A STUDY OF THE APPARENT VISCOSITY OF MILK AS INFLUENCED BY SOME PHYSICAL FACTORS[1]

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INTRODUCTION

For many years numerous studies of the viscosity of whole milk and cream have been carried out. The methods used by most of the investigators have been very empirical. No careful investigation of the viscosity of milk and cream at various rates of shear has been reported in the literature.

A great variety of conditions and methods were used to determine the viscosity of milk. This makes it impossible to compare the work of one experimenter with that of another, except in a general way, since one does not know whether or not their results are independent of the dimensions and peculiarities of the apparatus they used. The correction for kinetic energy or inertia has been ignored. Some investigators have made a comparison of the relative rates of flow of water and milk by means of an ordinary pipette, and have apparently assumed that this method gave a measure of viscous flow, since they have designated their results "relative viscosity." In most of the work the standard of comparison was water, and frequently no attempt was made to run the determinations at exactly the calibration temperature. The importance of careful temperature regulation is paramount when it is realized that the fluidity of water changes from 1 to 3 per cent for a change of 1° C. Most of the investigations have been carried out at widely varying temperatures, which increases the difficulty of the problem of weighing the relative value of the results. Dahlberg and Hening (*13*)[3] worked in a refrigerator where the temperature was kept between 3° and 4° C. Kobler (*20*) carried out most of his experiments within a temperature range of 15° to 18° C., while Taylor (*30*) worked at 20° C. Cavazzani (*12*) studied the viscosity of milk at 37°. A number of workers have ignored the difference in density between the calibration liquid, water, and the milk or cream whose viscosity was being determined. This would be a source of error in an Ostwald viscometer where the driving force is entirely due to the hydrostatic head of the contained liquid. The omission of such data as fat content, total solids, previous history of the sample, etc., also complicates the difficulty of making a quantitative comparison and estimation of the published work on the viscosity of milk and cream.

Another subject which has been largely ignored in the past is, how the apparent viscosity of skim milk is affected by different physical factors. In almost all the work done only the viscosity of whole

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[3] Reference is made by number (italic) to "Literature Cited," p. 672.

milk and the factors that influenced it have been considered. Very little study has been made of skim milk as a separate phase in which changes are taking place along with those (clumping and creaming) in the fat phase. Consequently, very little is known concerning the changes in whole milk which are actually due to the alterations taking place in the skim-milk phase.

No investigator of the viscosity of milk and cream has taken the later concepts of plastic and viscous flow into consideration in his work.

The conditions of flow which a liquid must fulfill when a given volume is forced through a capillary using various pressures to produce the flow, in order that it may be said to follow Poiseuille's law, are as follows:

$$\eta = Pt \text{ (constant)}^{4} \tag{1}$$

where η is the viscosity coefficient, P the pressure, and t the time of flow. This equation shows that the viscosity of a liquid which follows Poiseuille's law is independent of the pressure producing the flow. The extent to which the flow of milk through a capillary is in agreement with this relationship has never been accurately determined.

Since the conditions under which equation (1) holds experimentally are inconvenient for investigational work, the equation has been modified by correction factors so that the capillary need not be so small and so that high pressures can be used. Bingham and White (*8*) have used the equation in the following form:

$$\eta = \frac{\pi g r^4 Pt}{8v(l+\lambda)} - \frac{mv\rho}{8\pi t(l+\lambda)} \tag{2}$$

where η = viscosity coefficient.
g = gravitational constant.
r = radius of capillary in centimeters.
P = pressure in grams per square centimeter.
t = time of flow in seconds.
v = volume of flow in cubic centimeters.
l = length of capillary in centimeters.
m = constant whose value was taken as 1.12.
ρ = density of liquid.
λ = a correction to be added to the length of the capillary to correct for the modification of the stream lines at the terminals of the capillary, which cause a loss of pressure in overcoming friction.

The term involving m is generally called the kinetic energy correction, and, as will be seen from equation (2), it is a subtractive correction to be applied to Pt to cover a loss of head or pressure rising from the imparting of kinetic energy to the liquid. This correction is usually very small and approaches zero in the case of long, narrow capillaries, or in cases where the value of the pressure, P, is very small.

[4] This equation holds experimentally only for very long, narrow capillaries or for very small pressures.

EXPERIMENTAL

APPARATUS AND GENERAL PROCEDURE

This work was undertaken, first, to make a systematic study of the viscosity of skim milk under varying conditions of treatment; second, to see if some of the changes which take place in the viscosity of whole milk are due to changes associated with the fat or to changes in the skim-milk phase; and third, to investigate the rate of flow of milk through capillary tubes at varying pressures. Practically no work has been done on these phases of the subject.

The methods outlined below are general. The special procedure followed in each phase of the experimental work will be presented, together with the resultant data.

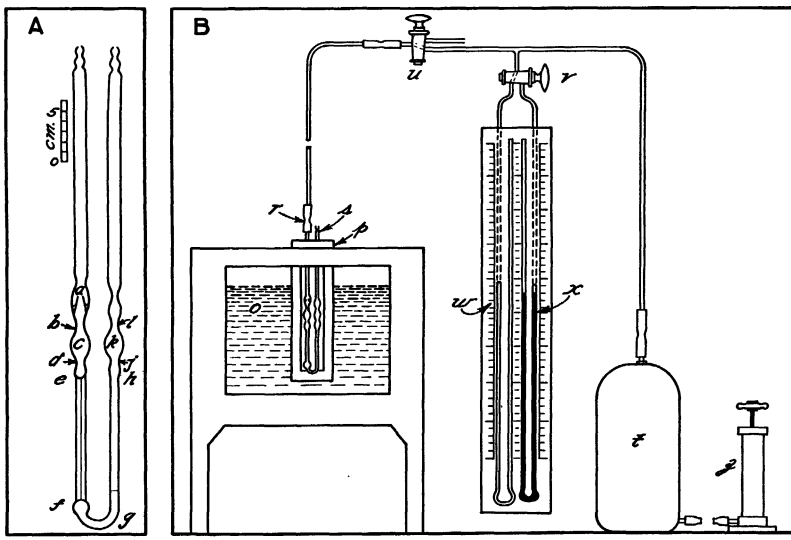

FIG. 1.—A, Important features of the Bingham viscometer; B, apparatus used to apply variable pressure to the viscometer

MILK USED

The milk used in the experiments was obtained from the Cornell University dairy herd. It was filtered through cotton into sterile bottles, and immediately after milking it was cooled to 0° C. to prevent, as far as possible, contamination or decomposition. When skim milk was desired, the fat was removed by centrifuging the properly cooled whole milk in 250 c. c. bottles at about 2,500 revolutions per minute for 30 minutes. The skim milk was carefully removed, filtered into sterile storage bottles, and cooled to about 0° C. In all cases dust contamination was guarded against.

Since most of the milk used in the experiments was obtained under conditions that would insure a low bacterial content and freedom from dirt, no attempt was made to get representative samples. The milk was taken from single cows at various stages of milking. Hence in many cases the ratio between total solids and milk fat was not always representative of normal whole milk.

The fat content was determined according to the Roese-Gottlieb method as modified by Mojonnier (Mojonnier and Troy (*22*)). The milk solids determinations were also carried out with the Mojonnier milk solids testing apparatus.

Apparatus

Figure 1, A, gives the details of the Bingham (*6*) viscometer, and Figure 1, B, shows a view of the whole set-up of the apparatus used. *t* represents a galvanized tank of about 25 liters capacity, with an automobile tire valve soldered to it to serve as an intake valve. Air was compressed into the tank by means of a hand pump *z*. Glass tubing connected the tank *t* to the manometers (*x* mercury and *w* water), and to the viscometer at *r*. At low pressures the water manometer, *w*, was used, while at higher ones the mercury manometer, *x*, could be utilized by turning the three-way stopcock, *v*, halfway around.

