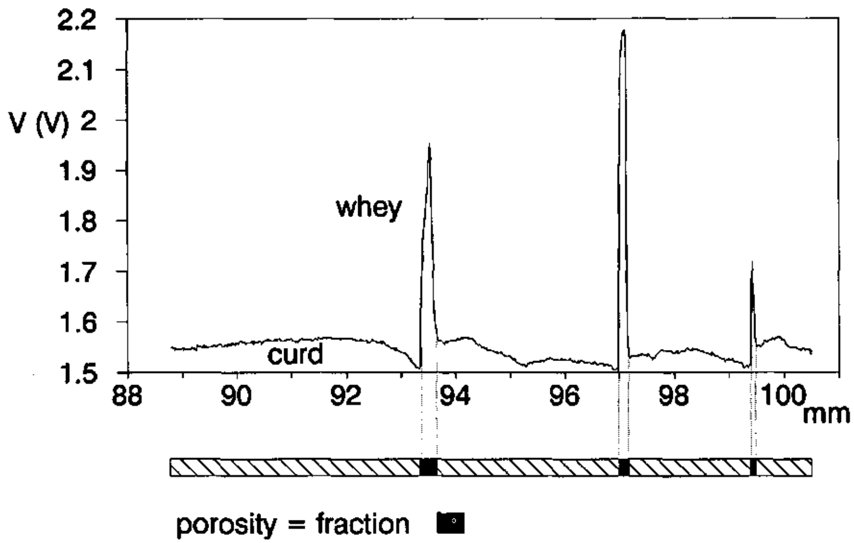


Fig. 2.8 Example of a part of the analogue signal of the photo-electric cell during a penetration in a curd bed. The conversion of the signal to a local porosity is also depicted.

exactly through its poles is not likely, so the apparent dimensions will be usually smaller than the real ones. The sum of the apparent pore widths as a fraction of the total penetration length through the curd block is the local porosity.

The resolution of this method is not exactly known. The fibre tip had a diameter of approximately 20 μm. Therefore, whey pockets smaller than the tip's diameter will reflect, at the maximum, only a part of the whey signal. In these cases the signal may, depending on the limits formulated in the software, be interpreted as originating from curd grains. The sample rate in the direction of the movement of the fibre is approximately one per 6 μm. Therefore, the shape of the pores may affect the resolution of the method. The resolution of the method may also depend on the characteristics of the curd grains. Curd grains are visco-elastic, therefore, the penetration of the fibre into the curd grains will be preceded by an indention of the grain, just like the final puncture of the curd grain will be preceded by stretching of the outer layer of the curd grain. These two effects will compensate each other to a certain extent. The resolution of the method can therefore not exactly be given, but should be estimated at approximately 20 μm. Finally it has to be noted that the fibre tip was very delicate and occasionally snapped. The production of identical fibre tips was until recently not possible, hence, therefore the resolution of the method may not always have been the same.

2.8 The water content of a curd block

The determination of the water content of a drained curd block is hampered by the rapid whey loss that occurs when curd blocks are taken out of the whey. The amount of whey lost will deviate, depending on the permeability of the block at that moment. Another source of experimental error is the amount of whey clinging at the outside of the curd block. In general, these two errors cause that the water content of moist curd blocks is underestimated and the water content of relatively dry curd blocks is overestimated. To minimize moisture loss, the curd block is put immediately into a plastic container. The container is sealed to prevent evaporation. The container is weighed, and the curd block is taken out and put into a mortar. The container is weighed again. The drip whey is removed and the container is weighed once more. The curd block is made homogeneous in the mortar or a mixer/blender. Three samples of 2 to 3 g are dried for 30 minutes at 159 °C. To conform to the NEN 3754 standard (1981) 0.3% is subtracted from the calculated dry matter content. The dry matter content of the drip whey is estimated at 6%. The total water content of the block is calculated.

2.9 Confocal Scanning Laser Microscopy (CSLM)

The inner structure of the outer layer of curd grains could be studied with CSLM. The major advantage of this technique is that pictures can be made at various depths (up to approximately 0.1 mm) without disturbing the sample by cutting. The apparatus used was a Biorad MRC 600, fitted with an Argon laser (488 μm) and a BHS filter. The curd grains were stained with Rhodamine B. The samples were conserved with Thiomersal (BDH chemicals).

3. Curd properties

3.1 Characterization of curd grains

The paracaseinate content in the curd grains will increase with time during cutting and stirring. However, syneresis rate depends partly on milk composition and in the new cheese vat (see Section 2.1.2) accurate control of the stirring conditions was difficult. Preparation of curd grains of a precisely known moisture content by means of a fixed time schedule was thus not feasible. We therefore determined the density of the curd grains (Section 2.2) as a function of time and started the experiments when the density of the grains reached a pre-set value.

The concentration distribution of paracaseinate inside a curd grain is not homogeneous, because syneresis proceeds from the outside, hence, the density will be an average value. The influence of the curd preparation upon the concentration profile is not known. However, curd grains of equal density, but of different size, will have a different concentration profile, because the surface area/volume ratio is proportional to $1/R$, i.e. larger curd grains have relatively little outer layer and a relatively large inner part. The concentration of paracaseinate in the central part of the curd grain is below the average, and the concentration of paracaseinate in the outer layer of a relatively large curd grain will be relatively high and/or the concentrated outer layer will be thicker.

The cube shaped curd grains were actually shaped like dice, with rounded corners (see Figure 3.3 a). The curd preparation took longer time (4 to 6 hours) than normal (1.5 hours), because of the unfavorable stirring conditions and particle shape and size. As expected, the preparation of curd grains cut with an 8 mm grid took less time than that for those cut with a 10 mm grid (approximately an additional hour).

The size of the pieces of is not determined by the cutting alone, as the largest curd pieces may be shattered at the subsequent stirring (Johnston et al. 1991). It is likely that the firmness of the curd pieces is also relevant hereby, as firm gel pieces may be pushed aside by the knife instead of being cut. The size of the curd grains at NIZO's experimental plant varied from very small curd fines to more than 10 mm for the largest diameter of the largest curd grains. The shape of the curd grains also varied greatly, some curd grains being angular, others rounded or disc shaped, and occasionally small clusters (of fused curd grains) were found. We compared the grain size distribution, determined by the method of Schaap (1970), of various batches of factory curd (see Figure 3.1) with the density distribution (see Figure 3.2).

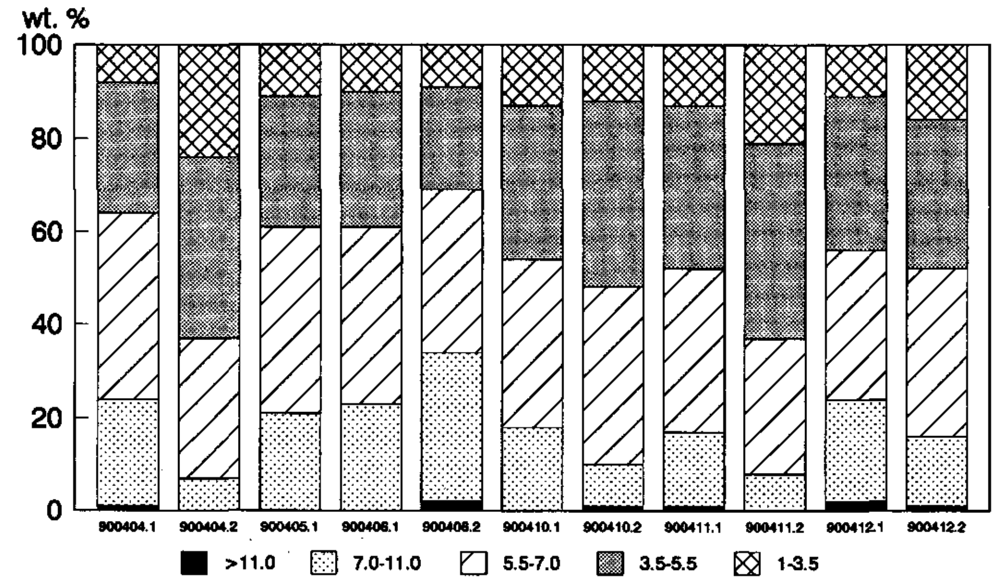


Fig. 3.1. The curd grain size distribution in NIZO's experimental plant according to Schaap's method. The legend shows the mesh sizes of the sieves. The date and batch number are given at the labels at the X-axis before and after the dot, respectively.

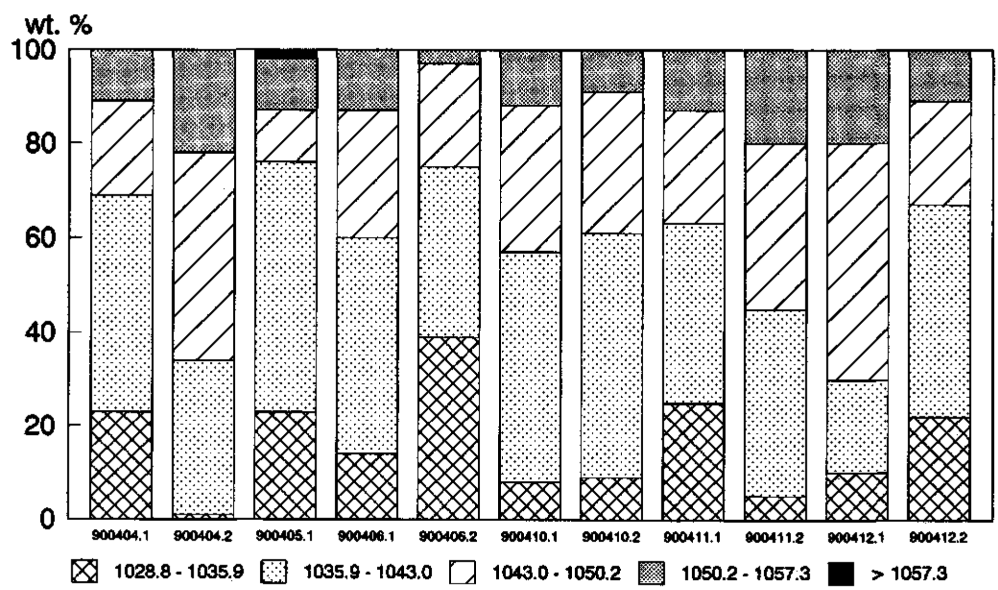


Fig. 3.2. The curd grain density distribution in NIZO's experimental plant. The date and batch number are given at the labels at the X-axis before and after the dot, respectively.

The extent of syneresis, hence density, is determined by the surface area of the curd grains and the syneresis time. Indeed, more small curd grains were correlated to a larger fraction of curd grains of a high density. This implies that shattering of large curd grains in later stages of curd preparation is minimal in practice. It should be emphasized, however, that determination of the curd grain size distribution by means of sieves will be influenced by the shapes of the curd grains. Moreover, it is possible to produce equal sized curd grains with different moisture content. Comparison of the curd grain size distribution from day to day in a cheese plant is a useful empirical tool, but comparison among various cheese manufacturers is seriously hampered due to the constraints mentioned above. In this thesis the relative remaining volume (l_0), i.e. the volume of the curd grains as a volume fraction of the original volume of milk, is used. The relative remaining volume can be deduced from the density distribution and is directly linked to the moisture content of the curd grains.

3.2 Whey expulsion and deformation of cube shaped curd grains

The curd grain flattener (see 2.4) was used to study the whey expulsion and deformation of cube shaped curd grains. Cube shaped grains of various density and size were compressed at various mechanical pressures. The vertical compression led to whey expulsion from the sides (the bottom and the top were considered impermeable) and also to a broadening of the curd grains in the horizontal directions. The grains hardly became barrel-shaped, as can be seen in Figures 3.3 a to 3.3 d. Apparently, the friction between test-piece and the bottom and top plates was very slight (Luyten 1988); these plates were made of perspex and glass, respectively.

The compression curves showed an elastic component (immediately after application of the stress) and a viscous one (at longer time scales); an example is shown in Figure 3.4. The apparent elastic deformation could be slightly larger than the real one in some cases, as some curd grains were not precisely cube shaped; the height of the curd grain was taken at the highest point at the start of the experiment, at the subsequent time interval the top of the curd grain will be flat, hence the elastic deformation may be slightly overestimated. Elastic recovery was clearly visible if the stress was released within a few seconds after the start of the compression. After 15 minutes of compression no elastic recovery was observable after release of the pressure. Presumably, the deformation at longer time scales leads to irreversible changes in the paracaseinate network. Our observation is in accordance with previous results

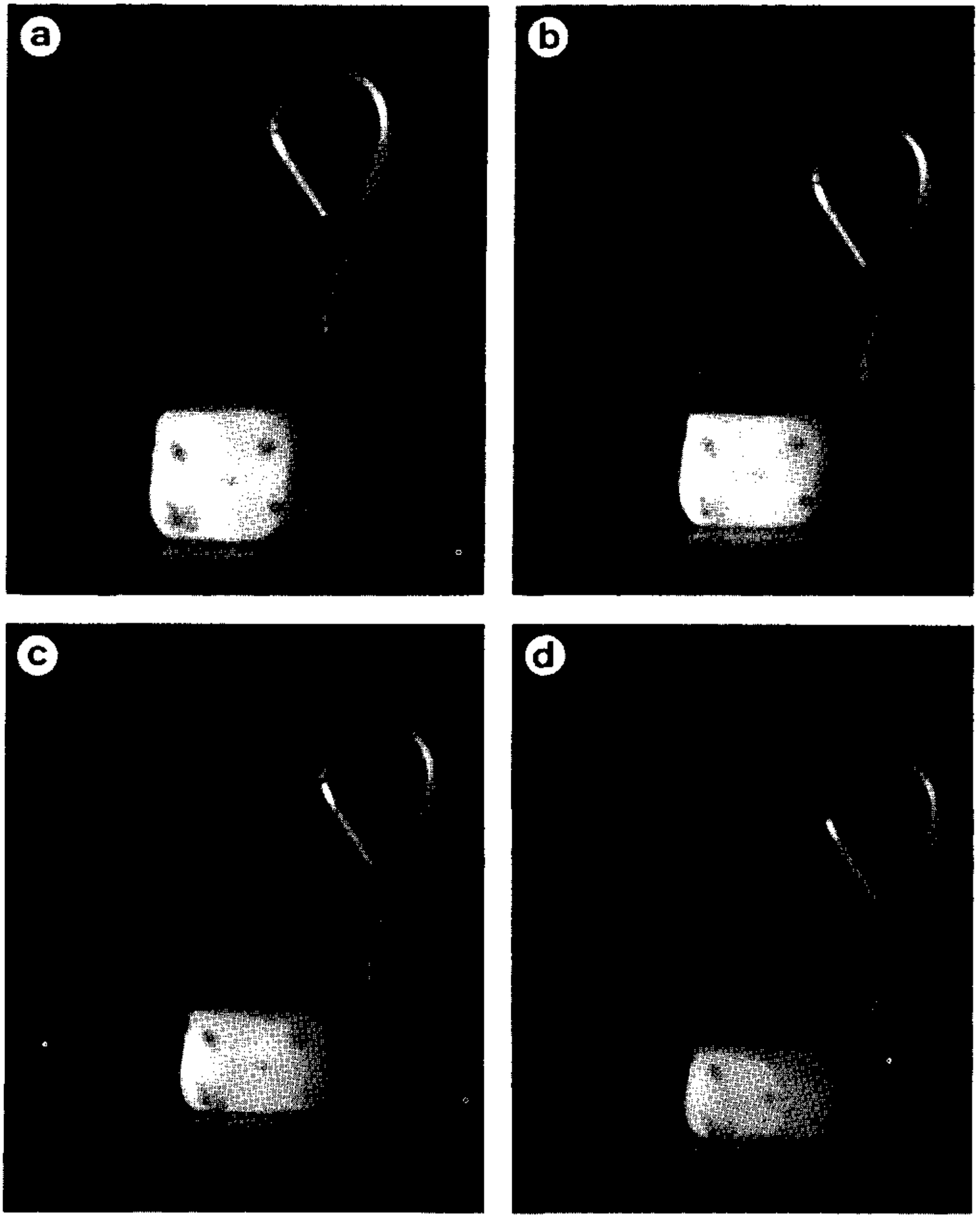


Fig. 3.3 The compression of a cube shaped curd grain at various times (t), 0 (a), 30 s (b), 300 s (c) and 900 s (d), respectively. Mesh = 10 mm, l_0 = 0.28, average p_m = 280 Pa.
The dots shown are made with an analine pencil.

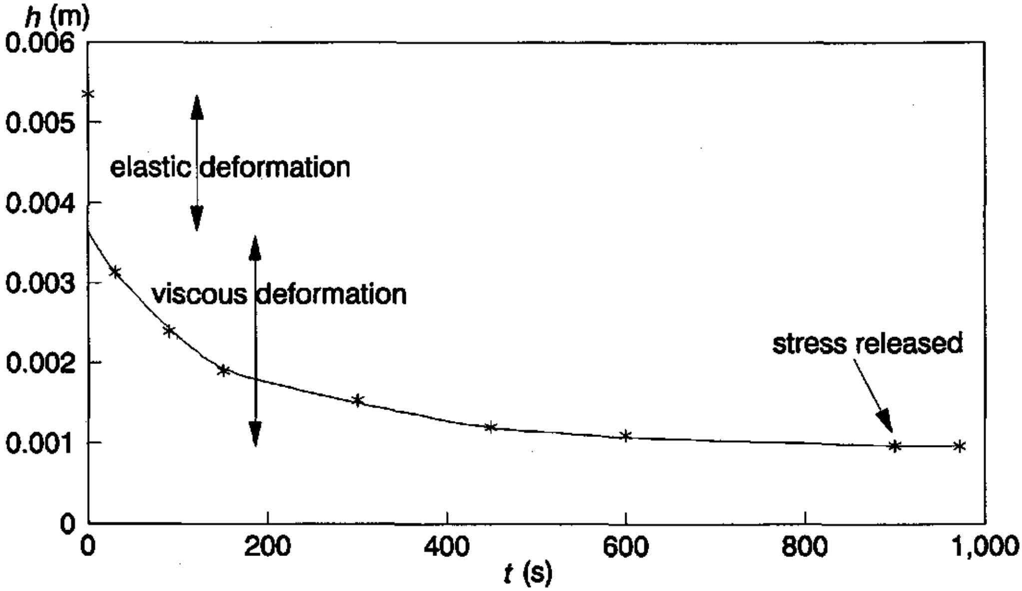


Fig. 3.4 The height (h) of a single cube shaped curd grain versus time (t) during a compression experiment. The average stress was 1210 Pa, i_0 = 0.28, mesh = 10 mm. At zero time the compression starts, and a very rapid elastic and a slower viscous deformation follow. At t = 900 s the stress was released, but the resulting elastic recovery was negligible.

on skim milk gels, their apparent mean relaxation time being approximately one minute (Zoon I 1989). The time scale of drainage is usually much longer, therefore viscous deformation will be overriding.

The results of the compression experiments showed considerable spread. This may have had several causes: the curd grains in a batch are not exactly identical, but have a, be it narrow, size distribution; the concentration of paracaseinate is only known within the restrictions of the density test; the cross-sectional area of the curd grains is slightly overestimated, because only the outer contours are taken. These complications can not be avoided completely, but the effect of the former two can be reduced by raising the number of replicates. Observation of curd grains that were left in the thermostatted bath without any stress, did not reveal any detectable change in the height or the cross-sectional area within the time scale of the experiments (15 min), hence, spontaneous compaction of the curd grains was small.

Within the pressure range tested (up to 3 kPa) and the time interval of 15 minutes a higher stress upon the curd grain generally resulted in a greater elastic and

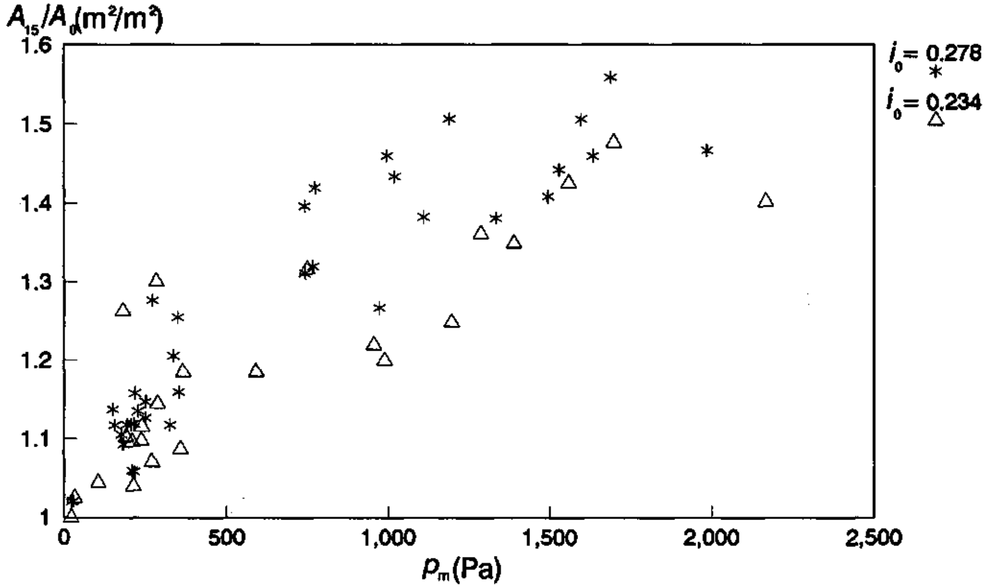


Fig. 3.5 The relative enlargement of the cross-sectional area of cube shaped curd grains (A_{15}/A_0) of two initial relative remaining volumes (i_0) after 15 min., at various stresses (p_m). Mesh = 10 mm.

viscous deformation. A smaller initial relative remaining volume (i_0) of the curd grain resulted in a smaller elastic and viscous deformation within the range tested ($0.29 < i_0 < 0.23$). The broadening of the curd grains slowly increased with the stress (see Fig. 3.5), though the horizontal cross section enlarged by a factor of at most about 1.6 in the case of 8 mm curd grains at a stress of 3 kPa (results not shown). A higher initial paracaseinate content appeared to result in slightly less broadening of the curd grain. In theory, the extent of broadening depends on the time scale of the experiment, because curd is a visco-elastic medium, but in practice variation in processing time is hardly possible. Therefore, it is likely that the limitation of the broadening of curd grains will also limit broadening of curd blocks, unless some junctions between the curd grains are broken. It should be noted that the curd grains in a curd bed can not move frictionless between adjacent curd grains, as the curd grains fuse; therefore, some bulging may take place, causing a slightly larger cross-sectional diameter than that obtained underneath the curd flattener. Square curd blocks are sometimes molded in cylindrical molds and when the corners of the curd block fit exactly in the mold, broadening of the cross-sectional area by a factor of 1.56 must be attained. This value is close to the maximum found for curd grains in the curd flattener. The deviation in moisture content in those curd blocks is usually increased (FNZ 1975). It is also known that in continuous drainage machines, e.g. the Casomatic, the dimensions of the accompanying molds can be varied only within narrow margins. Newer types of continuous drainage vessels are often equipped with interchangeable pipes.

The relation between the compression and the whey loss of curd grains can not be expressed as a characteristic number. In rheological terms the volume loss (due to density increase without moisture loss) in relation to the change in height of the sample is expressed as Poisson's ratio, and by analogy we introduce a pseudo Poisson's ratio:

$$\mu = 0.5\ (1 - \frac{\partial V}{V\,\partial \varepsilon_h}) \tag{3.1}$$

where

μ = pseudo Poisson's ratio (-)

V = volume (m^3)

ε_h = Hencky strain (-)

The Hencky or natural strain is a dimensionless strain corrected for the changed dimensions of the strained sample (Whorlow 1980):

$$\varepsilon_h = \ln \frac{h_t}{h_0} \tag{3.2}$$

where

h_0 = height at t = 0 (m)

h_t = height at t = t (m)

The pseudo Poisson's ratio will be smaller than 0.5 when the volume of the test-piece decreases. The pseudo Poisson's ratio after 15 min of compression appeared to be virtually constant (≈ 0.27), regardless of the initial relative volume (although it should be noted that the applied variation was rather small) or the applied stress (see Figure 3.6). The ratio of compression versus volume loss is evidently constant. The spread at low pressures is the result of inevitable increase in experimental error due to the small changes in cross-sectional area and height. The results of experiments with 8 mm curd grains were almost identical to the results shown, i.e. the size of the curd grains did not affect the pseudo Poisson's ratio. If this conclusion, the pseudo Poisson's ratio being constant regardless of size, initial relative volume and applied stress, also holds in the case of practical cheesemaking, we expect the curd grains

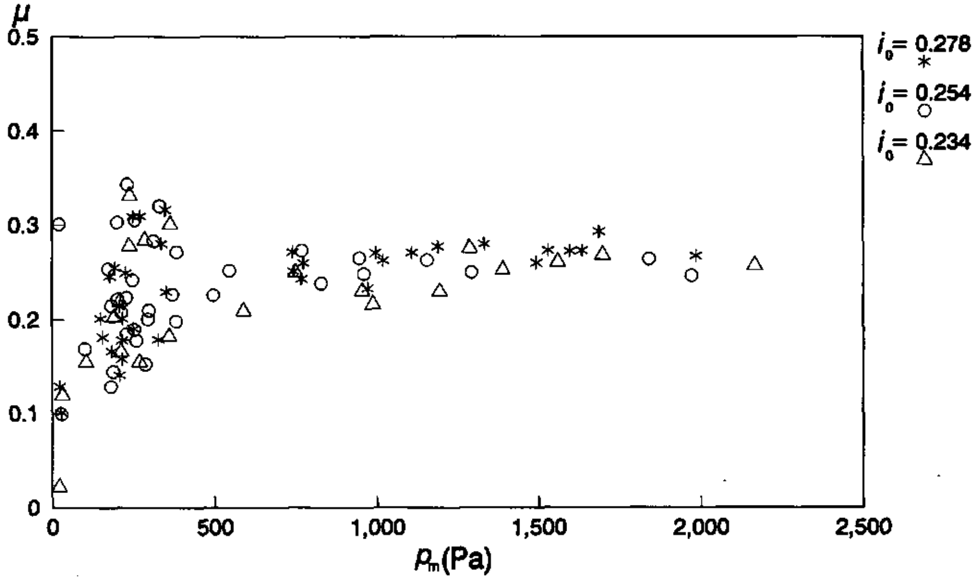


Fig. 3.6. The pseudo Poisson's ratio (μ) for curd grains at various stresses (p_m) after 15 min. The experiment was conducted with cube shaped curd grains of three relative remaining volumes (i_0). Mesh = 10 mm.

in a curd block to expel whey in constant proportion to the applied deformation of the curd grains (at the conditions identical to those in our experiments; pH = 6.6, T = 35°C, fat/paracaseinate ratio 3.0:2.7). The whey may be expelled from the curd block, but may also remain in the pores between the curd grains, depending on the drain off possibilities. Molding of round blocks of curd in square molds led to a decreased moisture content in the diagonal sectors (FNZ 1975), the stretching of the curd grains towards the corners of the mold is larger than the stretching towards the middle of the wall of the mold, the accompanying whey expulsion will be therefore increased at the diagonal sectors.

The expulsion of whey by curd has been studied by various workers (Kirchmeyer 1972, Van den Bijgaart 1988). The expression of whey from non-syneresed curd cubes was fitted by an equation introduced by Weber (1984), here given in modified form:

$$\frac{M_t - M_\infty}{M_0 - M_\infty} = \exp(-z\ t) \tag{3.3}$$

where

M_t = mass of curd grain at $t = t$ (kg)

M_∞ = mass of curd grain at $t = \infty$ (kg)

M_0 = mass of curd grain at $t = 0$ (kg)

z = experimentally determined rate constant (s^{-1})

t = time after starting syneresis (s)

The density of the curd grain slightly increases due to the expulsion of whey, as the density of the latter is lower than that of the matrix. Because of this the use of mass fractions is slightly misleading, therefore we preferred volume fractions. The mass of curd at infinity (M_∞) is 0.15 times the original mass (M_0), according to Weber (1984). However, our experiments indicated that the end point of syneresis can be at a value clearly lower than 0.15 (see Figure 3.7) times the original volume. The minimum

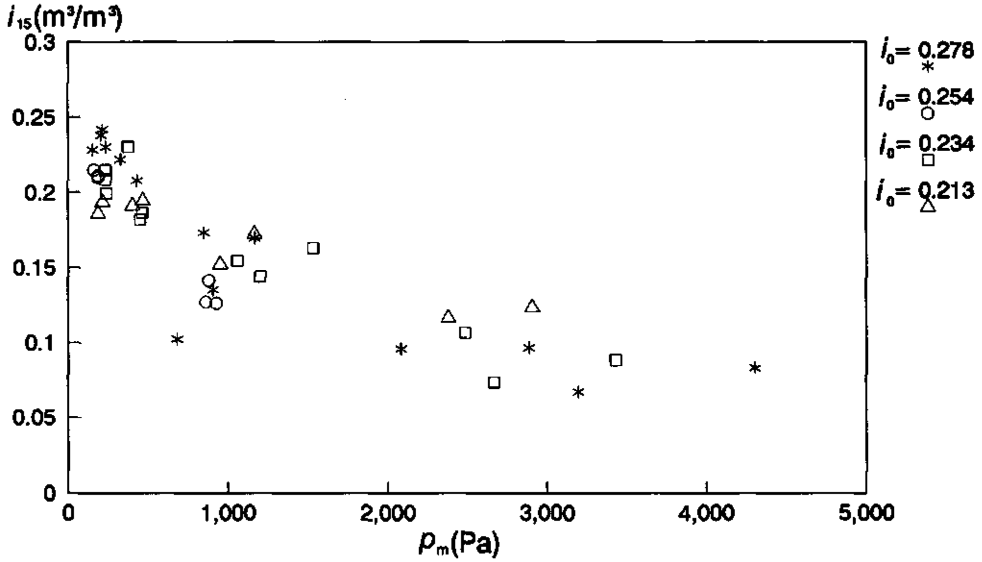


Fig. 3.7 The relative remaining volume of curd grains after 15 min. (i_{15}) of compression at various stresses (p_m) and different initial relative remaining volumes (i_0). Mesh = 8 mm.

remaining volume of the curd will consist of paracaseinate, fat and moisture. The latter is estimated by Walstra et al. (1985) at 1.4 g water/g paracasein at room temperature and physiological pH plus a little interstitial moisture for the gel of closely packed micelles. At pH = 5.2 and a temperature of 35 °C approximately 1.2 g water per gram paracasein is imbibed by the paracaseinate according to estimates by Walstra et al. (1985). Van den Bijgaart (1988) determined the minimum relative remaining volume in curd slabs, prepared of skim milk, at approximately 0.10 at pH = 6.67 and 0.07 at pH = 6.33 at 34 °C and a stress of 62 Pa. His results also indicate that the end point of syneresis depends on the exerted stress. Fat globules probably increase the amount of water per gram paracaseinate slightly (Walstra et al. 1985). Taking the above considerations into account and estimating the amount of fat remaining in the curd grains and that of paracaseinate at 3.0 kg and 2.7 kg per 100 kg of cheese milk, respectively, we estimate at the pressure range of our experiments the end point of syneresis at 0.10 times the volume of curd before cutting. The cross-sectional area between the values obtained at 30 s and 15 minutes was obtained by linear interpolation. Combining these results with the heights at the subsequent intervals yielded the (relative) remaining volume of the curd grains at intervening times. We tried to incorporate important factors affecting the expression of the curd grains, like exerted mechanical stress and initial relative remaining volume and initially also the surface area of the sides of the curd grains in the equation (3.3). Whereas Weber (1984) and Kirchmeyer (1972) used a factor exp($-t$), other researchers, e.g. Lawrence and Hill (1974) reported a volume of whey expelled proportional to a factor $t^{0.5}$. Recalculation to relative remaining volume yields in the latter case a factor of about exp($-t^{0.5}$). We tried various time proportionality factors, namely exp($-t$), exp($-t^{0.75}$) and exp($-t^{0.5}$), but only the last factor matched with the results over the entire time span, which agrees with the results of Lawrence & Hill (1974). The proportionality factor of the stress upon the curd grains was also tested in various modes, namely exp($-p_m^{0.5}$), exp($-p_m^{0.75}$) and exp($-p_m$); the latter gave generally the highest correlation coefficient (r^2), and best graphs of the predicted value/ experimental value versus the exerted stress and i_0. The considerations above led to equation (3.4):

$$\frac{i_t - i_\infty}{i_0 - i_\infty} = \exp(-\, k\, p_m \sqrt{t}\,) \tag{3.4}$$

where

k = constant ($Pa^{-1}.s^{-½}$)

i_t = relative remaining volume at $t = t$

i_∞ = relative remaining volume at $t = \infty$

i_0 = initial relative remaining volume

p_m = applied stress (Pa)

t = time after application of the stress (s)

The exerted force was kept constant, but the cross-sectional area increased during an experiment. Therefore the stress exerted upon a curd grain decreased. In equation (3.4) the average stress between two successive points of time was taken. The equation was used for both sizes of curd grains. The value $k = 4.10^{-5}$ $Pa^{-1}.s^{-1/4}$ generally gave a reasonable fit of the results (r^2 varied from 0.58 to 0.74), the average of the calculated results and the experimental ones was practically identical over the total time span. The fit was less accurate at very high stress. The surface area of the sides is not taken into account in equation (3.4), as it did not improve the fit.

Van den Bijgaart (1988) observed the permeability of skim milk gels concentrated by syneresis to be higher than that of gels from skim milk gels concentrated by ultrafiltration. The formation of a dense outer layer in the former gels would be expected to diminish the permeability of the syneresed gels, but apparently this effect is dominated by an opposite effect. Results by Van Dijk's (1982) "torsion flux" method, which showed that the permeability of a gel increased after deforming it, points to the importance of fracture. To investigate whether the skin cracked or not, CSLM micrographs were made of curd obtained of NIZO's pilot plant. The curd grains had a very condensed outer layer (Figure 3.8 a), that appeared to be fully intact. However, after exerting a small stress upon the curd grain, in this case caused by applying a cover glass, $\approx$ 100 Pa, the skin fractured (Figure 3.8 b). The flow through cracks will increase the permeability dramatically. The occurrence of macroscopic fracturing of rennet-induced skim milk gels at large deformation is highly likely, according to Zoon (II 1989). The experimental setup of measuring syneresis of Kirchmeyer (1972) - cubes of curd floating in a concentrated salt solution, causing strong osmotic effects - differed from that of Lawrence & Hill (1974) - curd grains in an agitated vat - and this may have caused the observed difference in syneresis rate.

The outer layer of our cube shaped curd grains showed already cracks before application of a stress. It is not known what is the cause of this.

The rate of the expression of cube shaped curd grains is governed by the rheological properties of the paracaseinate strands and/or by the resistance to flow. In other words, the stress exerted upon the curd grains rests upon the paracaseinate matrix and/or the enclosed whey. The viscosity of the paracaseinate matrix can not separately be determined, but it is possible to make a tentative calculation of the liquid pressure. Darcy's law has been applied to estimate the effect of several values for the one-dimensional permeability coefficient on the liquid pressure. A curd grain

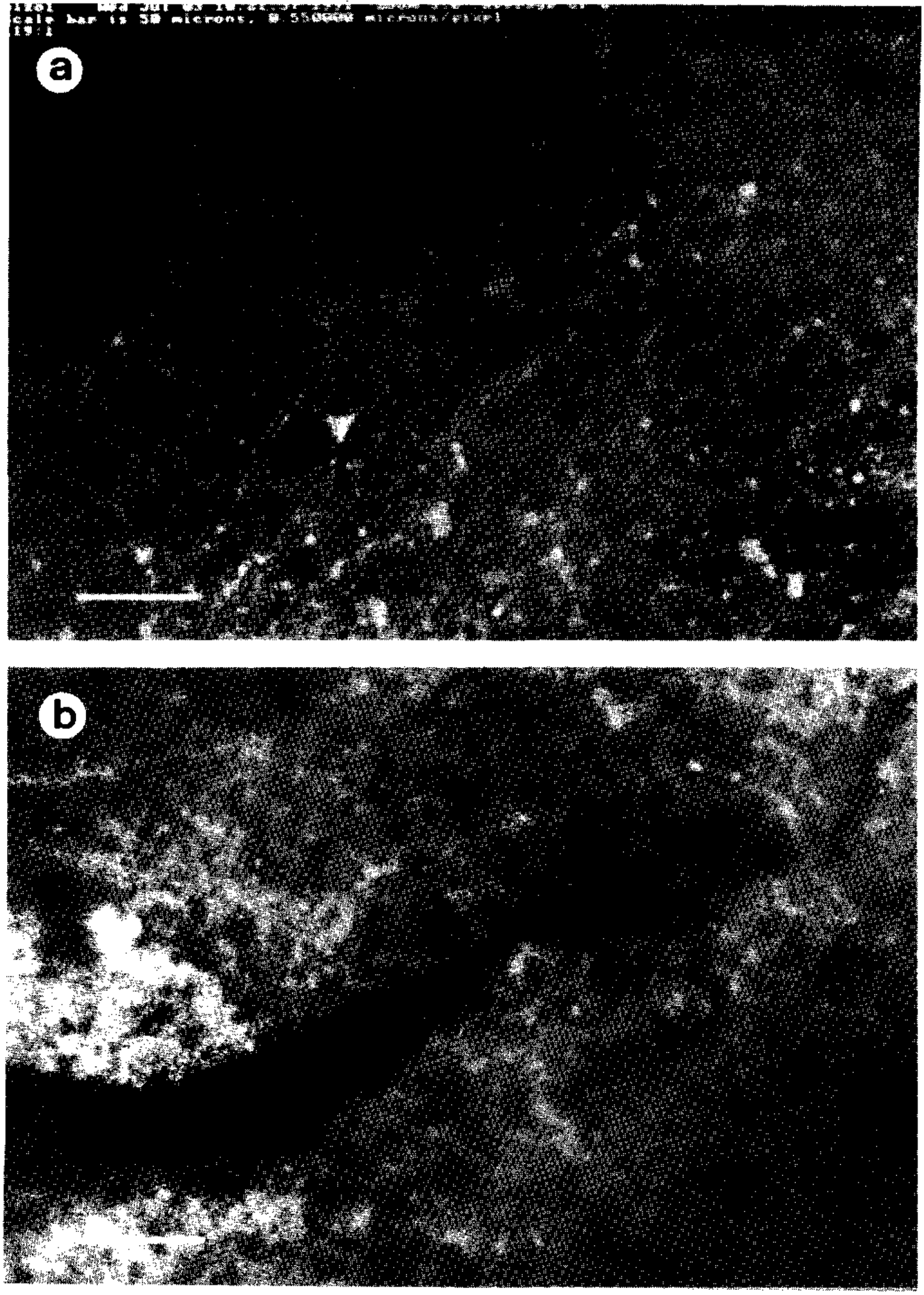


Fig. 3.8 A confocal scanning laser micrograph of the surface of a curd grain obtained from a commercial cheese vat without (a) and with (b) a cover glass. The bar is equal to 50 μm. The curd grain was conserved with thiomersal (Merck).

underneath the curd flattener is visualized as a rectangular box. The top and the bottom of the box are considered impermeable and the friction between curd grain and top and bottom plates is negligible. The flow of whey is actually two-dimensional, but in this approach we simplify it to a two-fold one-dimensional flow. The box is hereto hypothetically divided in a permeable left- and right-hand side and an impermeable front and back side, respectively in an impermeable left- and right-hand side and a permeable front and back side. The flow of whey across the planes of symmetry is zero. The whey originates from various places inside the curd grain, but we assumed that all whey originated from a source located at the middle planes. The distance between the middle plane and the outside of the curd grain is estimated at 3.10^{-3} m. As only half of the flow of whey actually goes across the front and back side (the other half goes across the left and right-hand sides), the volume of expelled whey, calculated from the height and the cross-sectional area of a curd grain at two subsequent times, has to be divided by two. The total surface area was estimated at 10^{-4} m^2. The following set of parameters was used: $\eta = 10^{-3}$ Pa.s, $x = 3.10^{-3}$ m, $A = 10^{-4}$ m^2. The permeability (B) was estimated at 10^{-14}, 3.10^{-14} or 10^{-13} m^2. These values were combined with various results of compression experiments into the integrated Darcy's law:

$$p_t = \frac{(\Delta V/2)\ \eta\ x}{\Delta t\ B\ A} \tag{3.5}$$

where

p_t = liquid pressure (Pa)

ΔV = volume decrease of curd grain in an interval (m^3)

η = dynamic viscosity (Pa.s)

x = distance (m)

Δt = time interval (s)

B = permeability (m^2)

A = surface area of the sides (m^2)

Table 3.1: The calculated liquid pressure (p_l) at three time intervals (t), for each at two levels of stress (p_m) upon the curd grains (i_0 = 0.28, mesh = 10 mm) for various permeability coefficients (B). The cross-sectional area of the curd grains increases in time, causing a decreasing stress upon the curd grains. The values of the liquid pressure shown in brackets are larger than the exerted stress upon the curd grains and are therefore unrealistic.

t (s)	p_m (Pa)	$\Delta V/\Delta t$ (m^3/s)	$B=10^{-14}$ (m^2)	$B=3.10^{-14}$ (m^2)	$B=10^{-13}$ (m^2)
			p_l (Pa)		
0-30	227	2.0 10^{-9}	(2950)	(983)	(295)
90-150	215	1.7 10^{-10}	(252)	84	25
600-900	203	2.4 10^{-11}	35	12	4
0-30	2007	3.4 10^{-9}	(5037)	1680	504
90-150	1670	2.7 10^{-10}	404	135	40
600-900	1375	3.4 10^{-11}	51	17	5

The calculated liquid pressures (Table 3.1) are probably an overestimate due to the assumptions stated above. If the permeability were larger than 10^{-13} m^2, the liquid pressure compared to the exerted stress becomes so small that the expression of a curd grain is practically determined by the rheological properties of the network. An initial permeability smaller than 10^{-14} m^2 is unlikely, as in that case some of the calculated liquid pressures would become more than ten times the exerted stress (Table 3.1). We may qualitatively conclude that, in spite of the probable decrease of the permeability in more expressed curd grains, the stress exerted upon the curd grain will soon predominantly be carried by the paracaseinate network. In other words: the Trouton viscosity of the network becomes the rate determining factor in the expression of curd grains in a curd column if the pressure on the curd-whey mixture is not very small.