The viscometer was connected to the pressure line by means of a three-way stopcock, *u*. This stopcock when turned in one direction connected the viscometer to the laboratory air, and when turned in the other connected it to the pressure line. The viscometer was held rigidly in a solid wooden frame, *p*, which fitted in a slot in the water bath, *o*, so that it could be replaced in the same position after removal from the water bath for cleaning.

The temperature of the water bath was kept constant $\pm 0.01°$ C. by means of an automatic mercury thermo regulator. All determinations were carried out at 25° C. A Beckmann thermometer was immersed in the water bath to check the temperature at frequent intervals.

Calibration

The Bingham viscometer used in this work was purchased from Eimer and Amend, and the capillary was specified as 500, according to the requirements set by Bingham (*6*). With such a capillary fluidities from 0.5 to 500 can be measured. This viscometer, if properly made, has all the desirable features of the Ostwald viscometer, and practically none of its objectionable ones. From the diagram (fig. 1, A) it will be noted that the viscometer is constructed so as to reduce the effect of the hydrostatic pressure of the contained liquid to zero. Each arm of the instrument is made as nearly as possible similar to the other in shape and height, and the bulbs have the same volume. The value of the density of the contained liquid need not be known with considerable accuracy. A trap is provided in one arm to make it possible to work with exactly the same volume of liquid at all temperatures.

With the Bingham viscometer the force driving the liquid through the capillary is entirely due to the pressure that is being exerted on the system, providing the viscometer is constructed so that the hydrostatic head of the contained liquid is equal to zero.

Inasmuch as it would be too difficult and laborious to construct a viscometer for ordinary work where all of the dimensions could be accurately determined by direct measurement, it is a common practice to calibrate the instrument with some suitable standard liquid. For a given instrument it will be noted that certain of the factors in equation (2) remain constant in all of the determinations and that these may be presented by C and C'. Hence

$$C=\frac{\pi g r^9}{8lv} \tag{3}$$

and for the kinetic energy correction factor,

$$C'=\frac{mv}{8l\pi} \tag{4}$$

Equation (2) now becomes:

$$\eta=CPt-C'\rho/t \tag{5}$$

where C and C' are constants, which may be determined.

In this work the value of C' was found by direct measurement. The volume, v, of the bulb, c (fig. 1, A), between the marks b and d was found to be equal to 4.0 c. c. and the length of the capillary 10 cm. Hence

$$C'=\frac{1.12\times 4.0}{8\times 3.1416\times 10}=0.01784$$

To determine the viscometer constant C, it was first necessary to solve equation (5), which gives:

$$C=\frac{\eta t+C'\rho}{Pt^2} \tag{6}$$

A number of viscosity runs were made with dust-free, freshly distilled water at 25° C. to determine the time of flow at known varying pressures for each limb of the viscometer. The mean value of the viscometer constant was found to be equal to 1.319×10^{-7}.

For the viscometer used in this work, equation (5) now becomes:

$$\eta=1.319\times 10^{-7}Pt-0.01784\rho/t \tag{7}$$

where η is the viscosity in centipoise.

The flow periods for each arm were found to be approximately the same, since no variation was greater than one-fifth of a second. Hence the correction for the hydrostatic pressure of the liquid in the viscometer was unnecessary with this instrument.

In the course of these experiments we tried to maintain a constant room temperature. The effect of slight variations in the temperature of the room and the corresponding effect on the pressure in the tank was one of the greatest sources of error with which the authors had to contend. This error could have been greatly reduced by placing the pressure tank in the water bath. The change in pressure due to slight changes in temperature during each determination was usually so small that it could not be detected on the manometers. Also it was impossible to measure time periods with greater accuracy than one-fifth of a second with an ordinary stop watch. In order to minimize the above sources of error as much as possible, the efflux periods throughout these experiments were largely maintained between 100 and 1,000 seconds. The stop watch was always kept wound to about the same tension, and at frequent intervals it was checked for accuracy by means of a standard chronometer.

THE INFLUENCE OF PRESSURE, AS A VARIANT, ON THE APPARENT VISCOSITY OF SKIM MILK, SKIM COLOSTRUM, RAW, PASTEURIZED, AND HOMOGENIZED WHOLE MILK, AND EVAPORATED SKIM MILK

It is rather surprising that most of the investigators have overlooked the effect of the rate of shear on the viscosity of milk and cream.

Galdi (*15*) attempted to determine the viscosity of a large number of liquids, including milk, by means of a Hirsch-Beck apparatus. His apparatus really consisted of a modified Ostwald viscometer connected to a source of pressure. He determined the relative viscosity of milk at a number of pressures, but his data show comparatively large inconsistent variations. His results vary between 1.57 and 1.67 and are of little value in showing the effect of the rate of shear on the viscosity of milk.

The only other reference covering the relation between the viscosity coefficient of milk and the pressure that could be found in the literature was a statement by Rothlin (*26*) that mixtures of emulsoids and suspensions such as milk, defibrinated and normal blood, show deviations from Poiseuille's law at low rates of shear. Rothlin (*25*) presented no results on milk, however, even in his more extensive paper.

If Rothlin's observations are correct the question as to absolute values for the viscosity of milk arises. If a physical "constant" shows variation with the conditions it is being subjected to when determined, it is obvious that these conditions should be specified. This is especially true where changes in the structure of the constituents caused by various kinds of treatment are being considered.

These series of experiments constitute a study of the influence of varying the rate of shear on the apparent viscosity of skim milk, skim colostrum, raw, Pasteurized, and homogenized whole milk, and evaporated skim milk. The viscometer was filled accurately with a definite volume of milk, in such a manner that the aliquot of the test milk was not passed through the capillary in the filling process. The viscometer was cleaned and dried for each individual determination.

The data which follow were selected from a number of experiments as being typical of the effect of the rate of shear on the viscosity of milk.

TABLE 1.—*Effect of varying pressure on the viscosity of skim milk*

Sample No.	Pressure (gm. per sq. cm.)	Average time of flow (seconds)	Viscosity (centipoise) at 25° C.
1	1,146.3	96.4	1.438
	982.0	112.6	1.442
	681.6	162.7	1.450
	480.3	231.4	1.458
	278.1	401.4	1.468
	150.1	743.4	1.470
2	981.2	109.0	1.393
	814.8	131.4	1.398
	682.2	157.2	1.403
	480.3	223.0	1.405
	278.1	385.0	1.408
3	981.2	117.2	1.500
	814.8	140.0	1.491
	681.6	168.8	1.506
	480.9	238.6	1.507
	278.1	415.6	1.519
	143.1	808.6	1.516
	71.6	1,612.8	1.516
4	981.7	113.3	1.452
	815.7	136.8	1.458
	682.4	163.9	1.464
	481.7	232.3	1.468
	278.7	402.2	1.474
	147.9	760.4	1.481
	71.9	1,579.2	1.496

TABLE 2.—*Effect of varying pressure on the viscosity of fresh skim colostrum*

Number of days after parturition	Pressure gm. per sq. cm.	Average time of flow (seconds)	Viscosity (centipoise) at 25° C.
4	1,306.14	104.4	1.781
	979.7	139.3	1.787
	679.3	201.6	1.797
	275.3	498.4	1.806
	132.21	1,051.2	1.831