3.3 The fusion of cube shaped curd grains

The force needed to break the junctions between curd grains was measured by the perforated piston method described in Section (2.6). In principle, tearing apart the two neighboring curd layers can occur either by fracture through the curd grains themselves and/or by fracture between the curd grains. The appearance of a fractured curd grain is slightly different from that of an intact curd grain. Careful examination of both curd layers after the splitting did not reveal any fractured curd grain. Moreover, a preceding coloring of the outside of the curd grains in the upper layer with Congo Red (Merck), which led to red colored circumferences after fracture did neither reveal any such fracture through a curd grain. These results agree with results by Luyten (1988), who concluded from her experiments that it takes at least 2 days of fusion before fracture occurs through the curd grains.

Macroscopically, the fractured layers of curd matched each other quite well, even when the layers were torn apart after a contact time as short as 1 *min*. It is however not sure whether the curd grains actually contact each other over the entire area. If this is not the case, the fusion areas are rather contact points that are distributed over the perforations in the piston.

The fracture stress was positively correlated with the fusion time and the exerted mechanical stress (see Figures 3.9 and 3.10).

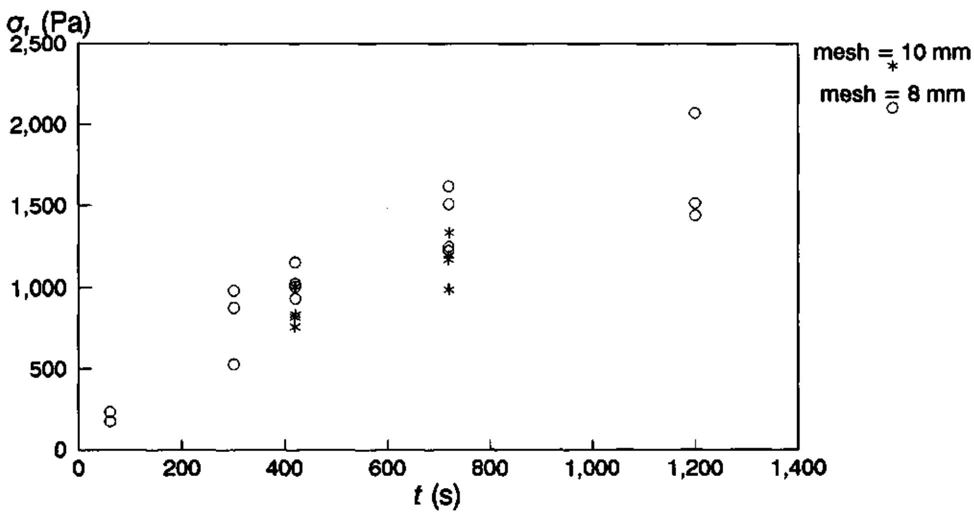


Fig. 3.9. The fracture stress (σ_f) of the junctions between cube shaped curd grains versus fusion time (t) for cube shaped curd grains of two different sizes. T = 34.5 °C, p_m = 905 Pa, l_0 = 0.28.

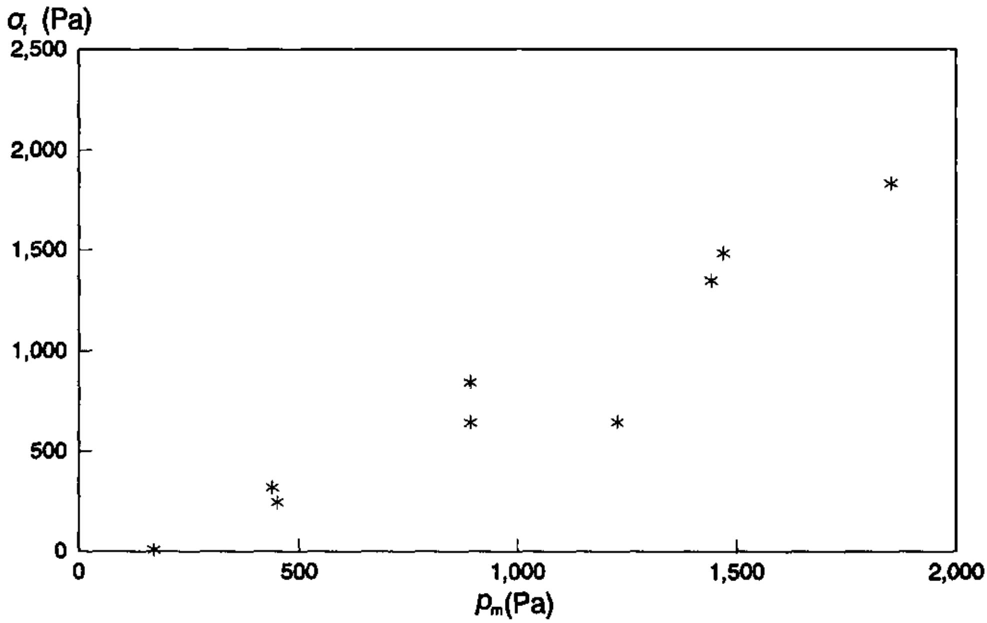


Fig. 3.10. The fracture stress (σ_f) of the junctions between cube shaped curd grains versus applied stress (p_m). Mesh = 10 mm, i_0 = 0.28, T = 34.5 °C, t = 7 min.

Fig. 3.10 suggests that a minimum stress is needed to accomplish fusion, but this was caused by the experimental conditions (the two layers of curd grains were separated by the bottom of the piston and the lowest stress applied was caused solely by the weight of the piston upon the bottom layer, which implies that there was virtually no stress exerted at the top layer of curd grains, and, accordingly, the curd grains in the upper layer will not touch those in the bottom layer). It is also known, that in a settled layer of curd grains in the whey already some fusion occurs, which implies that the minimum stress needed to create fusion is less than 20 Pa. The spread in the results was due to small variations among batches; measurements at various fusion times (or mechanical pressures) with curd grains prepared from one and the same batch gave less variable results. It appeared from preliminary experiments that the relative remaining volume of the curd grains (i_0) was positively correlated with the fracture stress. This agrees with the observation that smaller curd grains apparently fused slightly better than larger ones (see Figure 3.9), because the concentration of paracaseinate in the outer layers will be relatively low, or the concentrated layer will be relatively thin, in small curd grains. The increased concentration of paracaseinate will induce two opposite effects. The paracaseinate strands in the gel will be thicker and less flexible; and to accomplish fusion, deformation is needed and thicker strands will also hinder rearrangement to a greater extent. On the other hand, at a higher concentration of paracaseinate the number of reactive sites per unit surface area will be larger. It is likely that the first effect is overriding. The effect of the temperature is less clear: there may be an optimum fusion temperature (see Figure 3.11).

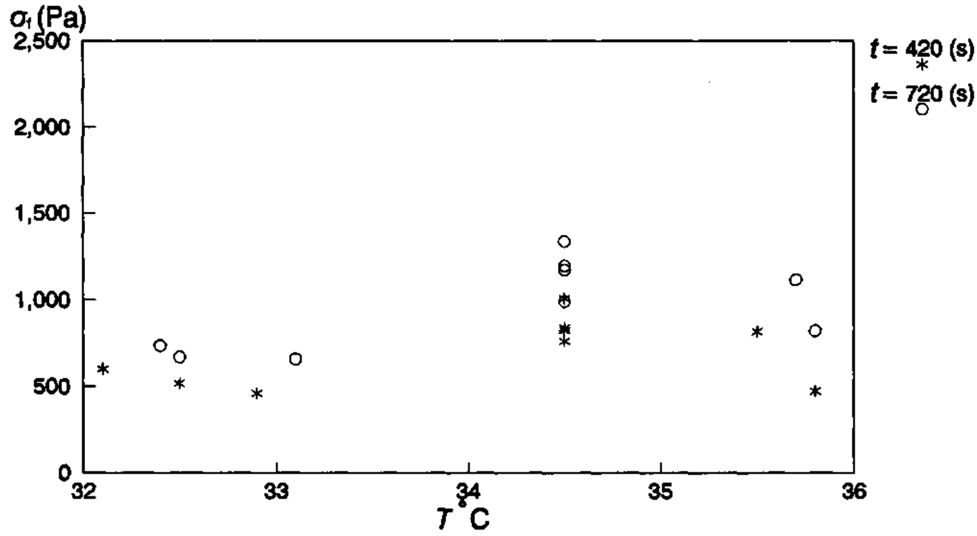


Fig. 3.11. The fracture stress of the junctions between cube shaped curd grains versus fusion temperature after 7 and 12 min of fusion. p_m = 905 Pa, l_0 = 0.28, mesh = 10 mm.

In practical cheesemaking enhancing fusion to a certain extent is common practice. A "resting" stage is often applied in a batch-wise drainage, during which the curd grains are left undisturbed after sedimentation; such resting may clearly promote fusion between adjacent curd grains, although their contact areas, hence the junction zones, are rather small. Cheesemakers often put perforated stainless steel plates on top of the curd bed a few minutes after the sedimentation. The exerted stress caused by these plates will not only increase the (macroscopic) contact area, hence the junction zones, but will also increase the fusion rate. In most continuous drainage machines the mechanical pressure upon the curd grains is gradually increased. A continuous drainage apparatus is always equipped with a buffer tank. The curd grains in the buffer tank are usually slightly cooled to slow down syneresis, but this cooling may affect fusion behaviour as well. Geurts (1978) observed that in a larger sized curd block, a more satisfactory closed rind was obtained than in a smaller curd block. This implies that the curd grains at the edges of the large curd block were fused better. The phenomenon must be ascribed to the faster temperature decrease of the smaller block. The curd preparation will affect the whey content of the curd grains, hence the viscous and elastic deformation and therefore the contact area between the curd grains, but also the fusion will be diminished at low whey content in the outside of the curd grains. Moreover the contact area per m^3 of curd grains will be determined by the size and shape of the curd grains. This probably caused that curd blocks of cube shaped curd grains were less coherent than the ones of factory curd.

3.4 Sedimentation of curd grains

Demixing of curd grains, caused by variation in sedimentation rate, into layers of curd grains of various average size and density is an undesirable phenomenon in drainage equipment. It causes variation in moisture content of the cheese (FNZ 1975) in batch-wise operated drainage vessels with one central inlet, like strainers. The curd grains in such a drainage vessel are distributed from the center of the vessel and they flow with the whey towards the edges of the vessel. To avoid an uneven height of the curd bed, the curd grains are mixed manually. In continuous drainage equipment, like the Casomatic, a thin layer of fine particles can be observed at the top of the curd bed in the drainage pipe, but it is not known whether this influences the moisture distribution or not.

An important characteristic in relation to sedimentation rate is the particle Reynolds number (Re):

$$Re = \frac{\rho_l \, v \, d_p}{\eta} \tag{3.6}$$

where

ρ_l = density of the liquid (kg/m^3)

v = stationary sedimentation velocity (m/s)

d_p = particle diameter (m)

η = dynamic viscosity of the liquid (Pa.s)

The Reynolds number is related to the type of flow around a particle. The following parameter set was used to estimate the Reynolds number; $\rho_l = 10^3$ kg/m^3, $\eta = 10^{-3}$ Pa.s and we further assumed $v = 0.05$ m/s and $d_p = 5.10^{-3}$ m; this results in Re =

250, i.e. in the intermediate region between laminar (Re < 0.1) and turbulent (Re > 1000) flow. The free settling velocity of one single spherical rigid particle in a Newtonian fluid can be calculated (Sakiadis 1984) from the general relation:

$$v = \sqrt{\frac{4\ g\ \Delta\rho\ d_p}{3\ \rho_l\ C_w}} \tag{3.7}$$

where

g = acceleration due to gravity (m/s²)

$\Delta\rho$ = apparent density (kg/m³)

C_w = drag coefficient (-)

The drag coefficient of spherical particles can be given as a function of the Reynolds number, in the intermediate region it may be represented (Sakiadis 1984) by:

$$C_w = \frac{24}{Re}\ (1 + 0.14\ Re^{0.7}) \tag{3.8}$$

In practice, the free-settling velocity of curd grains can vary due to variation in diameter, apparent density and drag coefficient. The original size of the pieces of curd is decisive in this matter, unless clusters of fused curd grains are formed. The apparent density depends not only on the density of the curd grain, thus the fat/paracaseinate ratio and the extent of syneresis, but also on the extent of the dilution of the whey, i.e. the amount of washing water added to the curd/whey mixture. In the absence of clustering of curd grains, the extent of syneresis is closely related to the size of the grains, as the syneresis rate is about proportional to the surface area. Other variables, especially the time of syneresis may cause differences within a batch. The apparent density of clusters can vary, depending on the apparent density of the fused curd grains and the amount of included whey. The drag coefficient depends on the Reynolds number, and therefore apparent density and diameter, and on the shape of the particle. The free-settling velocity of spherical curd grains can be iteratively derived from the equations 3.6, 3.7 and 3.8 (Table 3.2).

Table 3.2 The calculated free-settling velocity and Reynolds number of spherical curd grains of various size and apparent density.

d_p (m)	$\Delta\rho$ (kg/m^3)	v (m/s)	Re
$1.\ 10^{-2}$	15	0.061	615
$5.\ 10^{-3}$	15	0.034	170
$2.\ 10^{-3}$	15	0.014	27
$5.\ 10^{-3}$	20	0.041	204
$5.\ 10^{-3}$	40	0.062	314
$2.\ 10^{-3}$	50	0.031	63

Table (3.2) shows that in the case of curd grains of identical apparent density the ones with the largest diameter will, naturally, sediment fastest. In the case of equal sized curd grains with different apparent density, the ones with the highest density will sediment fastest. In practice, the curd grains with the largest diameter will also be the ones with the lowest (apparent) density. According to an FNZ report (1975), the smaller particles were found at the bottom of the curd block, but the (calculated) free-settling velocity of small particles (say 2.10^{-3} m) is, in spite of their higher apparent density, less than that of larger particles (Table 3.2). We had similar experiences in pails filled with cube shaped curd grains and a small amount of smaller curd grains. The comparison of calculated values and experimental results may be not completely fair, as the curd grains in fact are not spherical and the sedimentation rate of particles is reduced by the presence of other particles (hindered settling) (Sakiadis 1984). The fact that small curd grains were found at the bottom of the strainer does not necessarily imply that their free-settling velocity is higher, as smaller curd grains may fill the gaps between adjacent large curd grains and may have been sucked down in the curd bed when the whey was removed (the experience was based upon the drainage in strainers). Such an effect also happens in the drainage of sludge and is called fines migration (Novak et al 1988). On the other hand, small eddies may swirl up curd fines while leaving larger particles motionless. Such an effect may explain the above mentioned observations at the top of the Casomatic pipes (first paragraph of this section).

Cube shaped curd grains rotated when freely settling. Anisometric curd grains sank in a preferential orientation, regardless of their initial position. The preferential orientation of an anisometric curd grain is with its longest axes perpendicular to the direction of sedimentation; this orientation is attained after a short wobbling. The Reynolds number, based upon a diameter of a sphere having the same surface area, in the range 5.5 - 200 is known to result in a stable position of maximum drag (Sakiadis 1984).

3.5 Packing of curd grains

The type of flow when curd grains sediment, the angularity and the orientation of the particles and their firmness probably all affect the initial packing. The porosity is hard to estimate, and may vary with the particular conditions.

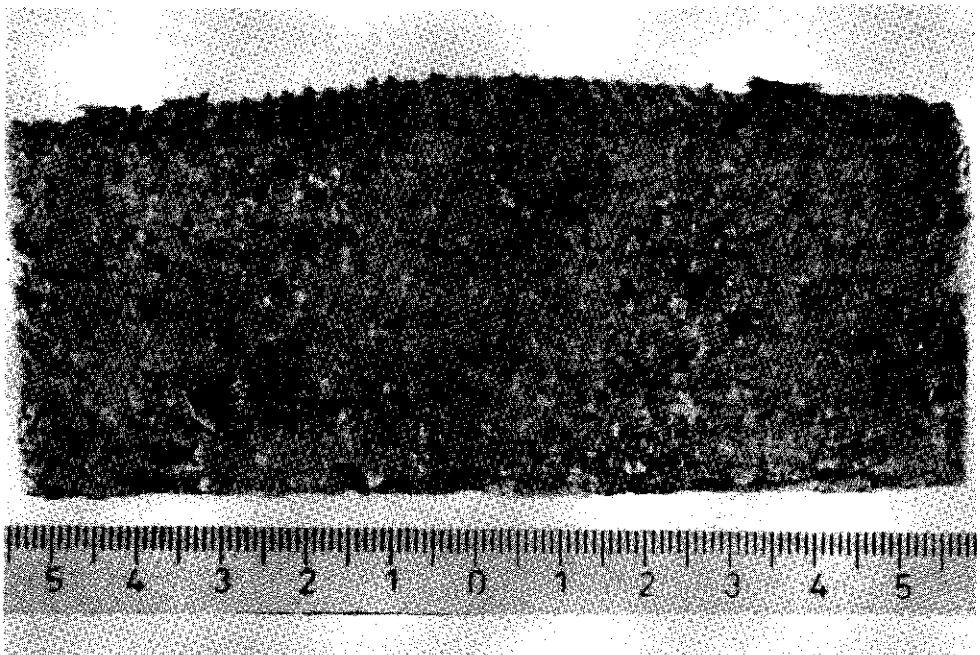


Fig. 3.12. Vertical cross-section through a curd bed after compression. The curd grains were obtained from the 40 l cheese vat. The outside of the curd grains had been colored with Congo red before the drainage. Note that the orientation of the curd grains near the wall is altered. The dark spots on the photo are caused by curd grains fallen out of the bed.

In the preceding Section it was mentioned that free-settling curd grains orientated with their longest axis perpendicular to the direction of sedimentation. Section 3.2 it was shown that expression of a curd grain results in a broadening and vertical compression. The combined effects upon the orientation the curd grain are shown in Figure 3.12.

Rüegg and Moor (1987) compared vertical and horizontal cross-sections of various cheese types and concluded that the apparent curd grain size in the horizontal direction was markedly larger than that in the vertical direction. As most of the whey will flow around the curd grains, it is likely that the resistance to flow of whey in a block in vertical direction will be greater than in the horizontal directions, i.e. the curd block will be an anisotropic medium. Injection of whey provided with a tracer, Congo red (Merck), in a block of draining curd in a cylinder with a whey outlet at the top gave clear evidence of the anisotropy (see Figure 3.13).

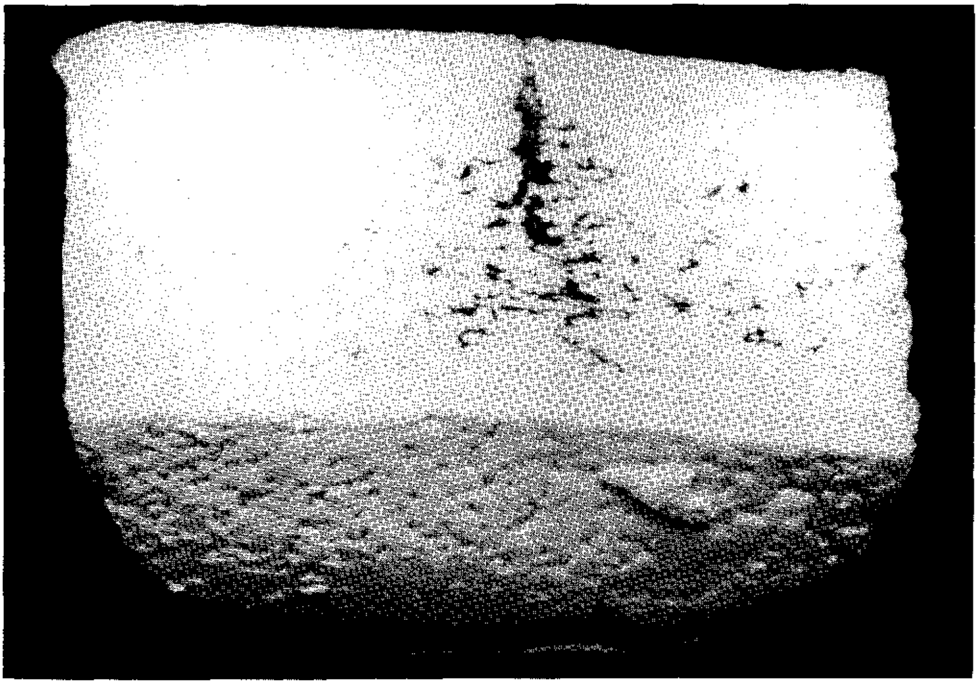


Fig. 3.13 The flow pattern of the whey, injected into a curd bed after 7 minutes of compression (≈ 400 Pa), made visible with Congo red. The curd grains were prepared in the 40 l cheese vat.

4. Effects of the drainage vessel upon drainage

4.1 Axial draining vessels

Batch-wise drainage was observed in various commercial installations. The curd layers produced were rarely thicker than 0.25 m, limiting the exerted stress upon the curd at the bottom to approximately 2.5 kPa (when the whey is allowed to drain). If the curd mass was cut in blocks in the drainage vessel, whey was expelled from the blocks, the blocks subsided slightly, causing gaps between them. Whey filled the gaps in between almost to the rim. The drainage time, i.e. the time curd was in a drainage vessel, was usually around 20 to 30 min, although longer drainage times were occasionally used at certain manufacturers. It seemed that the moisture content of the curd blocks made in batch-wise equipment was slightly lower than that of curd blocks made in continuous drainage equipment. However, it will vary among the manufacturers.

The experimental setup is described in Section 2.5.3. The whey in this setup flows through sieves at top and bottom of the curd bed and the sieves could in principle restrict the flow rate through the curd bed. Experiments by Valk (1986) did not confirm this; he glued thin highly permeable sponges to the sieves and compared the compression rates, which were observed to be not significantly dependent on the presence of the sponges. The flow of whey through the curd bed in a drainage column (see 3.5) was made visible by adding a tracer (Congo red) to the whey percolating through it. A considerable part of the flow leaked along the curd bed; Kerkhof (1979) already drew attention to it, but he neglected the consequences. The fraction of whey that leaks between the vessel and the curd block will depend upon the geometry of the vessel and on the packing of the curd grains; the latter will be subject to change during the drainage, but the leakage will never be zero. It may be negligible in very large vessels, but these could not be applied in this study. The direction of flow of the whey in a curd bed as described in the Section 3.5 - i.e. mainly in radial direction - combined with the leakage, also causes compression experiments as performed by Kerkhof (1979) to be unreliable. Drainage in our small scale axial drainage equipment did insufficiently resemble the batch-wise drainage in practice, therefore we abandoned this approach. The problem of leakage is rarely reported in literature, but its existence at other expressions seems likely, although its effect maybe not as dramatic as in case of curd grains.

The location of the curd block in the drainage vessel may affect the drainage in various ways: 1) Demixing of the curd grains according to size and/or shape may occur (see Section 3.4). 2) The temperature of curd blocks at the walls will be influenced by the wall temperature and the temperature is known to be an important variable affecting syneresis (Van den Bijgaart 1988) and fusion, hence, drainage behaviour. 3) Any leakage along the wall affects the flow of whey through the curd. 4) The curd blocks at the wall will adhere to it to a certain extent, retarding subsidence of the curd layer. 5) The curd blocks are sequentially taken out of the vessel; this may influence the temperature of the block as well as the duration and the magnitude of the stress exerted upon it.

4.2 Radial draining vessels

As far as known, radial drainage vessels are only applied in continuous drainage systems. Start-up and finishing the use of the continuous drainage equipment is always the difficult part to control, resulting often in an increased variation in moisture content (De Vries & Van Ginkel 1985). Normally the pipes are filled with whey before start-up. The curd/whey mixture is subsequently added to the drainage pipes. Whey and curd/whey mixture can usually be added independently, so the curd is kept under the whey. The curd blocks show per batch a slow decrease in water content of the subsequent blocks. In most types of drainage pipes the whey outlet is restricted by a back pressure. There is an exception: in one type, used to produce Edam cheese, no back pressure is applied. The geometry of the pipes varies, diameters range from 0.16 to 0.32 m, and the height of the pipes is between 1 and 3 m. The drainage time is usually less than 10 min. The water content of the curd blocks after drainage, although it varies with type of cheese, manufacturer, etc., is approximately 58 - 60%.

The total external pressure can be broken down into the stress upon the particles, the liquid pressure and the loss of pressure due to friction with the wall (Schwartzberg et al. 1985):

$$p_t = p_m + p_f + p_w \tag{4.1}$$

where

p_t = total external pressure (Pa)

p_m = stress upon the curd grains (Pa)

p_f = liquid pressure (Pa)

p_w = pressure loss due to friction to the wall (Pa)

The effect of the total external stress upon the liquid pressure was studied in the setup discussed at Section 2.5.1 The flow of whey results from a liquid pressure gradient between the center of the curd column and the outside. A general picture of the development of the liquid pressure can be given: a considerable external pressure (p_t) had to be applied to accomplish a detectable (> 5 Pa) liquid pressure drop within 15 min. Once established, the liquid pressure always increased with time (see Figure 4.1).

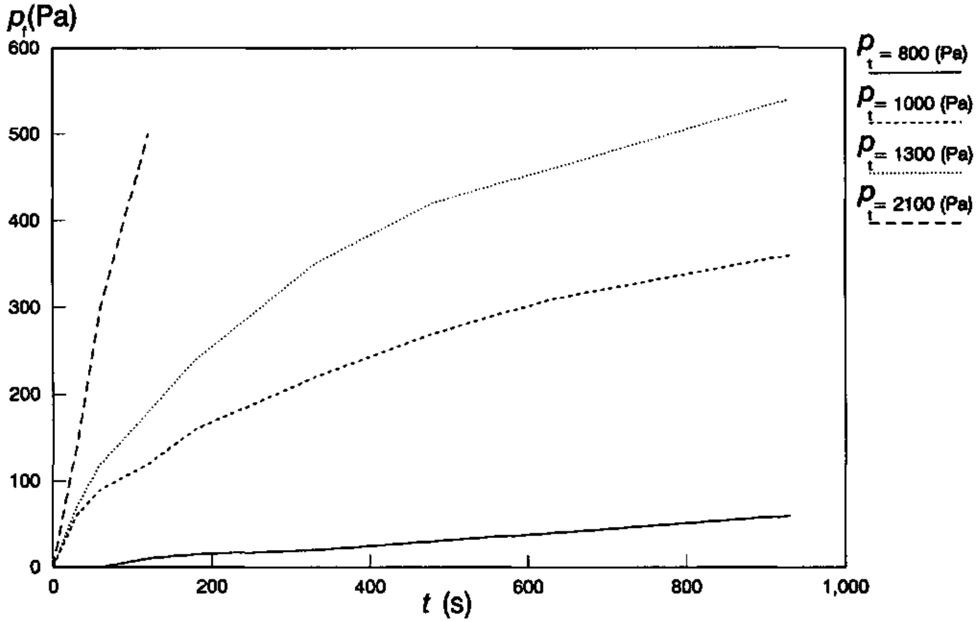


Fig. 4.1 The liquid pressure in the larger drainage column (R = 0.10 m) filled with factory curd (t = 40 min after end of curd preparation), to approximately 0.11 m (= h_0) at various exerted mechanical pressures (p_t).

Above this threshold value, any further increase in external pressure resulted in a faster increase of the liquid pressure. An external pressure of a few hundred Pa above the threshold level resulted in such an increase of the liquid pressure that the working limit of the liquid pressure transducer (500 Pa) was surpassed within 15 min. The liquid pressure could become virtually equal to the total exerted pressure in that case (results not shown); in other words, the drainage effectively stopped.

The diameter of the drainage vessel appeared to be an important variable in relation to the threshold value. In the larger vessel employed (R = 0.10 m), the external pressure needed (≈ 1000 Pa) to accomplish a detectable liquid pressure was lower than that (≈ 1700 Pa) in the small vessel (R = 0.06 m) (see Figure 4.2).

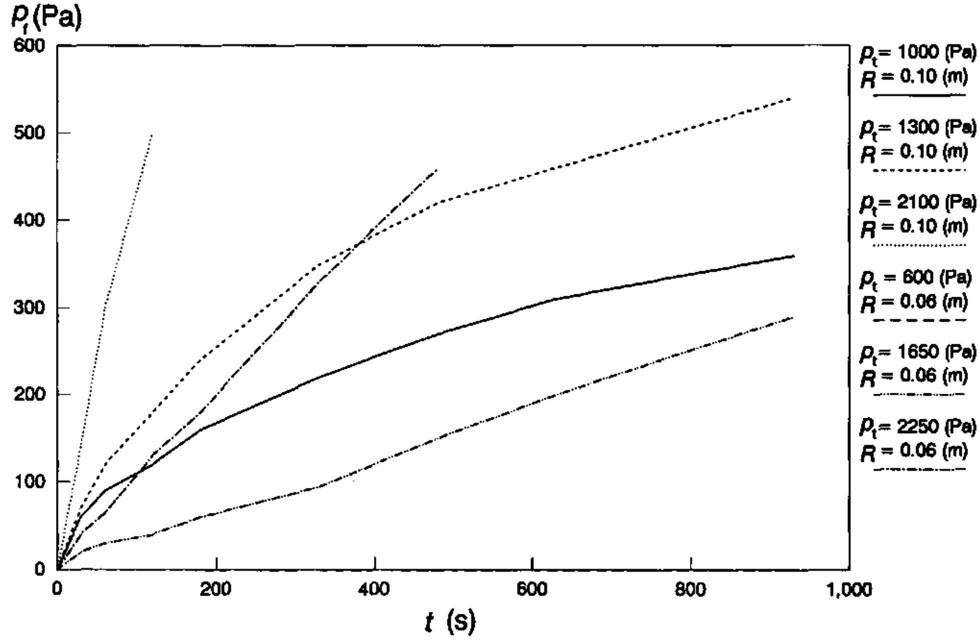


Fig. 4.2 The liquid pressure (p_l) in drainage vessels of two different radii (R) at various external pressures (p_t). Factory curd (t = 30 - 40 min) after drainage. h_0 = 0.11 m. It should be noted that in case of an external pressure of 600 Pa the line of the liquid pressure coincides with the X-axis.

The effect of the diameter of the drainage vessel upon the liquid pressure can be partly explained by Darcy's law (see equation 1.1). The flow rate in a cylindrical vessel decreases with increasing distance. An increase of the radius (R) will go along with a greater liquid pressure drop between the center and the outside of the vessel. Moreover, the ratio volume/outer surface area of a cylindrical vessel is equal to $2/R$, hence, the flow rate of whey through the outer layer of the curd bed per unit surface area has to increase with R to remove the same proportion of whey in the cylinder. The diameter of the vessel also influenced the loss of exerted mechanical pressure due to friction to the wall, the experimental setup of the pressure loss measurement is given in Section 2.5.4. The ratio of contact area between curd and the wall of the vessel over the volume of the curd in the cylinder is proportional to $1/R$; hence, the importance of wall friction in large vessels is relatively less (see Figure 4.3).

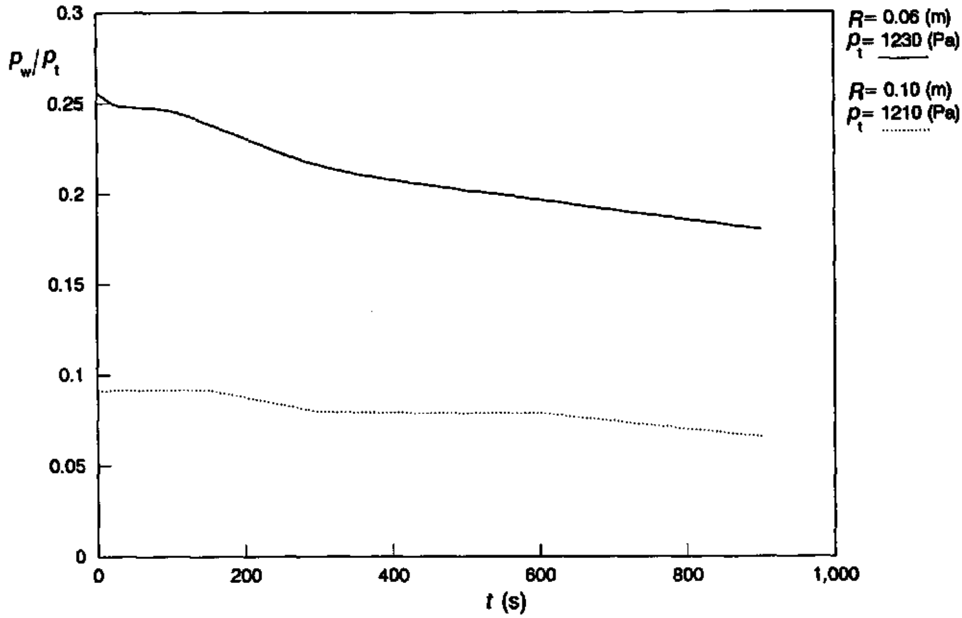


Fig. 4.3 The pressure loss at the wall (p_w), expressed as fraction of the exerted mechanical pressure (p_t), as a function of time in two drainage vessels of different radii. h_0 = 0.05 m, curd obtained from the 40 l curd maker.

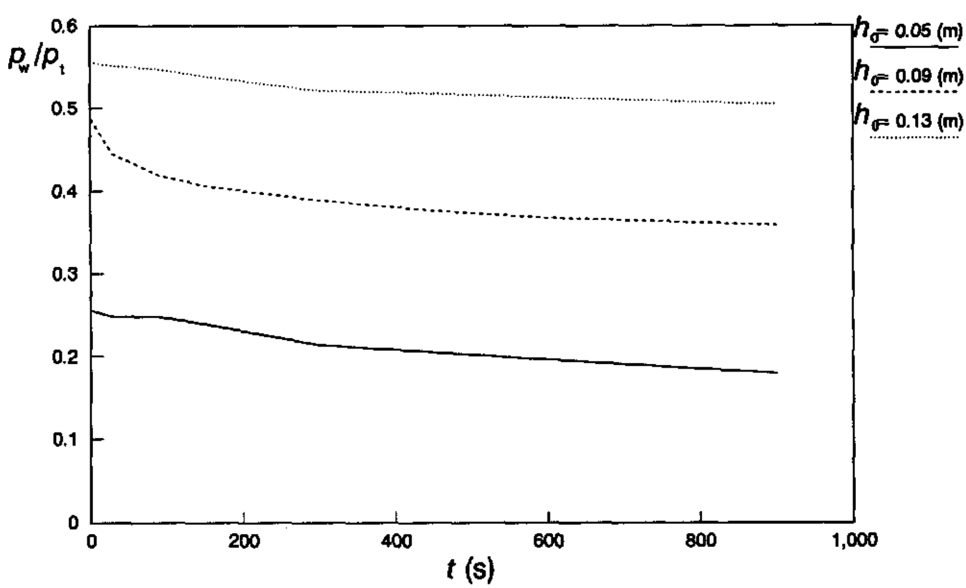


Fig. 4.4 The pressure loss at the wall (p_w), expressed as fraction of the exerted mechanical pressure (p_t), as a function of time, at various fill levels. p_t = 1035 Pa, R = 0.06 m, curd obtained from the 40 l curd maker.

The height of the curd column will determine the contact area between curd and wall. As expected, an increased filling level increased the friction to the wall (see Figure 4.4), hence, the pressure loss. As the height decreased in time, the pressure loss due to wall friction also diminished. An increased mechanical pressure resulted in a more than proportional pressure loss due to adherence to the wall (see Figure 4.5).

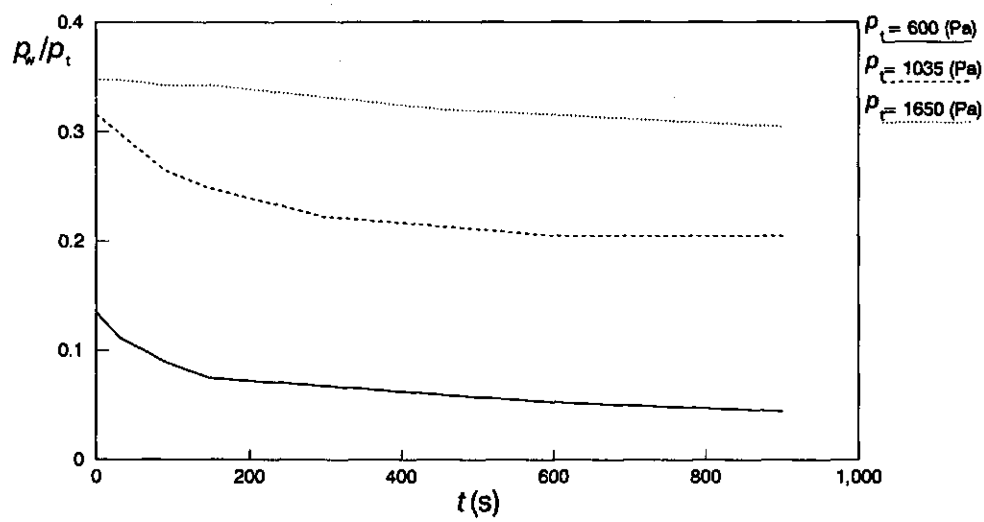


Fig. 4.5 The pressure loss (p_w), expressed as fraction of the exerted mechanical pressure (p_t), as function of time (t) at three exerted mechanical pressures. h_0 = 0.09 m, R = 0.06 m, curd obtained from the small scale curd maker.

Schwartzberg et al. (1985) reported that at increased compression speeds, which also implies higher stress levels, the pressure loss increased more than proportional. The various factors affecting wall friction could be reasonably fitted with equation (4.2):

$$p_w = \frac{k_1 \; h \; p_t^{2.5}}{R} \qquad (4.2)$$

where

p_w = overall pressure loss (Pa)

k_1 = constant ($Pa^{-1.5}$)

h = height as a function of time (m)

p_t = total exerted pressure (Pa)

R = radius of the column (m)

The factor k_1 = 6.10^{-6} $Pa^{-1.5}$ gave reasonable results in the test range of our experiments (R = 0.06 m or 0.10 m, h = 0.02 to 0.13 m and p_l = 600 to 1700 Pa). Equation (4.2) is not suitable for extrapolation beyond the limit of our experiments.

The vertical distance from the plane where the stress is applied has a tremendous influence upon the local stress upon the curd grains. This was illustrated in the following experiment: it was tried to measure the radial permeability of a curd bed, the setup is given in Section 2.5.2. It appeared that at high mechanical pressures the top layer of the curd became virtually impermeable, whereas a considerable whey flow still occurred in the lower layers. The latter made visible by adding Congo Red (Merck) to the percolating whey. Schwartzberg et al. (1985) had similar experiences for the compression of coffee grinds. In their experiments the coffee grinds were expressed in axial direction in a vertical transparent cell by an Instron machine. By placing movable, perforated cake section dividers, the relative compaction of various sections could be followed. It appeared that the top layers became the most compact ones, whereas the bottom sections were relatively less compacted. Although we could not quantify it, it must be assumed that the pressure loss near the wall of the vessel was larger than that in the center of the curd column. The liquid pressure will be highest in the center of the column. Moreover, in industrial drainage equipment the height of the curd column will determine the total pressure exerted, hence, the external pressure will depend on the location. In our experimental setup the height of the curd layers was so small that this effect could be neglected. The stress upon the curd grains will depend on its location, with respect to h as well as to r. The combined effects of increase in liquid pressure and pressure loss at the wall of the vessel with an increased external pressure may ultimately lead to a smaller stress upon the curd grains.

Applying the results above to practical cheesemaking in combination with equation 4.1, throws some light on current problems in cheesemaking. Jamming, i.e. a rapid decrease of permeability of the curd block, frequently occurs. The effect of the external pressure upon the liquid pressure can partly explain this: if the stress upon the curd grains is somehow higher than the threshold value, a sudden and rapid rise in liquid pressure occurs; hence, the permeability has become poor. In continuous drainage equipment, like the Casomatic, the outflow of whey is restricted, so a considerable part of the exerted stress is "carried" by the liquid. A decrease in the back pressure may therefore lead to jamming. The whey outlets in Casomatic drainage vessels have been equipped with valves, that close when a curd block is taken out of the column. Due to the sudden falling down of the curd column, the space between the wall of the vessel and the curd column is temporarily increased, and this could cause a tremendous increase of the flow of whey along the wall, if the valves were still open. The back pressure at the top outlet could become practically equal to the back pressure at the lower outlets, i.e. far smaller; in such a case, the stress exerted upon the curd grains increases dramatically, and this would cause jamming. It may also cause a rapid flow in which large particles are dragged along toward the filter grid covering the outlet. This may result in clogging of the grid. It has to be noted that some leakage along the wall of Casomatic pipes also occurs in normal operation (Heijnekamp personal communication). The important role of friction to the wall may explain that an Edam cheese drainage vessel that operates without back pressure, nevertheless works. Without considerable pressure loss at the wall, the stress upon the curd grains would become more than 10 kPa, because the height of the pipe is approximately 1 m. Such a stress is far too high to obtain satisfactory drainage, since it would cause jamming.

It was tried to block the friction to the stainless steel by coating it with chlorotrimethyl silane (Beckman Instruments) or teflon, but considerable friction remained. It must be noted, however, that teflon coated drainage systems are popular in the production of Edam cheeses, where the radius of the drainage pipe is only 0.08 m. It is known that the cheeses made in this equipment do not always have a smooth rind: sometimes the rind is ribbed. This has likely been caused by friction to the wall.

Besides the pressure loss, the wall also alters the orientations of the curd grains in its environment. The initial packing of the curd grains near the wall is distorted due to steric exclusion. We have some photographic evidence (Figure 3.12) that curd grains near the wall were not horizontally oriented after drainage, but were turned at an acute angle to the direction of the movement of the curd bed. In pressed cheese samples the curd grain patterns near the rind were also distorted (Rüegg & Moore 1987). An additional aspect of the friction to the wall is that the residence time of the curd grains in the drainage vessel may depend on their location. Emch et al. (1967) showed parabola-like profiles in cheese, made of layers of colored and uncolored curd, pressed one-sided in aluminum molds. It should be noted, however, that the mechanical pressures applied in his cheese presses were at least a hundred times those applied during drainage. "Residence time distribution" of curd grains in continuous drainage vessels is not really an appropriate term, as the process is not fully continuous (unloading occurs in discrete steps). To study the residence time we added an amount of dyed curd grains (annatto coloring at 30 times the normal dose added to curd grains and stirred for approximately 20 min) to the top of a Casomatic drainage pipe. The curd grains at the top became slightly mixed due to the influx of new curd/whey mixture: dyed curd grains were mixed over an amount of curd that was approximately 4 times the amount of dyed curd ($\approx$5 kg). The residence time of the curd grains was approximately 8 min. Every minute a curd block was unloaded. The height of the curd blocks cut off was about 0.2 m. The dyed curd grains showed an about parabolic profile in the curd block (Figure 4.6).