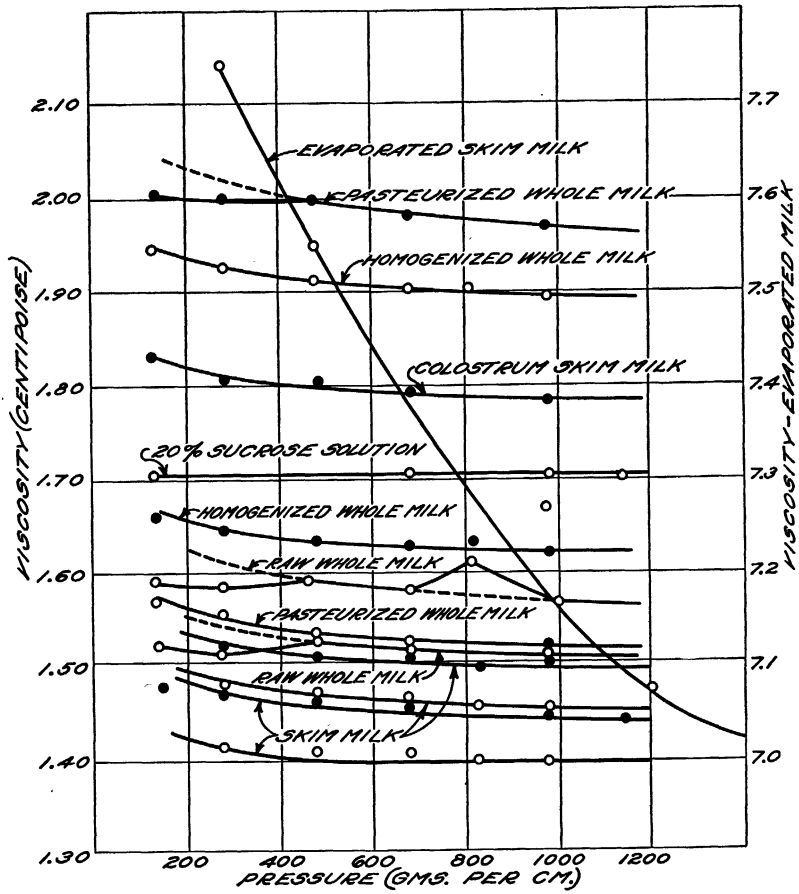

FIG. 2.—Decrease in viscosity of various kinds of milk as shearing force is increased

The viscosity of skim milk and skim colostrum at varying pressures was studied first. The results are given in Tables 1 and 2, and graphically in Figure 2. From these data it can be seen that the viscosity coefficient of skim milk is not constant but varies with the pressure. When the pressure is increased the apparent viscosity is slightly decreased. Skim colostrum (four days after parturition) also gave pressure-viscosity curves which resembled those of skim milk.

TABLE 3.—*Effect of varying pressure on the viscosity of raw whole milk*

Number of hours aged at 4° C.	Composition (percentage by weight) of—		Pressure (gm. per sq. cm.)	Average time of flow (seconds)	Viscosity (centipoise) at 25° C.
	Fat	Total solids			
4	3.58	12.86	1,306.9	91.9	1.548
			978.3	122.7	1.567
			812.1	151.9	1.613
			679.4	177.7	1.581
			477.5	254.0	1.591
			275.9	437.0	1.587
			131.8	917.8	1.593

TABLE 4.—*Effect of varying pressure on the viscosity of Pasteurized whole milk*

Number of hours aged at 4° C.	Composition (percentage by weight) of—		Pressure (gm. per sq. cm.)	Average time of flow (seconds)	Viscosity (centipoise) at 25° C.
	Fat	Total solids			
8	4.75	14.18	980.4	153.2	1.970
			680.1	221.7	1.981
			481.5	314.9	1.999
			277.2	548.5	2.001
			145.85	1,051.9	2.023
6	3.83	12.82	1,306.9	89.6	1.523
			979.7	118.2	1.511
			678.8	170.4	1.514
			478.8	242.6	1.524
			275.9	418.2	1.514
			138.0	834.6	1.522
1	----------	----------	1,308.5	88.4	1.511
			980.6	118.7	1.517
			680.9	171.2	1.526
			478.9	244.2	1.535
			276.7	427.4	1.555
			138.2	863.0	1.571

Experiments with whole milk are given in Tables 3 and 4, and are graphically represented in Figure 2. Much difficulty was experienced in attempting to determine the apparent viscosity of raw or Pasteurized whole milk. At the lower pressures it was practically impossible to obtain concordant results. It will be noted that the curves for raw and Pasteurized whole milk shown in Figure 2 are not all consistent, and that the apparent viscosity values at low pressures are much less than the theoretical (extrapolated) ones, shown by the broken lines. These discrepancies are due to the fact that at low pressures the time periods are sufficiently long to allow part of the cream to rise to the surface in the viscometer. This means that as the time of flow increases, more of the butter fat will have a chance to rise, and the composition of the milk flowing through the capillary will approach that of skim milk. Hence its apparent viscosity will tend to decrease with the longer time periods.

The results obtained with homogenized whole milk appear to support the above conclusion. In homogenized whole milk the fat globules are not clumped and are broken up into sufficiently finely

divided particles so that they remain suspended throughout the milk. With such a system a viscosity-pressure curve that resembles those of skim milk and skim colostrum can be expected. The results obtained with homogenized whole milk are given in Table 5, and are plotted as curves in Figure 2. The viscosity values obtained with homogenized whole milk were very consistent and reproducible.

TABLE 5.—*Effect of varying pressure on the viscosity of homogenized whole milk*

Number of days aged at 4° C.	Composition (percentage by weight) of—		Pressure (gm. per sq. cm.)	Average time of flow (seconds)	Viscosity (centipoise) at 25° C.
	Fat	Total solids			
1	2.94	11.64	1,307.8	94.8	1.616
			980.6	126.6	1.623
			815.6	152.2	1.626
			680.9	182.5	1.629
			480.3	259.3	1.636
			278.1	450.0	1.647
			136.4	920.0	1.659
1	4.63	14.08	1,306.9	110.6	1.892
			979.7	147.3	1.892
			812.7	178.4	1.902
			679.4	213.2	1.901
			479.7	303.7	1.915
			276.6	529.5	1.928
			134.46	1,059.6	1.947

The sample of evaporated skim milk studied in this series of experiments, showed the greatest variation of viscosity with pressure. A glance at Figure 2 and Table 6 makes this fact evident.

TABLE 6.—*Effect of varying pressure on the viscosity of evaporated skim milk*

Composition (percentage by weight) of—		Pressure (gm. per sq. cm.)	Average time of flow (seconds)	Viscosity (centipoise) at 25° C.
Fat	Total solids			
0.72	25.63	1,466.2	366.8	7.089
		980.4	562.0	7.252
		814.2	671.2	7.205
		480.3	1,186.2	7.513
		276.0	2,127.2	7.744

In order to make sure that the value of the capillary constant C was correct, and that the results, as obtained, were not due to some peculiarity of the apparatus, a set of runs were performed on a 20 per cent pure sucrose solution. According to Bingham and Jackson (7) this solution should have a viscosity of 1.704 centipoise at 25° C. As will be noted by referring to the data in Table 7 and Figure 2, the viscosity of the solution at all of the pressures was constant and averaged 1.704 centipoise. This shows that the apparatus was apparently not the cause of the variation in the viscosity of milk with pressure.

TABLE 7.—*Effect of varying pressure on the viscosity of a 20 per cent sucrose solution* [1]

Pressure (gms. per sq. cm.).	Average time of flow (seconds)	Viscosity (centipoise) at 25° C.
1,144.9	113.8	1.703
980.6	132.9	1.704
680.9	191.0	1.704
124.7	1,037.2	1.704

[1] Viscosity according to Bingham and Jackson (*7*) =1.704.

If milk were a truly viscous liquid, it should give a constant viscosity value with varying pressures, since according to Poiseuille's law the product of the pressure and time for a given set of conditions should equal a constant. This means that the pressure-viscosity curve should be a straight line parallel to the pressure axis. Since milk does not fit the requirements of the law of Poiseuille, but shows a slight variation with pressure, it can not be called a truly viscous liquid. No term which can be used to designate the flow of a liquid which deviates slightly from Poiseuille's law has come into common use. The terms "apparently viscous" and "plastico-viscous" have been used to designate flow of this type. Inasmuch as the viscosity of milk is not independent of the rate of flow, it can be readily seen that all of the conditions of measurement must be taken into consideration. Hatschek (*17*) says: "If the viscosity of a given sol varies with the shear gradient, single measurements at arbitrary and unknown shear gradients have no theoretical value, least of all as a foundation for hypotheses regarding structure."