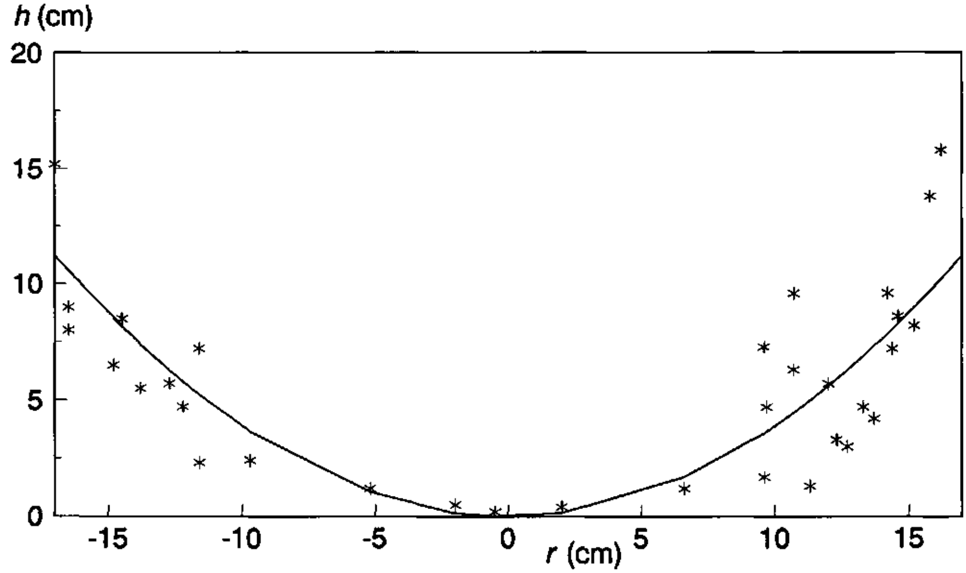


Fig. 4.6 The flow pattern of curd grains after drainage in a Casomatic drainage pipe.

At each time a curd block is removed from the pipe, plug flow occurs, but in between this may be different. If the flow of curd in the Casomatic is considered to be completely continuous, the Reynolds number can be estimated at about 10^{-5}, i.e. far in the laminar region. The velocity profile in case of laminar pipe flow is parabolic (Sakiadis 1984). Hence, onto the plug flow a laminar pipe flow is superimposed. The occurrence of a spread in residence time, in this case about 30 seconds, corresponding to half the height of block cut off, is relevant with respect to the production of cheese from successive batches of curd. The interval between drainage and pressing is varied in such way, that for the last curd of a batch the interval is shortest (see Section 1.5). If the curd block already contains some curd grains of the next batch (with a higher moisture content), it has a higher moisture content than expected.

A few dyed curd grains were found at the outside of subsequent blocks; apparently these curd grains got stuck at the grids near the whey outlets. Trailing curd grains may become problematic in case of switching from one type of cheese to another. Changing to other filter grids will probably put this right.

5. Processes inside the curd column

5.1 Compaction of curd columns

The compaction of a column of curd grains was tested in the apparatus described in Section 2.5.1. The results of the compression of single curd grains with the curd flattener led to the expectation that the compression of a column of curd grains will increase with the relative remaining volume of the curd grains. Fig. 5.1 shows a positive correlation between relative remaining volume and initial compression rate.

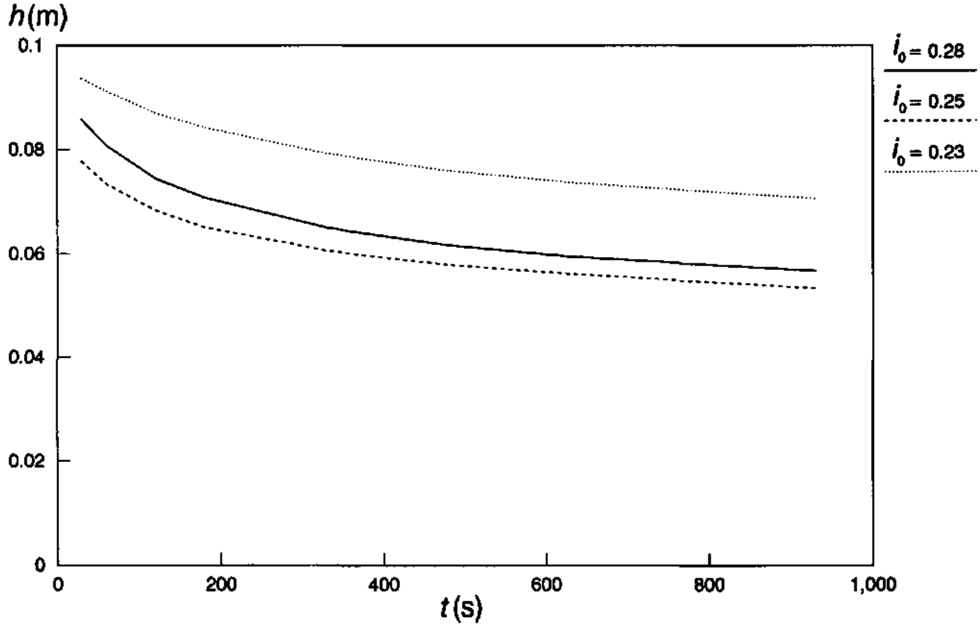


Fig. 5.1 The compression of a curd column filled with cube shaped curd grains of various remaining volume. p_t = 388 Pa, mesh = 8 mm, R = 0.06 m. Note that the initial height was not the same.

When the time after curd preparation in the case of factory curd was prolonged beyond normal (say, 30 min), the compressibility of the curd bed decreased. Effects within this period of time were not extensively studied. The slower compaction of the curd must be attributed to the pH drop, due to the lactic acid production by the starter bacteria. Zoon et al. (I 1989) reported a maximum in the storage modulus at about pH=6.15. In our case, the effect may have been more pronounced as syneresis is promoted by the lowering of the pH, which in turn, causes the moisture content of the curd grains to decrease in time.

The curd beds at 35 °C were compressible to a greater extent than those at 32 °C, which is remarkable as the initial packing is probably less dense at lower temperature, due to the firmer curd grains. The combined effect of a lower temperature and a prolonged time before drainage is shown in Fig 5.2.

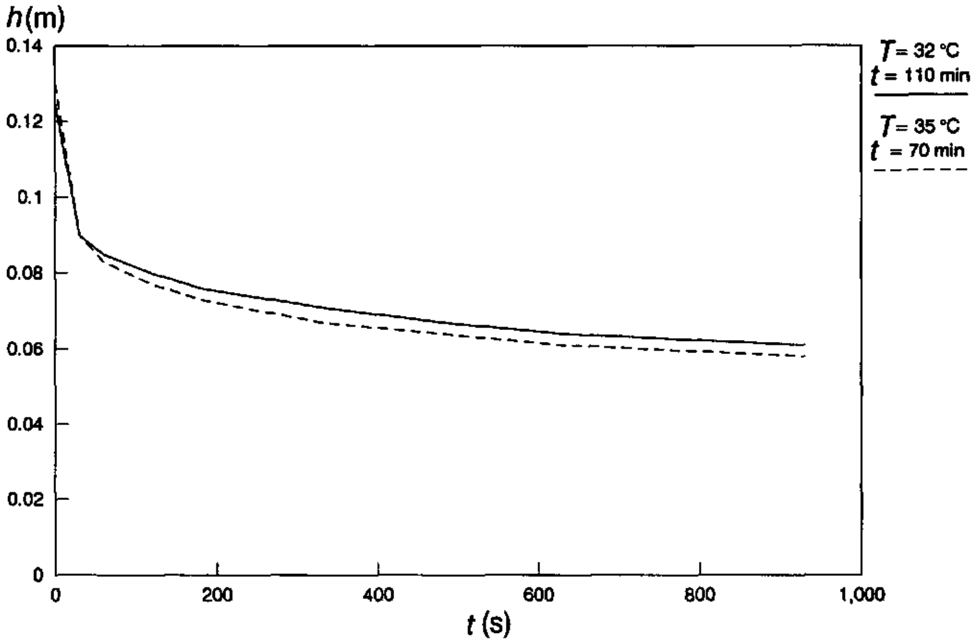


Fig. 5.2 The combined effects of a prolonged time after curd preparation and cooling upon the compaction of a curd column. The results shown pertain to the same batch of factory curd. R = 0.06 m, p_t = 1000 Pa.

Increasing the external pressure also increases the compression rate (Fig. 5.3). There is, however, a limit. Compaction is only possible when whey is expelled from the curd column, and this may be both enclosed whey and whey expelled from the curd grains. At a certain external pressure level, henceforth called the threshold level, the outflow of whey from the curd column becomes a limiting factor. The initial rapid compression, mainly due to the fast decrease of the porosity, is accompanied by a steep rise in liquid pressure, whereas at later stages the compression rate rapidly levels off and may virtually come to a standstill. An increased external pressure will therefore not automatically lead to a further expressed curd column (Fig. 5.4): it even may result in a less expressed curd column.

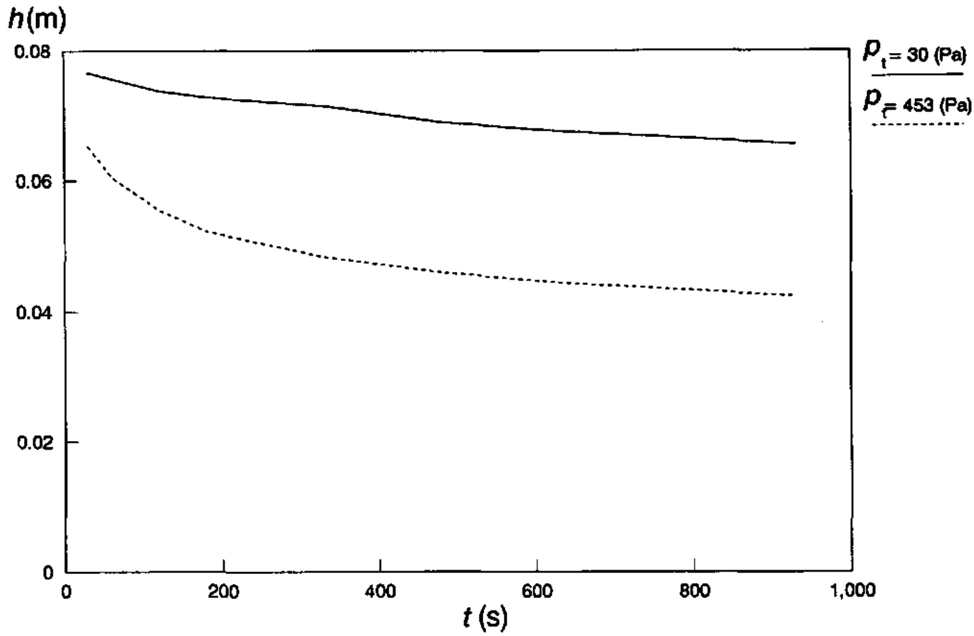


Fig. 5.3 The compression of curd beds at two levels of external pressure. R = 0.06 m, i_0 = 0.28, mesh = 8 mm

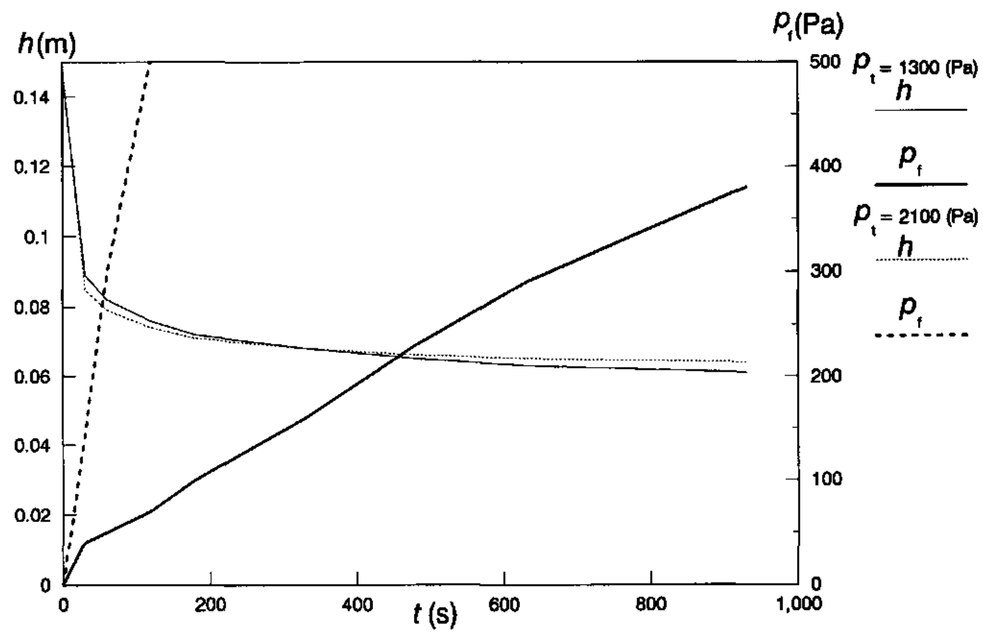


Fig. 5.4 The compression of curd grains and the liquid pressure drop in a curd column at two external pressure levels. Factory curd, R = 0.10 m, time after end of curd preparation 30-40 min.

The threshold level is primarily determined by the curd properties, but the relations strongly depend on the drainage vessel's properties. Radius of the column, contact area between the wall of the vessel and the curd, the stress upon the curd grains and the drainage time have an overriding effect and are mainly predetermined by the drainage system. The packing of the curd grains and the extent of fusion were not extensively studied, but are likely of importance. Firmer curd grains, which may result from a smaller relative remaining volume or a lower pH and/or temperature, yield a higher threshold level. A higher average relative remaining volume of the curd grains results in a higher liquid pressure (Fig. 5.5). It is caused by the greater whey expulsion from the higher moisture curd grains as well as by the greater deformability. Near this threshold value a simple correlation between compression rate and relative remaining volume can not be expected, since firmer curd grains cause on the one hand a higher threshold value, but on the other hand a slower initial rate of compaction.

The presence of curd fines may complicate the compression behaviour even more. It was observed that a small amount of crushed curd grains added to a column of cube shaped curd grains resulted in a slightly retarded compression rate as well as a significant liquid pressure, whereas without these fines the liquid pressure was below the detection level (results not shown). Presumably the interconnected pores between the curd grains become plugged by the migrating curd fines. In the literature the phenomenon is known as "blinding" (Novak et al. 1988). De Vries & Van Ginkel (1985) reported about 60 percent reduction of the curd fines in whey due to drainage. We did not study this phenomenon in detail, as it must be very intricate. Taking representative samples from a batch of curd is far from easy (Johnston et al. 1991). It is likely that not the amount of the curd fines will be the main factor, but rather their size relative to the pore sizes in the curd bed.

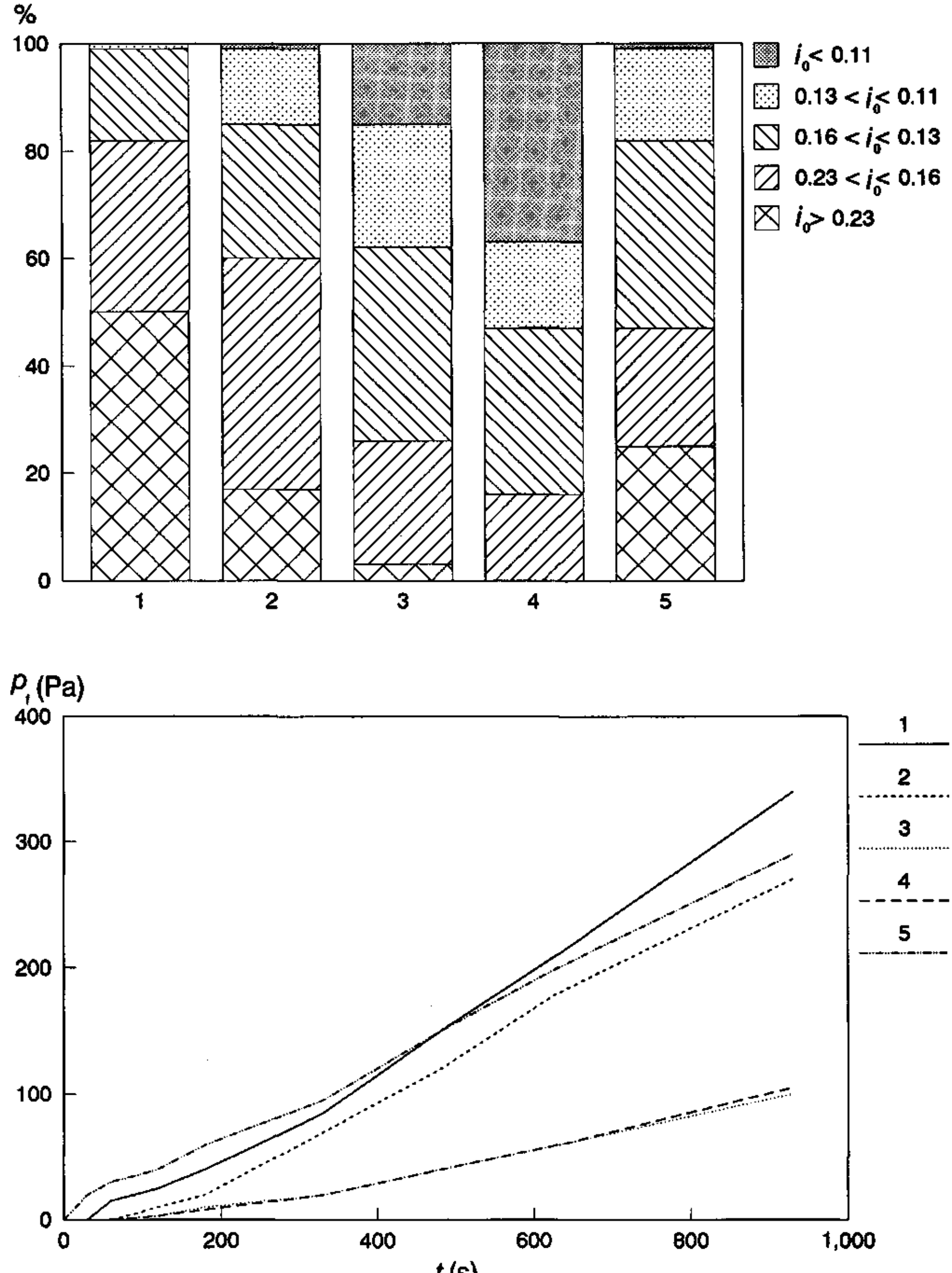


Fig. 5.5 (top) The density distribution - density being expressed as relative remaining volume (i_0) - of the curd grains from five factory batches.

(bottom) The liquid pressure in a column filled with curd grains of these batches at otherwise identical conditions. h_0 = 0.11 m, p_l = 1655 Pa, R = 0.06 m, time after end of curd preparation 20-40 min.

5.2 Porosity and apparent pore size distribution in curd columns

Visual inspection of cross-sections of curd blocks made in a Casomatic showed a wide variety with respect to the (apparent) pore size and shape. The largest pores were approximately 5 mm, and the shape varied from round to elongated, mainly in the horizontal plane, but weird shapes were found occasionally.

The porosity meter is described in Section 2.7. The standard deviation in the number and apparent size of the pores was rather large. The porosity showed a relative standard deviation of approximately 50%. This inaccuracy must be attributed to the dimensions of the system: the curd particles are not very small compared to the drainage column. Hence, only a few openings per measurement will be detected. To reduce the effects of this natural variation we conducted multiple measurements at concentric circles; to avoid ongoing compression, the weight at the top of the curd was removed. In the case of cube shaped curd grains each set of porosity measurements concerned a separate batch of curd grains, and the results shown are those of different batches.