It has already been noted that the viscosity of milk is a function of the pressure and decreases as the pressure increases. The assumption which Hatschek and Jane (*18*) make to account for this variation is that each particle must be surrounded by an adsorbed layer of liquid, which increases its effective volume and moves with it. This layer is assumed to be very labile, and it is more and more reduced in thickness as the rate of flow increases. The thicker the adsorbed layer the greater will be the viscosity. It will be seen that the decrease of viscosity with increased rate of flow will be related to the amount of this adsorbed film displaced, and that at pressures sufficiently high, the viscosity should approach a constant value.

Hess (*19*) has also offered an explanation for the decrease in viscosity of suspensions with an increase in shearing force. He considered that the suspended particles, due to their size, obstructed the normal telescopic flow of the dispersion medium, causing "dead" spaces immediately behind and ahead of the particles. These so-called dead spaces removed a part of the liquid from the normal telescopic flow of the dispersion medium and consequently increased the effective volume of the particle, and at the same time decreased the effective volume of the dispersion medium. He believed that as the shearing force increased the telescopic layers displaced more of the liquid in the dead spaces, and consequently the viscosity decreased as the shearing force increased.

THE EFFECT OF REPEATEDLY FORCING MILK THROUGH A CAPILLARY TUBE AT CONSTANT PRESSURE

Kobler (*20*) studied the effect of repeatedly running milk through a capillary, and of agitation, on the relative viscosity of whole milk. He forced it through a capillary 40 times, and found that the viscosity was materially diminished. For example his first reading was 1.77, his tenth decreased to 1.70, his twentieth to 1.65, while his values from the thirtieth to the fortieth remained at 1.60. However, after the milk was allowed to stand for 14 hours the viscosity of the sample was found to be 1.70. He also showed that he could diminish the viscosity of normal milk from 1.83 to 1.67 by 20 minutes of agitation, and that if he allowed it to stand for 14 hours the viscosity would return almost to the normal value, if the shaking had not been too severe. Kobler assumed that the decrease was due to the breaking up of a rigid structure in the milk which was capable of forming again on standing, provided the agitation had not been too severe. He made no attempt to explain the actual mechanism of this structure. It is probable that this structure, postulated by Kobler, was really a clumping of the fat globules, and that the decrease in viscosity noted was largely brought about by breaking up these clumps.

This set of experiments constitute a study of the effect of repeatedly running skim milk, skim colostrum, raw and homogenized whole milk through a capillary. The effect of protein and fat grouping as factors influencing the constancy of the viscosity was especially considered.

Much difficulty was experienced with raw whole milk, since the cream had a tendency to rise slowly and stick to the sides of the viscometer reservoirs during the progress of experiments. Churning also had to be guarded against. With homogenized raw milk there was no indication of the fat sticking to the viscometer.

The raw whole milk was secured immediately after milking and cooled to 4° C. It was aged at this temperature for a number of hours to allow the fat globules to clump thoroughly. The milk was next gently mixed by pouring it from one vessel to another. A sample was placed in the water bath and allowed to come to a temperature of 25° C. The milk was again mixed very gently; a portion was added to the viscometer, and continuously forced back and forth through the capillary at constant pressure. At the same time, another part of the same sample was examined under the microscope to note the state of aggregation of the fat globules. The milk was introduced into trenches in a blood-counting cell. A cover glass had been previously cemented over the trenches by means of a mixture of vaseline and paraffin, and after the milk was introduced into the trenches the open ends were sealed with the same paraffin mixture. This gave a thin uniform layer of milk. The microscope was adjusted so that the trenches could be examined in a perpendicular position. The degree of clumping of the fat globules and their tendency to rise either as individuals or as aggregates could be followed very closely. This procedure was repeated with the milk after it had been repeatedly forced through the viscometer capillary.

The milk which was to be homogenized was first carefully heated to 50° C., and then forced through the homogenizer at a pressure of over 4,000 pounds. It was immediately cooled to about 4° C. and kept at this temperature until used. Throughout this work all of the homogenized milk was subjected to the above treatment unless otherwise stated.

The results of this series of experiments are summarized in Tables 8 to 11.

TABLE 8.—*Effect of repeated forcing of fresh skim milk through the viscometer capillary*

Sample No.	Pressure (gm. per sq. cm.)	Number of times forced through capillary	Viscosity (centipoise) at 25° C.
1	682.9	1	1.361
		3	1.361
		5	1.361
		9	1.361
		11	1.363
		13	1.361
		15	1.362
		17	1.361
		19	1.363
		23	1.361
		27	1.361
		29	1.363
		35	1.363
		39	1.361
2	682.1	1	1.428
	682.1	3	1.426
	681.5	5	1.428
	678.8	7	1.427
	682.9	9	1.425
	678.8	11	1.428
	682.1	15	1.428
	682.1	19	1.428
	682.1	21	1.428
3	548.3	2	1.449
		4	1.449
		6	1.449
		10	1.450
		14	1.449
		16	1.450
		20	1.449
		24	1.449
		30	1.449
		32	1.450

In Table 8 the results obtained with skim milk are given. From these results it is apparent that continuously running skim milk through the capillary at constant pressure had absolutely no effect on the viscosity values, since they remained constant throughout each set of runs.

From the data in Table 9 it will be seen that the viscosity actually increased as the colostrum skim milk was run repeatedly through the capillary. This increase was probably due to a gradual increase in the viscosity of skim milk upon aging, for considerable time elapsed during the experiment. The higher the protein content the greater is the increase of viscosity with age. The deviation from a constant value tends to decrease as the composition approaches that of normal skim milk. The colostrum taken one day after parturition showed the greatest variation. Also it tended to stick to the walls of the viscometer reservoir, which resulted in poor drainage.

TABLE 9.—*Effect of repeated forcing of fresh colostrum skim milk through the viscometer capillary*

Days after parturition	Pressure (gm. per sq. cm.)	Number of times forced through capillary	Viscosity (centipoise) at 25° C.
1	683.4	1	3.460
	683.4	3	3.473
	683.4	5	3.485
	683.4	7	3.485
	683.4	9	3.485
	682.9	11	3.486
	682.9	13	3.497
	682.9	15	3.503
2	684.5	1	1.782
		3	1.785
		5	1.789
		7	1.789
		9	1.789
		11	1.786
		13	1.786
		17	1.787
		21	1.787
		23	1.787
3	690.9	1	1.518
	682.7	3	1.522
	682.7	5	1.522
	682.7	7	1.525
	682.7	9	1.525
	682.7	11	1.525
	682.7	13	1.525
	682.7	15	1.525

TABLE 10.—*Effect of repeated forcing of milk through the viscometer capillary*

Number of hours aged at 4° C.	Composition (percentage by weight) of—		Pressure (gm. per sq. cm.)	Number of times forced through capillary	Viscosity (centipoise) at 25° C.
	Fat	Total solids			
3	6.04	15.43	814.2	1	1.867
				3	1.847
				5	1.837
				7	1.828
				9	1.818
				11	1.816
				17	1.818
				27	1.818
				29	1.816
30	6.04	15.43	815.4	1	1.949
				3	1.915
				5	1.900
				7	1.883
				9	1.874
				11	1.868
				13	1.863
				17	1.857
				21	1.859
				25	1.857
6	3.58	12.87	814.0	1	1.640
				3	1.638
				7	1.634
				11	1.626
				15	1.626
				19	1.625
				25	1.625

The results obtained with raw whole milk are given in Table 10, and they indicate that the viscosity values decrease to a constant under the conditions of the experiment. With fresh Jersey milk the viscosity decreased from 1.867 to 1.816 centipoise. After aging for

about 30 hours, the effect of repeatedly running the same sample through the capillary was even greater, falling from 1.949 to 1.857. Similar results were obtained with Holstein milk, the viscosity dropping from 1.640 to 1.625.

A microscopic study of the whole milk which had been repeatedly run through the capillary, and that which had not been, showed that the decrease in viscosity, noted above, was correlated with a breaking up of the fat clusters. In Jersey milk especially the majority of the fat globules were initially present as clumps, but after being subjected to the above treatment the microscopic field showed very few clustered groups of fat globules. The portion of the sample which had been run back and forth through the viscometer showed very little tendency to cream after 20 minutes in the microscopic creamer, while the creaming of the control sample which was clumped was very rapid. Another source of decrease of viscosity which should be noted, was the tendency of the fat to stick to the inner walls of the viscometer reservoirs.

It has been noted that repeatedly running normal skim milk through the capillary had no effect on its viscosity, while with normal whole milk a marked decrease resulted, the effect being greater the higher the fat content of the milk. It was also found that the decrease in viscosity of whole milk was correlated with the breaking up of the aggregates of fat globules. In order to check the above conclusions homogenized whole milk was repeatedly run through the capillary at constant pressure. Representative data covering the results of these operations are included in Table 11. The viscosity values obtained with homogenized whole milk are as constant as those with normal skim milk, under the same experimental conditions. Since the fat globules in homogenzied whole milk are not clumped, this result would be expected. These experiments show that the decrease in viscosity of normal whole milk due to repeatedly running the same sample through a capillary or to agitation is accounted for by the breaking up of the clumps of fat globules.

TABLE 11.—*Effect of repeated forcing of homogenized whole milk through the viscometer capillary*

Number of hours aged at 4° C.	Composition (percentage by weight) of—		Pressure (gms. per sq. cm.)	Number of times forced through capillary	Viscosity (centipoise) at 25° C.
	Fat	Total solids			
8	3.58	12.87	814.0	1	1.830
				3	1.829
				5	1.830
				7	1.830
				11	1.829
				15	1.830
				23	1.830
6	2.94	11.63	816.7	1	1.586
			816.7	3	1.586
			816.7	5	1.586
			816.7	7	1.587
			816.7	9	1.586
			816.7	15	1.586
			816.7	19	1.586
			815.6	25	1.585
			815.6	29	1.585
			816.7	35	1.586

THE EFFECT OF HOMOGENIZATION ON THE VISCOSITY OF MILK

The influence of homogenization on the viscosity of whole and of skim milk was considered in this set of experiments. Much work has been done on the viscosity of homogenized cream, while the effect of this treatment in the case of skim milk and whole milk has received much less attention.

Buglia (*10*) demonstrated that homogenization increases the viscosity of whole milk, while it has practically no effect on skim milk. Wiegner (*32*) obtained results similar to those of Buglia for whole milk. Evenson and Ferris (*14*) also noted an increase in the viscosity of Pasteurized normal milk after it had been homogenized. Babcock (*2*) states that homogenization is very detrimental to the whipping qualities of cream, this effect being multiplied by raising the homogenization pressure. The work of Sherwood and Smallfield (*28*) is very interesting, since they studied, by means of a microscope as well as a viscometer, the effect of homogenization. They found that the rate of increase in viscosity of a sample of Pasteurized cream on aging was much greater if it had been homogenized, the increase being accompanied by a growing tendency of the globules to clump.

TABLE 12.—*Effect of homogenization on the viscosity of skim and whole milk*

Number of hours aged	Composition (percentage by weight) of—		Pressure (gms. per sq. cm.)	Viscosity (centipoise)	
	Fat	Total solids		Normal	Homogenized
6	0.11	8.87	277.3	1.383	1.362
			680.9	1.370	1.355
			980.4	1.360	1.351
8	.18	9.43	277.3	1.454	1.451
			680.4	1.432	1.422
			980.4	1.428	1.419
8	4.05	12.82	277.3	1.635	2.001
			680.1	1.623	1.998
			980.4	1.619	1.970
3	4.63	14.08	814.0	1.640	1.830
			814.0	1.640	1.831

Table 12 shows the effect of homogenization on the apparent viscosity of skim milk and whole milk. It is rather interesting to note that homogenization slightly decreases the viscosity of skim milk, while it materially increases the same physical property of whole milk. In the case of skim milk, it is probable that the state of subdivision of some of the protein clots which may be present is altered, when subjected to the violent physical forces of this treatment, so as to cause a slight diminution in viscosity.

A microscopical observation of the fat globules, before and after homogenization, showed that their average size had been greatly decreased. An increase in viscosity under the above conditions is quite in accord with the results of Odén (*23*), who studied the effect of decreasing the particle size on the viscosity. Hatschek (*16*) concluded that this augmentation was due to an adsorption film of the liquid phase around the particles, the thickness of which was independent of the particle size.

The same explanation can be used for the effect of homogenization on the viscosity of whole milk. Homogenization reduces the size of the fat globules, and at the same time increases the specific surface of the fat phase. Since the thickness of the adsorption film varies slightly if at all with the particle size, and the amount of adsorption depends upon the total surface, it can be seen that more of the skim-milk phase will be adsorbed, in the case of homogenized whole milk, and will no longer count as free liquid. This results in an increase in viscosity, due to a decrease in the volume of the dispersion medium and an increase in the volume of the dispersed phase. In other words, the augmentation of viscosity is probably due to the adsorption of the skim-milk phase by the fat globules, and consequently the homogenized whole milk becomes more viscous than ordinary milk of the same fat content. For example, Wiegner (*32*) reduced the average diameter of fat globules in milk from 2.9 μ to about 0.27 μ by the homogenization process. From viscosity measurements he calculated that in ordinary milk about 2 per cent of the casein is adsorbed by the fat, while the casein adsorbed in homogenized milk is about 25 per cent. This amount of protein adsorbed is probably too high due to his assumption that the adsorbed protein film had a density of about 1.4.

It was also found that when homogenized milk is aged at low temperatures for several days the viscosity rises. This is undoubtedly due to the altering of the proteins.

EFFECT OF AGING ON THE VISCOSITY OF SKIM MILK

When milk stands in contact with the atmosphere, at least a slight exchange of gases occurs. Adsorption of oxygen and nitrogen and a loss of dissolved carbon dioxide takes place. Probably there is a slow change in the solubility and equilibrium of the salts. Fat globules clump and rise, resulting in a cream layer at the surface. The proteins may be slowly denaturized. The milk contains enzymes, some of which are inherent and other of bacterial origin. These enzymes alter the composition of the milk with aging. It is apparent that the study of the influence of aging on the physical properties of milk is important, since much of the market milk and cream is kept for some time at low temperatures before being used.

Kobler (*20*) believed that an initial increase in the viscosity of fresh whole milk occurred due to the gradual loss of air bubbles which were present, and that the later increase was due to the proteins, in which case the viscosity increased until the casein was precipitated. The loss of small air bubbles from the milk should, however, cause a decrease in viscosity as measured with a capillary viscometer. Burri and Nussbaumer (*11*) allowed a sample of whole milk to stand for 12 hours at about 20° C., and found that the viscosity increased with aging. Evenson and Ferris (*14*) demonstrated that milk which had been aged for one week at 3° C. showed an increase in viscosity over that kept for one hour at 30° C. Dahlberg and Hening (*13*) also made an extensive study of the influence of aging on the viscosity of milk and cream and their results, in general, agree with those of the other workers.

Most of the recorded work on aging has been done with whole milk and cream. Much of the variation in the viscosity of whole milk, as has been previously shown, can be ascribed to a variation

in the degree of clumping of the fat globules. A study of the effect of aging on the viscosity of skim milk would show whether or not the augmentation noted on aging whole milk is due to a variation in the clumping of fat globules or to an actual increase in the viscosity of the skim milk phase.