Although it could not be measured at the start of the experiment, the porosity generally decreased in time. The loose packing of curd grains before compression was disturbed by the penetration of the sensor. Depending on the conditions (see Section 3.5) the initial porosity should be estimated between 0.2 and 0.5. A higher external pressure generally led to a faster decrease of the porosity. At external pressures below the threshold value, the porosity did not differ significantly between the "center" circle and the "rim" circle (see Fig. 5.6). At pressure levels above the threshold level, the porosity near the rind was lower than in the center (see Fig. 5.7) and the distribution of the openings in axial direction became very uneven. It should be noted that the porosity in the outer circle was measured at 1 cm from the rind and visual inspection indicated that nearer to the wall of the vessel the porosity was even lower. The large openings in the central part were also clearly visible. The decrease of porosity with time was caused by the decrease in (apparent) size as well as the decrease in number of the pores (see Fig. 5.8). With respect to the latter it should be noted that the probability of detection of small pores is less than that of larger pores. Eventual effects of the initial density of the curd grains upon the porosity of the curd bed were not significant. The applied variation in relative remaining volumes of the cube shaped curd grains was, however, relatively small compared to the differences between batches of factory made curd. The combination of dry matter content and

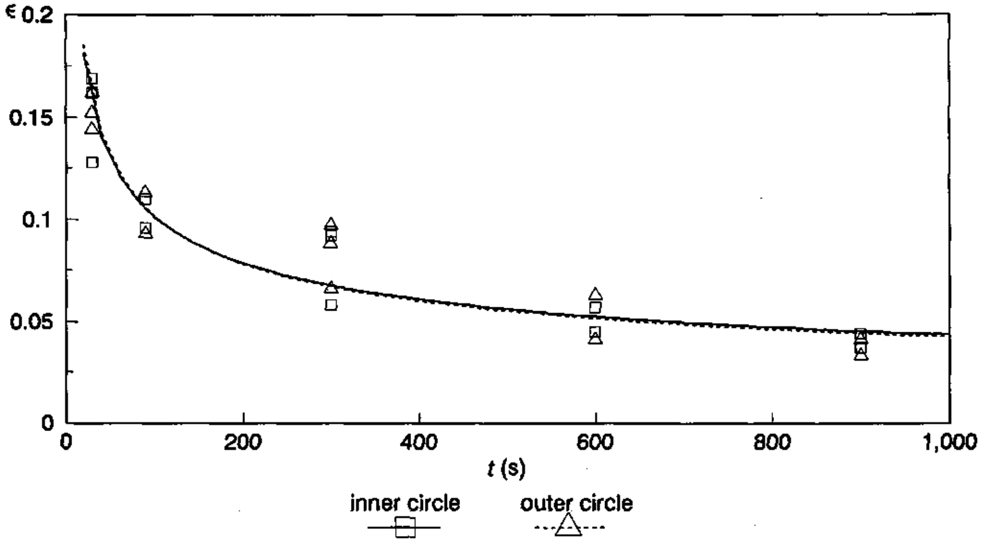


Fig. 5.6 The porosity (ε) near the wall of the vessel and in the central part of the curd column versus time at an external pressure below the threshold level. The variation in porosity between different batches caused the spread at identical points in time, the porosity at the outer and inner circle of one and the same batch was practically equal. R = 0.06 m, p_t = 530 Pa, l_0 = 0.23, mesh = 8 mm.

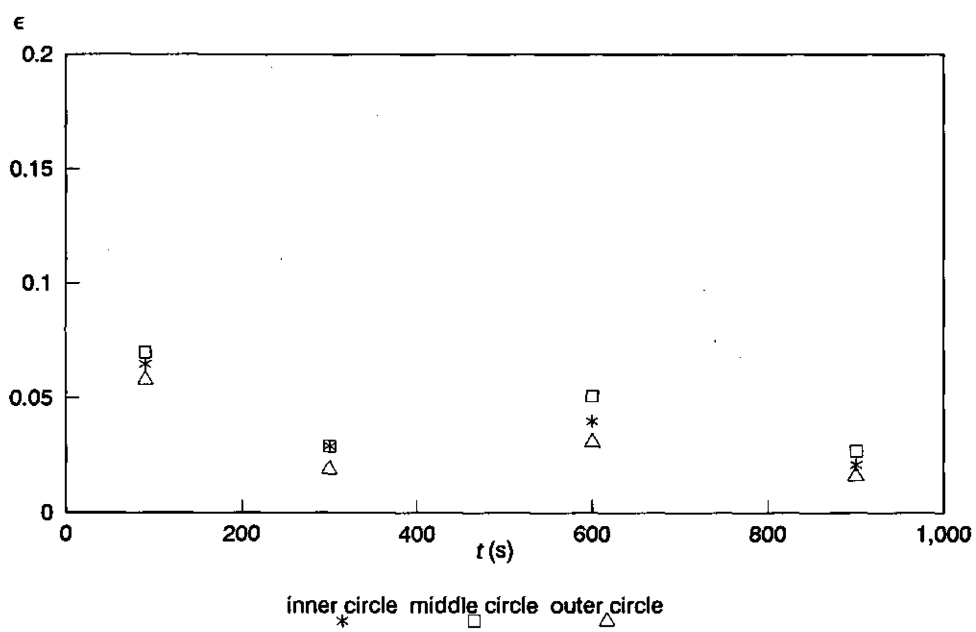


Fig. 5.7 The porosity of a curd column versus time at an external pressure level above the threshold level. The outer, middle and inner circle are located at r = 0.09 m, r = 0.05 m and r = 0.01 m, respectively. R = 0.10 m, p_t = 1670 Pa, i_0 = 0.26, mesh = 8 mm.

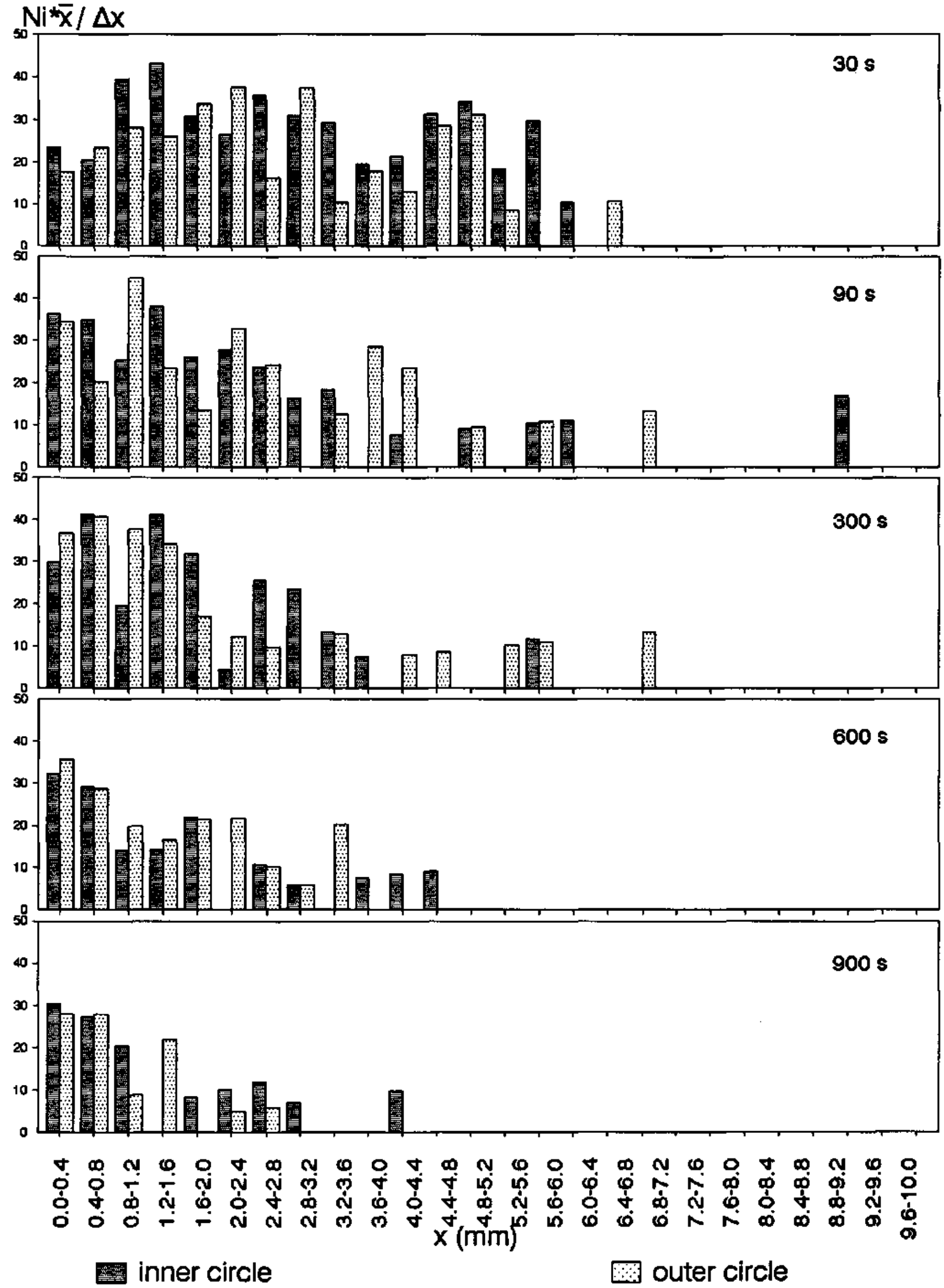


Fig. 5.8 The frequency distribution ($N_i\bar{x}/\Delta x$) of the apparent pore size (x) in a curd column at 5 points in time. R = 0.06 m, i_0 = 0.23, p_t = 530 Pa, mesh = 8 mm. ($N_i\bar{x}/\Delta x$) is, in first approximation, proportional to the pore volume.

porosity can be used to estimate the dry matter content of the curd grains (see Fig. 5.9).

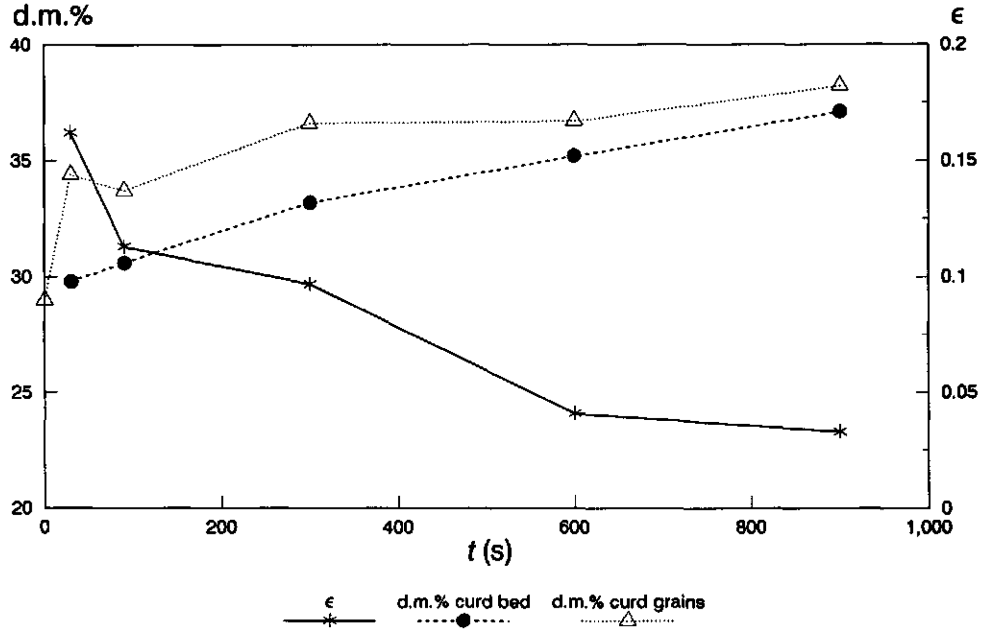


Fig. 5.9 The dry matter content of a curd bed, the calculated dry matter content of the curd grains and the average porosity of the curd bed versus time. R = 0.06 m, l_0 = 530, p_t = 530 Pa, mesh = 8 mm.

There are certain difficulties herein; the permeability of the briefly pressed curd blocks is very high and a certain whey loss when the curd block is taken out of the column can not be avoided. At later stages the whey loss is less. The dry matter content of the briefly pressed curd blocks is thus overestimated. The dry matter content of the whey in the pores in the curd block was estimated at 6%. The volume decrease of the curd block due to the decrease in porosity is clearly shown in Fig. 5.9. The dry matter content of the curd grains increased in time, and a small increase already represents a considerable volume loss of the curd grains. Thus the compaction of curd beds at these conditions depends both on decrease of porosity and on volume of the curd grains.

A series of experiments was conducted with curd taken from Tebel and Ost cheese vats at NIZO's experimental plant. The curd was not drained immediately, because the curd size distribution and the curd density distribution were determined first. The curd was drained 40 min after pumping the curd/whey mixture to the buffer tank, which is slightly later than normal. The density of the curd grains varied between batches, so measurements at different intervals had to be done on the same batch of curd. The same curd block was used, and 5 replicate measurements were taken at each time. The compaction of the curd column was stopped during the execution of replicate measurements, i.e., the mechanical pressure was temporarily suspended, to be restored directly afterwards. This procedure may have influenced the results somewhat. The small number of replicates led to a considerable spread in the results. Nevertheless, the porosity showed the same trends as in the case of cube shaped curd grains: above the threshold level of external pressure the porosity was lower near the rind than at the center, whereas the porosity at an external pressure below the threshold level was not significantly affected by the distance from the center. The density measurements revealed a wide spread from batch to batch. It was tried to link the density of the curd grains to the (change in) porosity of the curd block, but no clear correlation could be obtained. Differences in water content between curd blocks (R = 0.06 m) compressed at 1700 and 600 Pa could only be partly attributed to the higher porosity of the latter.

Finally it has to be remarked that due to the absence of any reference method, the results of the porosity meter could not be verified, but we feel justified to consider the trends to be correct.

In factory made curd blocks, about 25% of the weight after drainage is lost due to drip whey before brining. This whey must largely originate from the inside of the curd grains, as the porosity of the curd blocks after drainage is much smaller than 0.25. The remaining pores will be removed in the further process, but some defects, e.g. nests of holes near the rind (De Vries & Van Ginkel 1985) and the growth of molds just below the rind in cheese, must probably be attributed to incomplete removal of the last pores. That it happens mainly near the rind of the curd block is probably caused by the lower temperature in outer zone of the curd block (Geurts 1978), causing deformability and rate of fusion to be reduced.

5.3 Aspects of permeability

The permeability of the curd column could not directly be measured and a description of the failed approaches was given in Sections 4.1 and 4.2. It can be roughly estimated by using the Blake-Kozeny equation (equation 1.4) for curd beds with a porosity larger than 0.10. The permeability of a curd bed with a lower porosity can be calculated by taking the volume reduction of the curd column (Δh * A), the liquid pressure (p_t) and estimating the whey expulsion from the curd grains (equation 3.4). A description of the mathematics required to this approach is given in Appendix A. The permeability as a function of time can then be derived (Fig. 5.10).

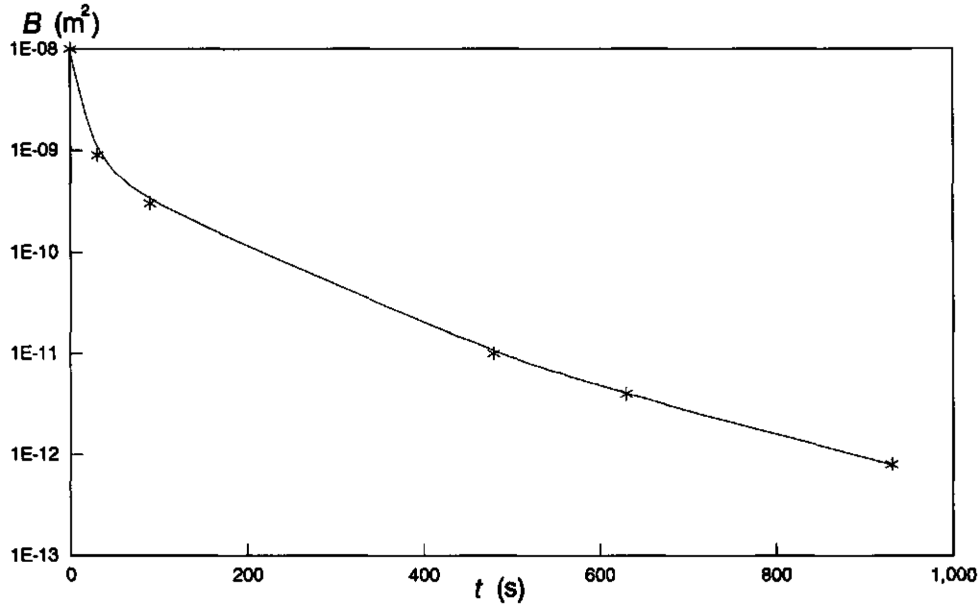


Fig. 5.10 The calculated permeability of a column filled with cube shaped curd grains as a function of time. p_t = 820 Pa, R = 0.06 m, mesh = 8 mm, i_0 = 0.25

It is seen that the permeability changes over several decades over the time interval. The very high permeability at the start of the drainage has consequences for the practical cheese making. In continuous drainage machines, e.g. the Casomatic, the first whey outlet is mounted relatively close to the top of the pipe. Although the flow of the whey at this outlet is restricted by a back pressure, the amount of whey flowing out of this outlet is large, because of the high permeability of the curd/whey mixture (leakage between the wall of the vessel and the curd may also contribute significantly). The curd grains may ultimately become uncovered, and therefore whey (usually first or second whey) is supplemented independently. In older drainage systems whey was recirculated hereto, but this causes microbial contamination.

Heijnekamp (personal communication) found at NIZO's experimental plant large deviations in moisture content in adjacent sectors taken from curd blocks after drainage in a Casomatic. Straatsma et al. (1984) gave results of the moisture content during cheesemaking. The variance within a cheese contributed for about 40% of the total variance in moisture content of the daily production. The spread in the number and (apparent) size of the openings in a curd bed will affect the spread in moisture content. To investigate the flow of whey through a curd block, colored whey was injected in a block of draining curd, the coloring became visible at the outside of the curd block at various places and at variable intervals of time. The latter observation points to variations in flow rate through the interconnected pores between the grains. The Hagen-Poiseuille equation is valid only for a straight capillary of uniform diameter:

$$\phi = -\frac{\pi R^4}{8 \eta} \frac{dp_f}{dx} \tag{5.1}$$

where

ϕ = flow rate (m^3/s)

R = radius (m)

η = dynamic viscosity of the liquid (Pa.s)

p_f = liquid pressure (Pa)

x = distance (m)

This equation cannot be used as such to predict the permeability of a curd column. It may, however, be useful to apply this formula to an infinitesimally small capillary inside the complicated network of channels. The smallest pore radius in a channel is the limiting factor for its total flow. Small differences in this limiting pore radius will according to the Hagen-Poiseuille equation, lead to rather large deviations in the flow rate. And the total flow will thus mainly be controlled by the channels with the largest minimum pore diameter, i.e. a small number. Poisson statistics may be appropriate to explain large variation in whey flow. Interconnected pores become more narrow and may eventually become disconnected. This process, caused both by reorientation of the curd grains and by deformation can be accelerated by the presence of curd fines that plug the pores. The whey flow from isolated pores is considerably retarded, because of the low permeability of the curd grains (say $B = 10^{-13}$ m^2, see Section 3.2) as compared to that of the pores between the curd grains in the drainage column. Straatsma et al. (1984) reported that a lower moisture content in the curd grains before drainage led to a smaller deviation in moisture content within the cheese. Experiments by Geurts (1978) also showed a reduced unevenness in moisture distribution in cheese made of curd grains stirred very dry. Curd grains containing more moisture have to expel more whey to attain the desired moisture content, the permeability of these curd beds should be higher hereto. However, the porosity of these curd beds at external pressures below the threshold level is lower or equal than that of beds of drier curd grains. The decrease in porosity will lead to considerable narrowing and/or sealing of most of the (initially) interconnected pores, causing (locally) a considerable decrease of the permeability. The local sealing will happen in the more moist curd bed before or at the same time that it would happen in a drier curd bed, hence, at a higher moisture content. The areas of a higher moisture content have to be compensated by relatively dry areas to obtain the desired average moisture content, hence, the standard deviation in moisture content will be considerably increased.

In theory, considerable sealing of pores may occur without a significant increase in the overall liquid pressure, as the overall liquid pressure is predominantly determined by the largest interconnected pores. Even in the case of a liquid pressure below the detection level, the existence of isolated pores can not be ruled out.

The moisture content of curd blocks of Casomatic drainage vessels is usually around 58-60% and estimating the porosity of those blocks to be a few per cent implies that the amount of the whey inside the curd grains is only slightly reduced in the vessel. Directly after drainage, the pressure exerted upon the lower layers in the curd block is dramatically increased, due to the sudden decrease in buoyancy. The average distance to the outside of the curd block decreases as result of the cutting of the curd column, whereas the permeability, especially of the central part of the curd block, is still considerable. Pressing a freshly cut curd block between two impermeable horizontal plates as illustrated in Fig 1.4 is, due to these plates, unlikely to be very effective with regard to whey expulsion. After molding, the outflow of whey really gets going, resulting in considerable whey loss during transport to the cheese presses; due to the unavoidable microbial contamination the spilled whey is practically worthless. Cutting the collected curd mass in blocks in a batch drainage systems also results in a rapid and considerable whey loss, but this whey is usually retained in the vessel.

Application of high stresses in an early stage of the drainage does not result in extensive whey expulsion, but causes jamming. This phenomenon is probably due to the following mechanism. A high external pressure leads initially to a rapid collapse of the curd grain packing, causing a substantial whey expulsion from the pores. The whey in the central part can only flow out through the outer layers of the curd column. Due to the rapidly decreasing permeability, the transport of whey from the center towards the rim becomes insufficient to keep up with the fast whey expulsion from the outer layer, leading to a further and more rapid narrowing of the pores in the outer layers. This, in turn, retards further whey transport towards the outer layer, causing a rapid sealing of the pores near the rind.

5.4 Computer modelling of the drainage system

It was tried to model the compression of a curd/whey mixture in a column and thereby predict the change in porosity. The input data were obtained from compaction of cube shaped curd grains in the small column R = 0.06 m (Section 2.5.1).