TABLE 13.—*Effect of aging on the viscosity of skim milk*

Number of days aged	Composition (percentage by weight) of—		Pressure (gm. per sq. cm.)	Viscosity (centipoise) at 25° C.
	Fat	Total solids		
0	0.19	9.18	983.9	1.500
			814.8	1.504
			682.2	1.506
			480.3	1.514
			278.1	1.522
			145.6	1.523
3			982.0	1.502
			814.8	1.504
			682.2	1.511
			480.3	1.517
			278.1	1.526
			147.0	1.531
			68.0	1.530
5			982.0	1.510
			814.8	1.513
			682.2	1.522
			480.9	1.528
			278.0	1.538
			148.1	1.538
			74.0	1.546
8			981.2	1.517
			814.8	1.525
			681.6	1.522
			483.0	1.541
			92.8	1.540

TABLE 14.—*Effect of aging on the viscosity of skim milk*

Number of days aged	Composition (percentage by weight) of—		Pressure (gm. per sq. cm.)	Viscosity (centipoise) at 25° C.
	Fat	Total solids		
0	0.12	9.87	981.2	1.500
			814.8	1.491
			681.6	1.506
			480.9	1.507
			278.1	1.519
			142.4	1.516
			71.3	1.517
3			982.3	1.518
			816.5	1.520
			683.2	1.525
			481.7	1.534
			278.8	1.539
			139.2	1.547
			67.3	1.554
5			981.7	1.518
			816.5	1.520
			683.2	1.525
			481.7	1.534
			278.8	1.539
			139.2	1.547
			67.3	1.554
8			983.7	1.557
			815.7	1.571
			683.3	1.568
			482.1	1.576
			278.8	1.586
			151.7	1.597

The samples of milk used in the foregoing experiments were obtained under the most sanitary conditions. Contamination was guarded against as much as possible. Sterilized bottles and pipettes were used throughout the work. The udder of the cow and the hands of the milker were thoroughly washed with dilute phenol and dried. The samples were milked directly into sterile cotton strainers which led into sterile Erlenmeyer flasks.

In the first set of experiments the effect of aging on the viscosity of skim milk was followed, and characteristic results are summarized in Tables 13 and 14 and in Figure 3.

Upon examining the data in Tables 13 and 14 and the curves in Figure 3, we note that, in general, the viscosity of skim milk increases with the progress of aging at low temperatures. Apparently this rise must be due to the changes that are taking place either in the composition or the state of subdivision of the milk proteins, or both. These changes may be brought about by bacterial and milk enzymes, or they may be due partially to the constituents of the milk not being in equilibrium.

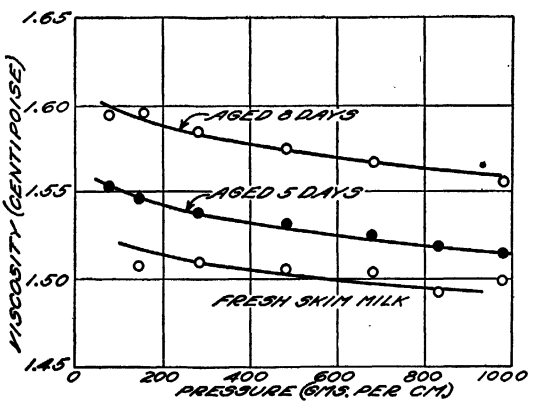

FIG. 3.—Increase in viscosity of skim milk with aging, and decrease in viscosity as shearing force is increased

In order to gain some idea as to whether or not the changes which were taking place could be attributed to acidity, determinations of the P_H and titratable acidity were made during the aging period. The results of this study are given in Table 15. In this series the milk was aged up to 25 days at about 3° C. and the effect of the storing on the viscosity, P_H, and titratable acidity were determined.

TABLE 15.—*Effect of aging at 4°–6° C. for a long period of time on some of the physical properties of skim milk* [1]

Number of days aged	Pressure (gm. per sq. cm.)	Time of flow (seconds)	Viscosity (centipoise) at 25° C.	P_H	Titratable acidity (percentage lactic acid)
1	680.8	160.7	1.433	6.78	0.14
3	680.0	164.8	1.467	6.80	.13
6	680.8	170.6	1.521	6.81	.125
9	681.6	170.8	1.525	6.83	.12
15	680.8	174.0	1.551	6.84	.11
21	681.6	174.2	1.555	6.84	.11
25	(Unable to run because of the formation of finely divided coagulum.)				

[1] Total solids=8.98 per cent; fat=0.076 per cent.

It will be seen that the apparent viscosity of skim milk gradually increased from 1.433 to 1.555 centipoise after 21 days of aging. It

was impossible to determine the "viscosity" of the milk on the twenty-fifth day because very finely divided particles were evident throughout the milk. The P_H also increased very slightly with time, and the titratable acidity lessened.

THE EFFECT OF PASTEURIZATION ON THE VISCOSITY OF SKIM MILK

This series of experiments was devoted to the study of the effect of Pasteurization on the viscosity of skim milk. Most of the Pasteurization-viscosity studies had been carried out with whole milk and cream, and the results of various workers are not all concordant. Woll (*33*), Babcock and Russell (*4*, *5*), Steiner (*29*), Evenson and Ferris (*14*), Dahlberg and Hening (*13*), and others have demonstrated that heating whole milk to Pasteurization temperatures causes a diminution of the viscosity. Achard and Stassano (*1*) and others do not agree with the majority of the workers on this subject, since they found a slight increase in the viscosity of milk when Pasteurized.

About the only work which has been done on the effect of Pasteurtization on the viscosity of skim milk is that of Whitaker, Sherman, and Sharp (*31*). They found a slight drop in viscosity when skim milk is heated to Pasteurization temperatures.

In this investigation the raw skim milk was introduced into an Erlenmeyer flask and stoppered to prevent evaporation. A thermometer was inserted through the stopper, so that the temperature of the milk could be carefully watched. The flask was placed in a water bath and the temperature was raised to about 62° C. and maintained there for 30 minutes. During this entire time the flask was continuously agitated to prevent local heating. At the end of 30 minutes it was plunged into ice water and agitated until the milk was cooled to about 4° C.

The results are summarized in Table 16.

TABLE 16.—*Effect of Pasteurization on the viscosity of skim milk* [1]

Number of days aged	Raw milk		Pasteurized milk	
	Pressure (gm. per sq. cm.)	Viscosity (centipoise) at 25° C.	Pressure (gm. per sq. cm.)	Viscosity (centipoise) at 25° C.
0	982.2	1.413	982.3	1.404
	682.4	1.423	683.2	1.410
	278.1	1.432	278.7	1.430
	117.9	1.439	118.0	1.429
4	982.2	1.436	981.2	1.420
	682.4	1.441	682.4	1.439
	277.1	1.452	278.1	1.446
	118.96	1.461	118.14	1.450

[1] Total solids=9.10 per cent; fat=0.15 per cent.

Table 16 brings out two important points; first, that Pasteurization slightly decreases the viscosity of skim milk. This agrees with the results of Whitaker, Sherman, and Sharp (*31*). Second, the average increase of the viscosity of Pasteurized milk due to aging, as found in these experiments, is almost the same as that of the raw milk. The process of Pasteurization should greatly reduce the number of organisms. In addition the organisms show very little action at a tempera-

ture of 3° to 4°C. These facts would indicate that the augmentation noted, which is practically the same in the Pasteurized and non-Pasteurized milk, is largely due to the altering of the proteins either by slow denaturization, by a shift of the equilibrium, by enzyme action, or by a combination of these factors.

THE EFFECT OF FREEZING ON THE VISCOSITY OF SKIM MILK

In the previous study it was noted that the viscosity of skim milk was slightly increased by aging at low temperatures. The next point considered was whether or not the viscosity of skim milk was affected by repeated freezing and thawing, and by aging in the frozen state.