The total exerted pressure (p_t) can be broken down into three partial pressures:

$$p_t = p_m + p_l + p_w \tag{4.1}$$

The weight of the (submerged) curd grains is neglected hereby. At relatively low external pressure, the overall liquid pressure gradient between the center and the outside of the column was below the detection level, hence, virtually zero. The voids between the curd grains, which were assumed to be uniformly distributed over the curd bed, do not carry a significant part of the pressure. The external pressure, in fact force per m^2, is carried by a smaller cross-sectional area of curd grains, hence the stress upon the curd grains can be (locally) higher than the overall pressure. The average local stress (p_m') upon the curd grains is equal to:

$$p_m' = \frac{p_t - p_l - p_w}{(1-\varepsilon)} \tag{5.2}$$

where

p_m' = average local stress upon the curd grain (Pa)

p_t = total exerted pressure (Pa)

p_l = liquid pressure (Pa)

p_w = pressure loss due to friction (Pa)

ε = porosity (-)

The total pressure loss (p_w) at the wall can be described with equation (4.2):

$$p_w = \frac{k_1\, h\, p_t^{2.5}}{R} \qquad (4.2)$$

In fact the pressure loss depends on the vertical distance from the plane where the external pressure is applied (Section 4.2), but here the pressure loss was assumed to be constant throughout the curd column. The total pressure loss was divided by two to obtain an average. The volume of the curd column is composed of the volume of the pores and the volume of the curd grains. If the volume of the curd grains can be predicted and the volume (in fact, height) of the curd column is measured, the porosity can be calculated. The initial porosity was estimated and initial volume of curd grains ($V_g(0)$) can then be calculated. It was tried to predict the decrease of the volume of curd grains by equation (3.4), which was originally derived to describe the expression of a single curd grain:

$$\frac{i_t - i_\infty}{i_0 - i_\infty} = \exp(-\,k\, p_m \sqrt{t}\,) \qquad (3.4)$$

The calculation scheme is given in Figure 5.11.

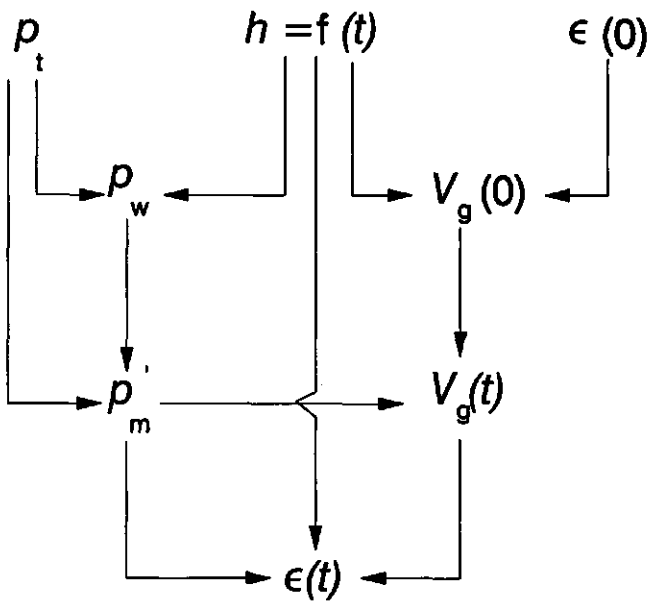


Fig. 5.11 The scheme to calculate the porosity (ε) from measurement of the height of a curd column (h) and the volume of the curd grains (V_g). The volume of curd grains is calculated by means of the equation for the compression of a single cube shaped curd grain (equation 3.4).

At external pressures below 400 Pa, the porosity decreased monotonically. The predicted porosity depends to a large extent on the unknown initial porosity, but taking reasonable values for the latter the calculated porosity as a function of time appeared realistic, although we had no porosity measurements at such a low external pressure. This implies that the behaviour of a single curd grain is probably a reasonable model for the expression of a column of these curd grains in this case. At external pressures above 400 Pa, the calculated porosity increased after an initial decrease. This happened at an earlier stage for the higher external pressures. A significant increase of porosity is unrealistic and must be attributed to an overestimated volume decrease of the curd grains. At high external pressure levels (say, greater than 1000 Pa) the liquid pressure soon plays an important role and in the relatively simple model this factor is not taken into account; it leads to an overestimated stress upon the curd and thus to an overestimated decrease of the volume of the curd grains. The increase in porosity at external pressures in the range 400 - 1000 Pa, as followed from the calculations, was contrary to our expectation. In reality, the expression of curd grains in a column may well be less than is the case for a single curd grain; this may be due to the limited deformation possibilities in the curd column and/or the locally retarded flow of whey (although an overall liquid pressure between the center and the outside was not found). The increase in cross-sectional area in the case of a single curd grain is not identical to that of these grains in a batch, which implies that the stress upon the curd grains (p_m) in a column may decrease faster than is implicitly assumed in equation (3.4).

It should be realized that the situation in a curd column is far more complicated than assumed in most filtration models, e.g. (modified) Terzaghi models (Leclerc and Rebouillat (1985). In our case, the particles are deformable (visco-elastic), they can be expressed and they partially fuse with each other. Nevertheless, our model seems to work fairly well, up to pressure of about 400 Pa, and maybe higher pressures if the curd grains are more rigid. That the model does not work for pressures above the threshold level is only to be expected. In the intermediate pressure range, some elaboration of the model could be tried.

6. General discussion and conclusions

Various types of drainage vessels exist and even for identical drainage systems the mode of operation varies among plants, whereby the way of curd preparation and/or the shaping/pressing of the curd blocks may be tuned to the particular drainage system in use. Apparently there are several different ways to achieve the two aims of the drainage: separation of the curd grains from the whey and the formation of a coherent block of curd.

Nevertheless, the ideal drainage process has not been developed yet. It should yield identical curd blocks with a moisture content of about 47% (in the case of 12 kg Gouda cheese), for which pressing is only needed to obtain a well-closed rind.

The study of the drainage of curd is complicated by the many, often mutually dependent parameters that determine the process. The properties of the curd grains play an important role, and to eliminate variations in drainage behaviour due to variation in the curd grains a standardized curd preparation was developed for this study. The new curd preparation process resulted in practically uniform curd grains that could easily be characterized by their density. Besides the uniformity, other major differences between the model curd grains and those prepared in factories were: the presence of cracks in the outer layer of the curd grains before stress application and the absence of starter culture. The density of the curd grains can be recalculated to the relative remaining volume (i_0) and/or whey content of the curd grains. Besides this property, there could be other (minor) factors that had some influence upon the drainage behaviour of this model curd grains. The same characterization was applied to curd grains that were produced in NIZO's pilot plant; again, the density (distribution) appeared to be an important variable. But there are parameters that may become important too, such as pH and temperature. These were (mostly) not varied in the case of model curd grains. The size distribution of the curd grains is usually monitored in cheese plants, but in experiments with model curd grains of two different sizes its importance for the drainage process seemed to be minor. On the other hand, adding a small amount of curd fines to the model curd grains did cause appreciably slower drainage. Further research on the role of curd fines in the drainage process will be useful.

The drainage system affects the drainage process in various ways. Obvious characteristics of the drainage vessels are: drainage time and temperature, manner of whey discharge, and duration and magnitude of the exerted pressure upon the curd grains. But there are also less known parameters that play an important role in the drainage process. Leakage of whey between the wall of the vessel and the curd mass can become a major factor. Friction at the wall can limit the stress exerted upon the curd grains to only a small fraction of the total exerted stress. These two processes may dominate the drainage if it is performed in relatively small vessels. The wall of the vessel alters the orientation of the curd grains close to it.

Inside the drainage system various processes take place, and it was tried to study them separately. The deformation of and whey expulsion from a single cube shaped curd grain under stress were closely correlated with each other. An interesting result was that such a curd grain could be expressed to a very low whey content within a reasonable time. Important variables like drainage time, applied pressure and initial whey content were the (major) parameters determining the extent of expression. The rheological properties of the paracaseinate strands become soon the determining factor for the rate of expression. The outer layer of a factory made curd grain is initially very dense and no cracks were observed. On the other hand, application of a small stress (say 100 Pa) upon the curd grain led to immediate formation of numerous small cracks in the outer layer; consequently, it may be expected that the behaviour at expression of a cube shaped curd grain still is an adequate model for factory curd. The expression of a single curd grain was compared to the expression of a column of curd grains, but there are two fundamental differences: in a column the flow of whey from between the curd grains can be restricted and the deformation of curd grains can be limited due to geometrical constraints. A simple computer model indicated that at low external pressure the expression of a single cube shaped curd grain could be used as a model for the expression of a column of these curd grains. At pressures above this level the model indicated that the expression of curd grains was retarded, although a liquid pressure between the center and the outside of the curd column could not always be found. It should be realized, however, that despite the formation of many isolated pores, some interconnected pores may still remain, and the liquid pressure is predominantly determined by the latter and may be still be below the detection limits.

Application of pressure upon the loosely packed curd grains leads to their reorientation, and this causes a rapid decrease of size and number of the openings between them. At the contact areas between curd grains junctions, i.e. ensembles of bonds between two adjacent curd grains, are formed. These junctions may limit the extent of reorientation. It was tried to study the fracture stress of the junctions in well defined conditions. At a constant macroscopic fusion area the fusion time, the exerted pressure, temperature and probably the reactivity and stiffness of the outer layer of the curd grains were among the dominating factors. The contact area between curd grains in a curd column is difficult to determine, but it will certainly increase in time. The extent of fracturing of the junctions depends on their strength, the exerted pressure and the geometrical possibilities. The porosity, i.e. the volume of the whey filled pores as a fraction of the total volume of the curd bed, decreases in time due to the reorientation and deformation of the curd grains. Reorientation probably causes a faster decrease. The compression of a curd column is directly linked to flow of whey leaving the drainage vessel. The flow occurs predominantly through the interconnected pores, whereby the largest pores contribute most. A decreased porosity will generally lead to a decreased permeability. The permeability can become so small that a liquid pressure between the center and the outside of the curd column can be measured, the value of the exerted pressure at which this occurs is called threshold level. It is primarily determined by the curd properties, but the relations strongly depend on the properties of the drainage vessel. Pressures above the threshold level usually cause a lower porosity near the outflow surface and an increased inhomogeneity of pore distribution throughout the curd column. Unfortunately, the threshold level is rather low in practical cheesemaking.

In the current equipment the removal of whey is hampered by the fact that a large amount of the whey remains inside the curd grains. The stress exerted upon the curd grains inside the curd column is insufficient to drive out all whey. The major question is therefore: how can this stress upon the curd grains be increased without narrowing the pores between the curd grains to such an extent that the permeability of the curd block becomes a limiting factor in drainage. A solution could be creating very thin curd layers that can drain at all sides and experiments indicate that relatively low water contents (approximately 53 %) can indeed be obtained in a short period of time (15 minutes), but from the perspective of current cheesemaking, especially for hard and semi-hard cheese types, curd blocks should be large.

In the upper layer in a continuous drainage pipe, e.g. Casomatic, a loose packing of curd grains can be found. This packing of curd is so permeable that when whey is discharged the curd grains at the top of the curd column can become uncovered. The amount of removed whey can be adapted by changing the back-pressure or the drainage time, which is relevant because steady states are not reached. Ideally so much whey should be removed that the occurrence of a sizeable liquid pressure can just be avoided. This is difficult to achieve in liquid pressure controlled drainage vessels, as the amount of removed whey can be controlled only indirectly. Direct control of the actual whey removal rate, possibly combined with a well-controlled curd/whey mixture input, may be a better option. This can only be part of the solution as a large amount of whey inside the curd grains still remains. A high pressure is necessary to accomplish considerable whey expulsion of the curd grains within an acceptable period of time. The resulting reorientation of the curd grains can be limited when strong junctions between the curd grains have been formed. It may therefore be taken into consideration to create conditions that promote fusion. Drier curd blocks are less deformable and satisfactory rind formation may need then special attention, but the reward: a considerable reduction of the amount of drip whey, may be worthwhile further efforts.

Appendix A: Calculation of the permeability of a radial drainage column

The permeability of a column of curd grains is calculated for an idealized system of uniform particles. The Blake-Kozeny equation is used to calculate the permeability in the region porosity larger than 0.10:

$$B = \frac{d_p^2 \, \varepsilon^3}{150 \, (1 - \varepsilon)^2} \tag{1.4}$$

The diameter of the curd grains d_p was estimated at 6.10^{-3} m, and results of various porosity measurements were used. The initial porosity (ε) is estimated at 0.3. At a porosity smaller than 0.1, the Blake-Kozeny equation was not applied. Porosity data for this region were calculated from the experimental results, obtained from expression tests with the arrangement described in 2.5.1. The following assumptions were made. The flow of whey is completely determined by the flow between the curd grains. The porosity and permeability are uniform throughout the column. Wall friction and the apparent weight of the curd grains are not taken into account, therefore the exerted pressure is constant throughout the curd column. The main consequence of these assumptions is that we introduce an overall value for the permeability of the whole column, that may be considered as a practical calculation quantity.

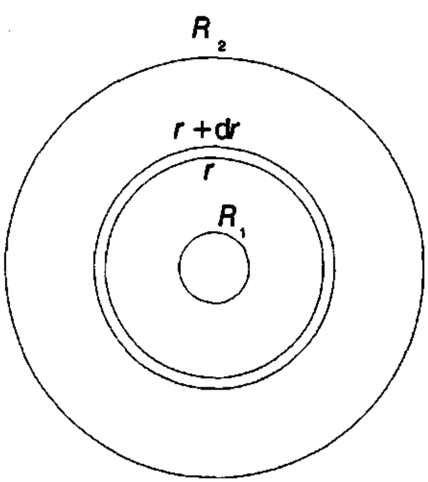


Fig. A.1 A schematic drawing of a horizontal cross-section through the curd column showing the cylindrical coordinate system. R_1 is the radius of the glass filter, R_2 is the radius of the curd column.

The flow rate of whey at r (see Fig. A.1) can be calculated by Darcy's equation:

$$\phi = -2\,\pi\,r\,h\,\frac{B}{\eta}\,\frac{\mathrm{d}p_l}{\mathrm{d}r} \qquad (1.1)$$

At $r + \mathrm{d}r$ the flow rate is equal to:

$$\phi + \mathrm{d}\phi = -2\,\pi\,r\,h\,\frac{B}{\eta}\,\frac{\mathrm{d}p_l}{\mathrm{d}r} - 2\,\pi\,h\,\frac{B}{\eta}\,\frac{\mathrm{d}}{\mathrm{d}r}(r\,\frac{\mathrm{d}p_l}{\mathrm{d}r})\mathrm{d}r \qquad (\mathrm{A}.1)$$

The net flow of whey results from both compaction of the column and whey expulsion from the curd grains. The net change in "free" whey volume per unit of time at r can be described as:

$$\mathrm{d}Z = \frac{\mathrm{d}}{\mathrm{d}t}(2\,\pi\,r\,h\,\varepsilon)\,\mathrm{d}r \qquad (\mathrm{A}.2)$$

where

Z = net free whey volume change (m^3/s)

ε = porosity (-)

r = radial variable (m)

h = height (m)

t = time (s)

The whey expulsion rate from the curd grains is a function of the exerted stress, initial moisture content and time:

$$\frac{i_t - i_\infty}{i_0 - i_\infty} = \exp(-\,k\,p_m\,\sqrt{t}\,) \qquad (3.4)$$

The resulting function is complicated and therefore less suitable for further handling. To avoid this difficulty the amount of expelled whey was calculated at times 30, 90, 150, 300, 450, 600 and 900 s from (equation 3.4). The whey expulsion rate within each of these intervals was assumed to be constant. Furthermore the whey expulsion was linked directly to the stress upon the curd grains. So the following function is obtained:

$$Q = k_q\,p_m \qquad (\mathrm{A}.3)$$

where

Q = volume of whey expelled per volume of curd grains per unit of time (m^3/m^3s)

k_q = time dependent constant (Pa^{-1}.s^{-1})

A volume balance results in:

$$\phi + d\phi - \phi = -\frac{d}{dt}(\varepsilon\ 2\ \pi\ r\ h)dr + 2\ \pi\ r\ h\ dr\ Q \qquad (A.4)$$

or, accounting for (1.1) and (A.1):

$$\frac{B}{\eta}\frac{1}{r}\frac{d}{dr}(r\frac{dp_l}{dr}) = -Q + \frac{d\varepsilon}{dt} \qquad (A.5)$$

The total exerted mechanical pressure is equal, in case of negligible wall friction, to the sum of the liquid pressure and the stress upon the curd grain:

$$p_t = p_m + p_l \qquad (4.1)$$

Equation (4.1) can be used to link the whey expulsion rate (equation A.3) and the liquid pressure. Equation (A.5) then turns to:

$$\frac{B}{\eta}\frac{1}{r}\frac{d}{dr}(r\frac{dp_l}{dr}) = -k_q\ p_t + k_q\ p_l + \frac{d\varepsilon}{dt} \qquad (A.6)$$

With boundary conditions:

$$r = R_1 \rightarrow p_l = p_1 \qquad (A.7)$$

and

$$r = R_2 \rightarrow p_l = 0 \qquad (A.8)$$

As reference liquid pressure the liquid pressure at the outer surface is taken. To solve equation (A.6) a new dependent variable Π is introduced:

$$\Pi = k_q\ (p_l - p_t + \frac{1}{k_q}\frac{d\varepsilon}{dt}) \qquad (A.9)$$

Where p_t and $d\varepsilon/dt$ are assumed to be independent of r (see forgoing considerations). Equation (A.6) then changes into:

$$\frac{1}{r}\frac{d}{dr}\left(r\frac{d\Pi}{dr}\right) - \frac{\eta\, k_q}{B}\,\Pi = 0 \tag{A.10}$$

The boundary conditions (A.7) and (A.8) now become:

$$r = R_1 \;\rightarrow\; \Pi_1 = k_q\left(p_1 - p_1 + \frac{1}{k_q}\frac{d\varepsilon}{dt}\right) \tag{A.11}$$

$$r = R_2 \;\rightarrow\; \Pi_2 = k_q\left(-p_1 + \frac{1}{k_q}\frac{d\varepsilon}{dt}\right) \tag{A.12}$$

The numerical value p_1 is obtained from experimental data on the liquid pressure at the center, R_1 = 0.01 m, and the wall of the vessel, R_2 = 0.06 m. Furthermore we introduce:

$$r = \xi\sqrt{\frac{B}{\eta\, k_q}} \tag{A.13}$$

Introduction in equation (A.10) yields:

$$\frac{d^2\Pi}{d\xi^2} + \frac{1}{\xi}\frac{d\Pi}{d\xi} - \Pi = 0 \tag{A.14}$$

The boundary conditions turn into:

$$\xi_1 = R_1\sqrt{\frac{\eta\, k_q}{B}} \;\rightarrow\; \Pi = \Pi_1 \tag{A.15}$$

$$\xi_2 = R_2\sqrt{\frac{\eta\, k_q}{B}} \;\rightarrow\; \Pi = \Pi_2 \tag{A.16}$$

Equation (A.14) represents the modified zero order differential equation of Bessel. It has two solutions, namely $I_0(\xi)$ and $K_0(\xi)$. The general solution is:

$$\Pi = \alpha\, I_0(\xi) + \beta\, K_0(\xi) \tag{A.17}$$

The boundary conditions yield the coefficients α and β:

$$\alpha\ I_0(\xi_1) + \beta\ K_0(\xi_1) = \Pi_1 \tag{A.18}$$

$$\alpha\ I_0(\xi_2) + \beta\ K_0(\xi_2) = \Pi_2 \tag{A.19}$$

From (A.18) and (A.19) the coefficients α and ß have to be solved with reference to (A.11), (A.12), (A.15) and (A.16). To this end we need a numerical value for $d\varepsilon/dt$ for the time interval concerned. The unknown permeability (B) is maintained as such in our solution for the sake of the iteration procedure. To evaluate the mathematical solution the derivatives of the Bessel functions must be obtained:

$$I_0'(z) = I_1(z) \tag{A.20}$$

and

$$K_0'(z) = -K_1(z) \tag{A.21}$$

The values of $I_0(z)$,$K_0(z)$,$I_1(z)$ and $K_1(z)$ were taken from Olver (1965) and partly calculated using IMSL routines. Introducing the solution (A.17) in (A.9) we obtain p_f as function of r for the time interval concerned. Substitution of this p_f in equation (1.1) yields a relation between ϕ and B. Since the flow rate and liquid pressure are experimentally determined, the permeability can be calculated. The remaining equation contains B implicitly in the factor $d\Pi/d\xi$:

$$B = \left(\frac{\phi}{2\ \pi\ R_2\ h\ \dfrac{d\Pi}{d\xi}}\right)^2 \eta\ k_q \tag{A.22}$$

It was solved iteratively. The dynamic viscosity was estimated at 10^{-3} Pa.s, R_2 = 0.06 m, ϕ, p_f and h were obtained from the results of the compaction of a curd column. It has to be noted that the factor k_q is probably slightly overestimated (see Section 5.4). Moreover the term $d\varepsilon/dt$ was not exactly known for the circumstances given, therefore it was assumed to be zero.

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List of symbols

A	area	m^2
B	permeability	m^2
C	concentration	kg/m^3
C_s	surface concentration	kg/m^3
C_0	initial uniform concentration	kg/m^3
C_w	drag coefficient	-
d_p	diameter of particle	m
e	void ratio	-
e^*	final void ratio	-
g	acceleration due to gravity	m/s^2
h	height	m
h_0	height at $t = 0$	m
h_t	height at $t = t$	m
i	relative remaining volume of curd	-
i_0	initial relative remaining volume of curd	-
i_0	initial relative remaining volume of curd at infinity	-
i_t	relative remaining volume at $t = t$	-
k	constant	$Pa^{-1} \cdot s^{-1/2}$
k_e	first order rate constant	s^{-1}
k_1	constant	$Pa^{-1.5}$
k_q	time-dependent constant	$Pa^{-1}.s^{-1}$
k_Ω	first order rate constant	s^{-1}
M_t	mass of a curd grain at $t=t$	kg
M_0	mass of a curd grain at $t=0$	kg
M_∞	mass of a curd grain at $t=\infty$	kg
p_f	pressure on the liquid	Pa
p_m	stress upon the curd grains	Pa
p_m'	average local stress upon the curd grains	Pa
p_t	external pressure	Pa
p_w	pressure loss due to wall friction/adhesion	Pa
Q	relative whey expulsion rate of the curd grains	s^{-1}
r	radial variable	m

R	radius	m
t	time	s
$<v>$	superficial velocity	m/s
v	stationary sedimentation velocity	m/s
V	volume	m^3
V_g	volume of the curd grain	m^3
x	distance	m
z	experimentally determined rate constant	s^{-1}
Z	net "free" whey volume change	m^3/s
α	volume fraction of paracaseinate	-
α_0	volume fraction of paracaseinate in milk	-
α_t	volume fraction of paracaseinate in a curd grain	-
β	volume fraction of fat	-
γ	volume fraction of whey	-
ε	porosity	-
ε_h	Hencky strain	-
Θ	volume ratio fat/paracaseinate	-
η	dynamic viscosity	Pa.s
μ	pseudo Poisson's ratio	-
ρ_f	density of fat	kg/m^3
ρ_g	density of curd grain	kg/m^3
ρ_l	density of liquid	kg/m^3
ρ_m	density of paracaseinate matrix	kg/m^3
ρ_w	density of diluted whey	kg/m^3
Φ	flow rate	m^3/s
Ω	volume of whey in the curd per unit volume of dry matter	-
Ω^*	final volume of whey in the curd per unit volume of dry matter	-

Summary

Cheese making starts with transformation of the liquid milk into a gel by proteolytic enzymes and/or acid producing bacteria. The gel is cut into pieces. The protein matrix contracts, by which whey is expelled from the pieces, this process is called syneresis. The process of whey expulsion is enhanced by stirring and usually heating. Finally fairly rigid curd grains and a large amount of whey are obtained. The subsequent separation of whey and curd grains is called drainage of curd. For most types of cheese, the obtained curd mass is subsequently pressed, salted and ripened. This study is mainly aimed at the drainage in case of Gouda cheese, but some aspects may be applicable to other cheese types as well.

Drainage of curd not only separates (most of) the whey from the curd grains, but it also leads to the formation of a coherent mass. The drainage is not an isolated process, but its outcome depends heavily on the preceding curd preparation and the subsequent shaping and pressing. The study of the drainage process therefore requires a well-controlled curd preparation. In our conditions large-scale curd production was often not possible, but scaling down of the curd making process led to curd grains that had only little resemblance to those produced on factory scale. A new way of curd preparation was therefore developed. It enabled the production of almost identical cube shaped curd grains. The basic features of the new apparatus were: the gel was cut in cubes by two wire grids, and the cubes were stirred by subsequently pumping an amount of whey and large air bubbles through holes in the bottom of the cheese vat. The delicate curd pieces were hardly broken up by the resulting gentle stirring. As the used air is toxic to starter bacteria curd was prepared without starter.

The curd grains were characterized by measuring their density in thermostatted sodium chloride solutions of various concentrations. The density can be recalculated to a moisture content or relative remaining volume, i.e. the volume of curd grains as a fraction of its volume before syneresis. The density measurement could, in the case of uniform curd grains, replace the various empirical methods currently applied to determine the moment to begin with drainage. However, in case of factory made curd other factors may also be of importance, e.g. pH, temperature and the amount of curd fines.

The uniform curd grains were used to study the expression and deformation of a single curd grain in a uni-axial compression setup. The compression led to an instantaneous (elastic) and a slower viscous compression of the curd grain. Release

of the stress within a few seconds after the start of the compression led to a clearly visible recovery; this was not the case after 15 minutes of compression. The elastic and viscous compression increased with the exerted stress (p_m) and initial relative remaining volume of the curd grain (i_0). The extent of compression increased with time (t). The relative remaining volume at time t of a single curd grain (i_t) could be expressed as:

$$\frac{i_t - i_\infty}{i_0 - i_\infty} = \exp(-\ k\ p_m \sqrt{t}\ ) \tag{3.4}$$

where i_∞ is the relative remaining volume at infinity and k is a constant (4.10^{-5} $Pa^{-1}.s^{-½}$).

The expression also led to horizontal broadening of the curd grain. The broadening increased with the exerted pressure and decreased slightly with decreasing initial remaining volume of the curd grain. At maximum, the broadening increased the original cross-sectional area to about 1.6 times. The extent of compression and volume decrease of the curd grain appeared to be closely correlated. The rheological properties of the paracaseinate strands probably become soon after the start the rate-determining factor at expression. The resistance to flow of whey may be a rate limiting factor at the start of the expression. It was observed in CSLM photographs that the surface layer of the cube shaped curd grains showed cracks. In the outer layer of curd grains obtained from factory made batches no cracks were observed, but, after application of a stress, cracks were formed.

The fracture stress of fused curd grains could be studied at constant macroscopic fusion area with a newly developed technique. The fracture stress was positively correlated with the fusion time and the exerted pressure. The initial remaining volume also showed a positive correlation with the fracture stress, within the small test range. The temperature also had an effect upon the fracture stress: the highest fracture stress was obtained at about 35 °C and higher or lower temperatures both led to somewhat lower values.

The sedimentation rate of curd grains may vary due to differences in apparent weight and density, but the fact that small curd grains are usually found at the bottom of a settled layer of curd grains can not be attributed hereto. Small curd grains can, however, fill the gaps between adjacent larger curd grains. The cube shaped curd grains rotated when freely settling. Anisometric curd grains sank with their longest axes perpendicular to direction of sedimentation, regardless of their initial position.

Due to preferential orientation of the curd grains and the deformation of curd grains the curd bed has to be considered an anisotropic medium. The flow of whey occurs mainly through the interconnected openings between the curd grains, and the permeability of the curd bed in the horizontal direction will be greater than that in the vertical direction.

Various types of drainage equipment are used to perform drainage, depending on the scale of production, the variety of cheese produced and the cost/benefit ratio. Batch drainage systems are mostly used in small scale production units, whereas continuous drainage vessels are commonly used in bulk cheese production. Both types have been realized in several, somewhat varying constructions and also the mode of operation varies from plant to plant. It was tried to study the effects of various designs upon the drainage by the construction of small scale drainage vessels. Scaling down of the often applied batch drainage vessels could not be done adequately, as the leakage of whey between the vessel wall and the compressed curd column contributed significantly to the flow of whey. Vertical perforated cylindrical pipes were used as a model for the continuous drainage vessels. Obvious parameters are drainage time and temperature, whey discharge conditions, and duration and magnitude of the exerted pressure. Other relevant parameters are the pressure loss due to the friction of the wall and the leakage of whey between the wall of the vessel and the curd. The packing near the wall is less dense due to steric exclusion. The friction at the wall alters the orientation of the adjacent curd grains: the curd grains are turned to an acute angle to the direction of movement of curd column.

Experiments with colored curd grains in a Casomatic drainage pipe showed that curd grains were slightly mixed at the top. The flow of curd grains through the pipe can be considered as a plug flow with a parabolic flow superimposed on it. A trail of colored curd grains at the rind of the subsequent blocks was observed, these curd grains probably got stuck at the filter grids near the whey outlets.

The compaction of a curd/whey mixture in the vertical drainage columns initially increased when the exerted pressure and/or the initial remaining volume of the curd grains increased. However, above a certain external pressure, called threshold level, the transport of whey out of the column becomes rate determining; the compression then is accompanied by a fast increase in liquid pressure. The threshold level is primarily determined by the curd properties, but the relations strongly depend on the drainage vessel's properties. Whey discharge conditions, the contact area between curd and the wall, the exerted stress upon the curd grains and the drainage time are mainly determined by the drainage vessel. The packing of the curd and the extent of fusion are likely to be relevant, but were not extensively studied. The whey content and the firmness of the curd grains and the presence of curd fines had significant effects.

Visual inspection of cross-sections of curd blocks made in a Casomatic showed pores in various sizes and shapes, the largest ones being about 5 mm. The curd blocks lost a considerable amount of whey after the drainage. This drip whey originated largely from the inside of the curd grains.

The porosity of a curd column could be measured with a newly developed porosity meter. The working principle of the apparatus is a moving optical fibre that penetrates the curd bed. The difference in scattering properties of curd grains and whey in the pores allows discrimination between either. The porosity of a curd bed so estimated, showed a large standard deviation, as the number of pores was rather small. The porosity generally decreased in time, which was due to decrease in the number and in the (apparent) size of the pores. Significant effects of the initial relative remaining volume upon the porosity were not detected. The compaction of a curd column at an external pressure level below the threshold value resulted from the decrease of porosity as well as from the whey expulsion from the curd grains. In this case, the porosity did not differ significantly between the central part and the outer regions. A higher external pressure led to a faster decrease of the porosity. At an external pressure above the threshold level the porosity of the outer region became lower than that of the central part.

The permeability of a curd block decreases over several decades during the drainage process. Initially the permeability is very high. The permeability is mainly determined by the interconnected pores, whereby the largest pores contribute most. The pores can become disconnected due to reorientation and deformation of the curd grains. Application of pressures above the threshold level finally do not result in further expressed curd columns, but cause jamming. The high pressure causes a substantial reorientation and deformation, hence, the permeability decreases very rapidly. The flow of whey from the central region becomes insufficient to keep up with the fast whey expulsion from the outer layer, causing a further decrease of the porosity in the outer region. This, in turn, retards further transport towards the outer layer, causing a rapid sealing near the rind.

A simple computer model was made. The expression of a single cube shaped curd grain was used as a model for the expression of a batch of these curd grains. It appeared that the model gave reasonable results at low external pressures. At high external pressures the model was inadequate, as the transport of whey from the pores between the curd grains becomes a rate determining factor, and this factor is not taken into account in the model. In the intermediate pressure range the model predicted a too fast expression of the curd grains, although the overall liquid pressure was below the detection limits. The latter does not rule out the existence of isolated pores, hence the liquid flow may locally be retarded. The deformation of curd grains in a curd bed may also be retarded due to fusion and geometrical constraints.

Samenvatting

Kaasmaken start met het stremmen van melk door stremsel toe te voegen en/of aan te zuren (doorgaans m.b.v. zuurvormende bacteriën). De gestremde melk wordt in stukjes gesneden. Wei treedt uit, dit noemt men synerese. De synerese wordt versneld door te roeren en veelal ook door te verhitten. Na verloop van tijd heeft men vrij stevige deeltjes en een grote hoeveelheid wei verkregen. De scheiding van de deeltjes en de wei noemt men drainage van wrongel. De wrongelmassa wordt vervolgens geperst, gezouten en gerijpt. In dit proefschrift is de bereiding, zoals die voor Goudse kaas wordt toegepast, het uitgangspunt geweest.

Het doel van het drainageproces is meestal tweeledig; het afscheiden van het grootste deel van de wei en het bereiden van een samenhangend wrongelblok. De drainage kan niet los worden gezien van de wrongelbereiding en het persen van wrongelblokken kan eventuele tijdens de drainage ontstane verschillen weer ongedaan maken. De studie van het drainageproces vereist dan ook een zeer goede beheersing van de wrongelbereiding. Een extra complicatie hierbij vormt de bereiding van wrongel op kleine schaal. De conventionele methode van wrongelbereiding resulteert, bij de bereiding op kleine schaal, in zeer fijn gesneden wrongel, welke niet representatief is voor de fabrieksmatig bereide wrongel. Een verwant probleem is de karakterisering van wrongel, aangezien op voorhand niet bekend was welke kenmerken van de wrongeldeeltjes doorslaggevend zouden zijn. Een nieuwe methode van wrongelbereiding is ontwikkeld om aan bovenstaande eisen te kunnen voldoen. De gestremde melk werd hiertoe met twee draadramen in kubusjes gesneden, waarna er een hoeveelheid wei in de wrongelbereider werd gepompt. De grote luchtbellen, die vervolgens werden ingebracht, zorgden voor een zeer milde menging. De wrongel werd bereid zonder zuursel.

De vrijwel uniforme deeltjes werden gekarakteriseerd m.b.v. een dichtheidsmeting. De deeltjes werden hiertoe in een serie zoutoplossingen met toenemende dichtheid gestrooid. De dichtheid is direkt gerelateerd aan het weigehalte van de deeltjes en aan het zogenaamde relatieve volume (l_0), dit is het volume van het deeltje t.o.v. het volume van de uitgangsmelk. Ook in het geval van fabrieksmatige wrongelbereiding bleek de methode bruikbaar, maar andere procesvariabelen kunnen ook een rol spelen bij de drainage, bijvoorbeeld pH, temperatuur en de hoeveelheid stofwrongel.

De kubusvormige wrongeldeeltjes werden gebruikt om de uitpersing en

deformatie van één afzonderlijk deeltje te bestuderen. De deeltjes zijn visco-elastisch. Het uitoefenen van een uni-axiale druk leidt tot een momentane indrukking gevolgd door een langzame viskeuze vervorming. Indien de druk binnen enkele seconden werd weggenomen trad momentane terugvering op. Na 15 minuten compressie bleef de terugvering achterwege. Zowel de elastische als de viskeuze vervorming namen toe met de druk (p_m) en het initiële relatieve volume van de deeltjes (i_0). Toepassing van hoge druk leidde ertoe, dat de deeltjes konden worden uitgeperst tot een zeer laag relatief volume. De uitpersing kan grofweg worden samengevat in onderstaande vergelijking:

$$\frac{i_t - i_\infty}{i_0 - i_\infty} = \exp(-\, k\, p_m \sqrt{t}\,) \qquad (3.4)$$

waarin i_∞ het relatieve volume is op (tijd) $t = \infty$, en $k = 4.10^{-5}$ $Pa^{-1}.s^{-½}$.

Naast de uitpersing resulteerde de compressie ook in een vergroting van de dwarsdoorsnede van de deeltjes. De optredende vergroting was wat hoger voor een hogere druk en een hoger initieel relatief volume. Het oppervlak van de doorsnede werd hoogstens ongeveer 1,6 maal de oorspronkelijke waarde. De vergroting van de dwarsdoorsnede is ondermeer relevant bij het "stoppen" van wrongel. Bij het stoppen, d.i. het overbrengen van de wrongelblokken in een kaasvat, mogen de dimensies van de wrongelblokken niet teveel verschillen van die van het kaasvat, omdat anders de wrongeldeeltjes de noodzakelijke vervorming moeilijk kunnen bereiken. Tevens bleken uitpersing en vervorming van wrongeldeeltjes in hoge mate gecorreleerd te zijn. Het stoppen van ronde blokken in vierkante kaasvaten, leidt dan ook tot grotere vochtgehaltespreiding binnen een kaas.

Uit de resultaten van deze compressiemetingen bleek dat de reologische eigenschappen van de paracaseïnematrix waarschijnlijk al gauw de snelheidsbepalende factor vormen. De afvoer van wei uit een deeltje zou beperkend kunnen zijn in het begin van de compressiemeting. Uit microscopische beelden bleek dat er in de oppervlaktelaag van de kubusvormige deeltjes scheuren aanwezig waren. In fabrieksmatig bereide wrongel was de buitenlaag gesloten, echter na het aanbrengen van een (geringe) druk ontstonden ook daarin scheuren.

De wrongeldeeltjes vormen onderling bindingen; dit noemt men vergroeien. Bij constant macroscopisch contactoppervlak werd de kracht nodig voor het verbreken van deze bindingen gemeten. Deze kracht nam toe met de vergroeiingstijd, de persdruk, en het initiële volume van de deeltjes. Bij 35 °C waren de bindingen steviger dan bij lagere en hogere temperaturen.

Verschil in valsnelheid van wrongeldeeltjes kan leiden tot ontmenging. De kubusvormige deeltjes hadden geen voorkeursoriëntatie, maar de anisomere wrongeldeeltjes wel. Als gevolg hiervan en de optredende afplatting (t.g.v. de uitgeoefende druk) is de permeabiliteit, die wordt bepaald door de openingen tussen de deeltjes, in vertikale richting kleiner dan in horizontale richting.

Het gebruikte type draineerapparatuur is afhankelijk van de bedrijfsvoering. Batch draineersystemen worden veelal gebruikt bij de ambachtelijke kaasbereiding. Continue draineerautomaten worden uitsluitend toegepast in de industrie. Er bestaan verscheidene uitvoeringen van beide types. Het nabootsen van de batch draineermachines op kleine schaal bleek niet mogelijk, omdat lekkage van wei tussen wand en wrongel een overheersende rol bleek te spelen. Vertikale geperforeerde pijpen werden gebruikt als model voor continue draineer automaten. Belangrijke parameters zijn: draineertijd en -temperatuur, wijze van wei-afvoer en druk(verloop). Het drukverlies als gevolg van wrijving met de wand bleek zeer fors te kunnen zijn. De oriëntatie van de deeltjes wordt ook door de wand beïnvloed.

Bij praktijkproeven in een continue draineerautomaat bleek dat er behalve propstroming ook sprake was van een zekere parabolische pijpstroming. In de roosters voor de weiaftap bleven nogal wat deeltjes achter.

Zolang de weiafvoer geen belemmering vormt, kan de uitpersing van de wrongel/wei massa worden versneld door de druk te verhogen. Maar, als de uitgeoefende druk te hoog wordt, ontstaat er een aanzienlijke vloeistofdruk in het wrongelbed. De druk waarbij dit gebeurt noemen we de drempelwaarde. De hoogte van de drempelwaarde hangt zowel af van de deeltjeseigenschappen als van de eigenschappen van de draineermachine. De poriën in een wrongelblok uit een draineerautomaat bleken zeer uiteenlopend van vorm en grootte. De wrongelblokken verliezen, nadat ze uit de draineermachine komen, nog circa 25% aan lek- en perswei; deze wei komt grotendeels uit de deeltjes.

De porositeit, dat is het volume wei in de poriën als fractie van het totale volume, van een wrongelblok kon worden gemeten met een zogenaamde porositeitsmeter. Hierbij wordt een optische sensor, die onderscheid kan maken tussen de deeltjes en de wei in de poriën, in een wrongelbed gestoken. De porositeit nam af in de tijd, waarbij zowel het aantal als de grootte van de gedetecteerde openingen afnam.

De volume vermindering van een wrongelkolom bleek zowel te wijten aan afname van de porositeit als aan afname van het deeltjesvolume. Bij toepassing van een druk boven de drempelwaarde werd de porositeit aan de buitenkant van de wrongelkolom lager dan in het centrum. Bij lagere druk werden hierin geen significante verschillen gevonden.

De permeabiliteit van een wrongelblok neemt enorm af tijdens de drainage. De stroom van wei verloopt vrijwel geheel door een netwerk van verbonden poriën tussen de deeltjes. De grootste poriën leveren de grootste bijdrage. Indien de poriën als gevolg van reoriëntatie en deformatie van de deeltjes plaatselijk worden geblokkeerd, neemt de permeabiliteit snel af. In het geval van "dichtslaan" treedt er een sterke verdichting op vlak langs het uitstroomoppervlak waardoor het weitransport in sterke mate belemmerd wordt.

Een computermodel werd gebruikt ter vergelijking van de uitpersing van één afzonderlijk deeltje en de uitpersing van een verzameling van deze uniforme deeltjes. Het model gaf aan dat de uitpersing bij lage druk in grote lijnen hetzelfde verliep. Bij hoge druk speelt de snel toenemende vloeistofdruk een wezenlijke rol, maar aangezien deze grootheid niet was opgenomen in het model, waren de voorspelde resultaten niet in overeenstemming met de werkelijkheid. Tussen 400 en 1000 Pa verliep de uitpersing van één afzonderlijk deeltje sneller dan die van een kolom met deeltjes. Twee mogelijke oorzaken hiervoor zijn: een deel van de wei bevindt zich in geïsoleerde openingen, dan wel de uitpersing van de deeltjes in een wrongelbed is vertraagd als gevolg van vergroeiing en/of beperkte mogelijkheden voor deformatie.

Curriculum Vitae

Jan Coen Akkerman werd op 31 augustus geboren te Ouwsterhaule. In 1980 behaalde hij zijn atheneum diploma op het Nassau College te Heerenveen. In hetzelfde jaar begon hij aan de toenmalige Landbouwhogeschool. Tijdens de studie werd er stage gelopen bij Melkunie Holland te Woerden en Opmeer en bij Marigold Foods Inc. te Rochester, MN., USA. De doctoraal fase bestond een 3 maands vak bij informatica, een 6 maands vak bij proceskunde en eveneens een 6 maands vak bij zuivel. In 1987 werd de studie afgerond, waarna dit vier jarige onderzoek werd begonnen.