The samples of milk used in this series of experiments were prepared in the same manner as those in the previous parts. Each sample was divided into several portions which were poured into sterile stoppered bottles. In every case one bottle of the milk was kept in ice water until the initial run was made, while the others were taken into a cold storage room where a temperature of −14° C. was maintained. Before making a viscosity determination the frozen sample was thawed out by immersing the bottle in lukewarm water. All samples were filtered before they were introduced into the viscometer. Filtration was necessary because of the presence of a small amount of finely divided precipitate in the frozen samples which would plug the viscometer.

The effect of repeatedly freezing and thawing, and of aging in the frozen state, on the viscosity of skim milk is summarized in Tables 17 and 18.

TABLE 17.—*Influence of aging on the viscosity of skim milk in the frozen state* [1]

Sample	Pressure (gm. per sq. cm.)	Number of days aged	Viscosity (centipoise) at 25° C.
Raw sample 1	980.6	None.	1.505
	680.2	None.	1.513
	980.6	1	1.412
	680.2	1	1.420
	980.6	33	1.472
	680.2	33	1.475
Raw sample 2	980.6	None.	1.475
	680.9	None.	1.479
	980.6	31	1.389
	680.9	31	1.391
Pasteurized sample	979.9	None.	1.462
	679.5	None.	1.468
	979.9	1	1.446
	679.5	1	1.447
	979.9	20	1.461
	679.5	20	1.470

[1] Raw sample 1, total solids=9.63 per cent, fat=0.17 per cent; raw sample 2, total solids=9.42 per cent, fat=0.08 per cent; Pasteurized sample, total solids=9.06 per cent, fat=0.096 per cent; aged at −14° C.

In spite of the fact that all of the samples of raw skim milk were subjected to almost the same treatment before and after freezing, and were aged under the same conditions, the results do not appear to be as consistent as would be desirable. A slight precipitate was always noted in the frozen samples. It was necessary to filter the frozen milk before making the viscosity determination in order to remove this precipitate so that it would not plug the capillary. Since one freezing caused the formation of a small amount of precipitate and a

decrease in the viscosity as shown in Table 17 it seemed reasonable to suppose that repeated freezing and thawing would produce increasing amounts of precipitate. This apparently was not the case, however, as shown in Table 18. Part of the milk was repeatedly frozen and thawed once each day for a week. At the end of a week this sample had about the same viscosity as another aliquot which was kept frozen the entire time. In all of the cases where a slight viscosity drop was noted, it always occurred when the skim milk was frozen the first time, and a small amount of finely divided coagulum was formed. It is interesting to note that the viscosity of the frozen skim milk dropped with the first freezing, but when aged for some time in the frozen state at −14° C., it increased until the normal value of the milk before freezing was almost reached.

TABLE 18.—*Influence of repeated freezing and thawing on skim milk* [1]

Pressure (gm. per sq. cm.)	Number of days aged	Number of times frozen	Viscosity (centipoise) at 25° C.
980.6	None.	None.	1.493
812.6			1.496
277.5			1.507
980.6	1	1	1.397
812.6			1.400
277.5			1.413
980.6	7	1	1.515
812.6			1.518
277.5			
980.6	7	7	1.514
812.6			1.515
277.5			1.513

[1] Total solids=9.65 per cent; fat=0.10 per cent; aged at −14° C.

EFFECT OF DILUTION ON THE VISCOSITY OF SKIM MILK

Many workers in searching for a shorter and a more convenient method for the determination of total solids and also for the detection of possible cases of watering, have attempted to establish a straight line relationship between the viscosity of whole milk and its composition. In the previous parts of this paper, the way in which the viscosity can vary depending on the previous treatment of the milk has been noted. This variation is especially marked in the case of the effect of the fat on the viscosity. The general application of the various formulas proposed assumes a constancy of the effect of the various constituents of milk on its viscosity. Such an assumption is unwarranted except to a very limited extent. It should be possible to eliminate one of the variable factors by the removal of the fat, but even under such conditions any relationship between the viscosity and the composition would apply only to milk samples which had the same previous treatment, and such a relationship would therefore not be general in its application.

Babcock (*3*) developed a very empirical formula which was supposed to express the relationship between the viscosity and the total solids. Babcock and Russell (*4*) later limited the use of this method by showing that the effect of fat was not constant but varied with the state of aggregation. Both Bogdan (*9*) and Oertel (*24*) concluded that the viscosity was closely related to the composition of the milk. However, the inner resistance to flow was especially sensitive to the fat

content. Taylor (*30*) believed that the total solids not fat could be calculated, if one knew the viscosity and the percentage of fat, by means of a formula which was based on the assumption that fat has a constant effect on the viscosity and varies only with the quantity. Babcock (*3*) showed that this relation did not hold, since the influence of a given amount of fat on the viscosity of milk is variable. Evenson and Ferris (*14*) compared Pasteurized normal milk with remade milk by means of the viscosity method. They assumed that a linear relation existed between the difference in the viscosity of milk and of water, and the total solids. Kooper (*21*) attempted to show that viscosity was a linear function of the total solids content, and could be used to detect cases where milk had been diluted with water. He believed that if one knew the viscosity of a diluted milk, the percentage of added water could be calculated by means of a constant (0.1384) which he obtained by dividing the average viscosity (1.588) by the average total solids content (11.472) of 50 samples of milk. This so-called constant is based on a rather illogical assumption, namely, that at zero concentration (water) the viscosity would also be zero. On the other hand, when he used this constant to calculate the added water, he subtracted the viscosity of water from the viscosity of the milk.

The effect of aging, Pasteurization, and the state of aggregation of the fat particles on the viscosity values has already been pointed out. Samples of milk might contain the same amount of milk solids not fat, and the composition of the milk solids not fat still shows enough variation to affect the viscosity.

In this set of experiments the viscosity of skim milk, systematically watered, was considered.

The skim milk was prepared as previously described, and was diluted with freshly distilled water. The water was always run into the milk from a burette until the desired dilution was made. The diluted samples were next stirred and left for two hours to allow the constituents to come to equilibrium.

The results of this study are summarized in Tables 19 and 20, and are graphically shown in Figure 4.

TABLE 19.—*Effect of dilution on the viscosity of fresh Guernsey skim milk from morning milking* [1]

Dilution water and milk (by volume)		Milk solids not fat (percentage by weight)	Time of flow (seconds)	Viscosity (centipoise) at 25° C.
0	100	9.34	163.0	1.457
10	90	8.41	154.9	1.381
20	80	7.47	147.8	1.319
30	70	6.54	141.4	1.258
50	50	4.77	128.8	1.143
80	20	1.87	112.2	0.993
100	0	0.00	----------	0.894

[1] Total solids=9.46 per cent; fat=0.12 per cent; aged 6–8 hours at 4° C.; pressure=681.9 grams per square centimeter.

TABLE 20.—*Effect of dilution on the viscosity of fresh Guernsey skim milk from morning milking* [1]

Dilution water and milk (by volume)		Milk solids not fat (percentage by weight)	Time of flow (seconds)	Viscosity (centipoise) at 25° C.
0	100	9.27	161.8	1.440
10	90	8.34	153.4	1.365
20	80	7.42	146.8	1.305
30	70	6.49	140.1	1.245
50	50	4.63	127.4	1.130
80	20	1.85	110.8	0.980
100	0	0.00	----------	0.894

[1] Total solids=9.40 per cent; fat=0.13 per cent; aged 6–8 hours at 4° C.; pressure=680.2 grams per square centimeter.

The data plotted in Figure 4 indicate that the relation between the viscosity and the milk solids not fat is expressed by a line slightly curved. However, for practical purposes where slight dilutions are being considered, a straight line relationship between the apparent viscosity of skim milk and its composition can be assumed.

A 10 per cent dilution resulted in lowering the viscosity of skim milk from 1.457 to 1.381 centipoise in one case, and from 1.440 to 1.365 in another. This means that the former was decreased by 0.076 centipoise and the latter by 0.075 centipoise by the same dilution. In a previous part a rise in viscosity of skim milk almost as great as the decrease noted above was observed, by simply allowing the milk to remain at a low temperature for several days. Since fresh skim-milk samples have occasionally been found to have a viscosity from 1.324 to 1.592 the viscosity method alone would not be reliable for detecting small amounts of added water.

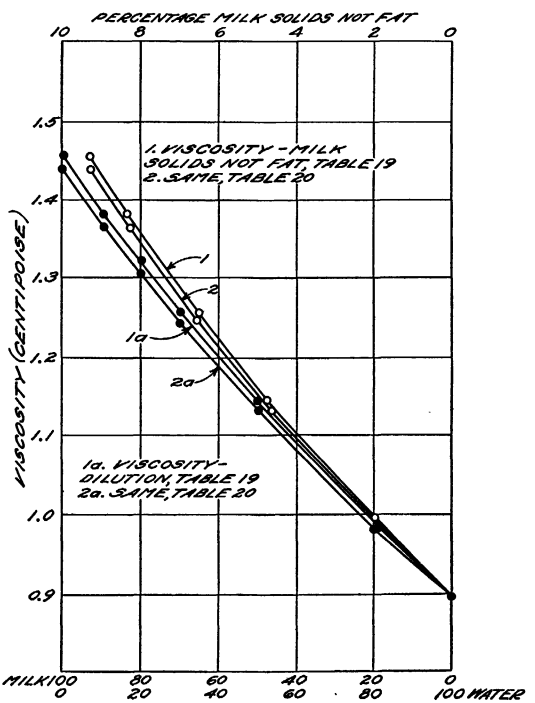

FIG. 4.—Decrease in viscosity of skim milk with progressive dilution with distilled water compared with the percentage of skim milk in the mixture and with the total solids content

DISCUSSION

The experiments reported here have shown that even the viscosity coefficient of skim milk is dependent on the shearing force used in determining it. The percentage variation in the viscosity coefficient

of normal skim milk through the range of shearing force used was small, and this slight variation could therefore be disregarded for many purposes; but the fact that such a variation does exist should not be lost sight of. The viscosity of milk can not be accurately expressed as a single value without at the same time giving the shearing force under which it was obtained.

In order to express the pressure in terms of the shearing force which is independent of the size and length of the capillary, the following relationship between shearing force and pressure was used.

$$F=\frac{rgP}{2l} \tag{8}$$

where F is the shearing force, and r and l are the radius and length of the capillary, P the pressure in grams per square centimeter, and g the gravitational constant.

The radius (0.0108 cm.) of the capillary was obtained approximately by substituting the value for C in equation (3).

Substituting the values in equation (8), the following relation between shearing force and pressure is given:

$$F=0.530\,P \tag{9}$$

The shearing force used in this work as calculated by equation (9) varied from about 36 to 780 dynes. The curves (see fig. 2) bent more sharply at the lower shearing pressures, while at the higher pressures the viscosity coefficient approached more nearly a constant limiting value.

The viscometers which are frequently used for determining the viscosity of milk, such as the ordinary Ostwald viscometer, probably operate at shearing forces between 25 and 100 dynes. They thus operate on that part of the curve where the viscosity coefficient is changing most rapidly with shearing force. Viscometers of this type must be constructed very nearly alike in order that they may give the same viscosity coefficient with the same sample of milk.

The decrease in the viscosity coefficient with increasing shearing force is not due to the breaking down of a structure in the skim milk; otherwise repeatedly running the same sample through the capillary would accomplish the same purpose. Also the increase in the viscosity of skim milk by aging can hardly be explained on the basis of a structure formed, for if this were the case one would expect that the structure would be broken down again by repeatedly running the aged sample through the capillary. The experiment with colostrum skim milk showed that the viscosity actually increased while the milk was being run repeatedly through the capillary.

Homogenization of milk and cream shows important viscosity effects; the fat globules are greatly reduced in size in both; the fat globules in the homogenized cream are markedly clumped, but clumps are practically absent in homogenized milk. This is the reason why homogenized milk does not cream to any appreciable extent, and explains why the viscosity values are so uniform with homogenized whole milk as compared with raw whole milk.

Repeatedly running normal skim milk and homogenized whole milk through the capillary of the viscometer at shearing forces from 360 to 550 dynes had no effect on the viscosity coefficient. Raw

whole milk subjected to the same treatment decreased in viscosity during the first 10 times through the capillary and after that up to 25 times through the capillary practically no further decrease in viscosity occurred. Microscopic observations indicated that this decrease in viscosity was due to the breaking up of the clumps of fat globules. Experiments in another connection have shown that as the temperature is raised the fat globules are held in the clumps less tenaciously so that it is highly probable that the decrease in viscosity due to running raw whole milk repeatedly through the capillary would have been much greater if the experiment had been carried out at a lower temperature. These experiments indicate that mechanical agitation in which air is not incorporated in the milk would have no effect on the viscosity of skim milk or homogenized whole milk but would tend to decrease the viscosity of milk in which clumps of fat globules are present.

The experiments on the effect of freezing on the viscosity were not very extensive, but they probably give an indication of the general influence of freezing on skim milk.

The decrease in the viscosity of skim milk due to dilution with water was shown to be represented by a slightly curved line. Attention should be called to the fact that as milk is diluted with water the hydrogen ion concentration decreases, as shown by Sharp and McInerney (*27*). This change in hydrogen ion concentration might produce a change in the hydration of the proteins so that until further experiments are carried out one is not justified in using this data in studying the relation between viscosity and concentration under the same conditions.

There is little doubt that taking a large number of samples, a relation exists between the total solids and the viscosity of milk, but because of the large probable error and the many factors which effect it, such as aging, Pasteurization, clumping of the fat globules, variation in the composition of the total solids, etc., the use of the viscosity as a substitute for the total solids determination of individual samples of milk is of limited value. Because of these same variables and due to the possibility of a wide variation in the viscosity of normal milk, the viscosity determination alone can not be used as a test for small amounts of added water.

CONCLUSIONS

The viscosity coefficient of whole milk, condensed skim milk, and even skim milk is not independent of the rate of shear, but decreases as the rate of shear is increased, approaching a constant value at high rates of shear.

The bending of the viscosity pressure curve is greatest in the region of shearing force which is commonly used for determining the viscosity of milk and milk products; therefore different investigators determining the viscosity of the same sample of milk would hardly obtain exactly the same viscosity coefficient, unless the viscometers which they used were nearly identical.

Mechanical agitation may cause a decrease in the viscosity of milk containing clumps of fat globules due to the breaking up of these clumps. Mechanical agitation produces no decrease in the viscosity of skim milk or of homogenized milk.

Skim milk progressively increased in viscosity with age. The aged skim milk could not be brought back to the viscosity value which it had when fresh by repeatedly running the aged sample through the capillary.

Homogenization caused a distinct rise in the viscosity of whole milk, while it caused practically no change in the viscosity of skim milk.

Pasteurization of skim milk at 62° C. for 30 minutes caused a slight decrease in viscosity when determined at 25° C.

Frozen skim milk held one day showed a decreased viscosity, but after it had aged in the frozen state for several days the viscosity increased to near that for the fresh sample.

Repeatedly freezing and thawing skim milk once each day for seven days produced the same effect on the viscosity as holding aliquot for the same length of time in the frozen condition.

The viscosity values obtained after diluting skim milk with various amounts of water fell on a slight curve, showing that the viscosity is not strictly a linear function of the total solids.

These experiments indicate that the viscosity of a sample of milk does not necessarily indicate accurately the total solids content except possibly for very restricted groups of samples.

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