THE DENSITY OF MILK AT LOW TEMPERATURES [1]

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SUMMARY

The densities of a variety of herd milks from representative sources in the Washington, D. C., area were determined at low temperatures, to establish volume-weight relationships more accurately than was possible from existing data.

Density measurements were made in duplicate over a range of 1 to 10°C. on 101 samples of milk. Specially designed pycnometers, having a capacity of about 46 ml., were used in refrigerated water baths controlled to within ± 0.02° C. The percentage of milk fat in most of the samples was determined by the Babcock method, and in the remainder by the Mojonnier method. The percentage of total solids in 85 samples was determined gravimetrically.

The percentages of fat, total solids, and nonfat solids covered the following ranges, respectively: 3.1 to 6.4; 11.6 to 16.1; and 8.2 to 10.2. The range of densities at 0.95, 4.95, and 9.85°C. were, respectively: 1.0312 to 1.0386; 1.0322 to 1.0373; and 1.0298 to 1.0368.

Formulas for calculating the density of milk were derived from the data by the method of least squares. The results emphasize that density is more closely correlated with the percentage of nonfat solids than with the percentage of fat in milk.

Information on the density of milk having different percentages of fat for temperatures of practical interest has been available for many years. Values in tabular form (3) are used generally by milk processors for calculating the payments for milk, and for estimating weight yields of dairy products from the volume in gallons and the percentage of fat by weight. The tables are based on a study of the density of milk which was made by Bearce (2) at the National Bureau of Standards about 45 yr. ago on a relatively few samples. Several values at low temperatures were not used, because they could not be satisfactorily included in the formulation of a simple equation for densities between 20 and 50° C. Some doubt concerning the accuracy of the data was expressed in the report. This was attributed to some separation of fat in the samples during the experiments, and to the fact that the values for densities at low temperatures were obtained by extrapolation from the determinations made at 20° C. and higher. The suggestion was made that further work should be done using a method for determining density which would be more adapted to the nature of milk.

Published information concerning the density of milk at low temperatures is rather meager. Wegener (15) reported values for pasteurized milk in the range

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of 10 to 75° C., but did not include the effect of milk composition. Thomsen (14) constructed a table for calculating the weight of milk per gallon over the range of 36 to 160° F. (2.2 to 71.1° C.) which is based on a combination of the early data from the Bureau of Standards and those of Jacobson (5). He verified experimentally a random number of the values. Short (13) determined the density of raw milk between 10 and 45° C., and reported the variation of the temperature coefficient of density for milks of different composition. Recently, Whitnah *et al.* (16) investigated the density of milk and found a smooth curve for density vs. temperature near 4° C. The average temperature of maximum density was −5.20° C.

Reliable density values are especially needed in the low temperature range, since milk is now largely stored in farm tanks and transported in tank trucks at temperatures near 40° F. (4.4° C.). Therefore, this investigation of the density of milk over the range of 1 to 10° C. was made in order to fill the void in the existing information, and to obtain data which are necessary for the preparation of density tables for practical use. Tables which give the density of milk at low temperatures in pounds per gallon for different percentages of fat and nonfat solids will be presented in another publication.

EQUIPMENT AND MATERIALS

Pycnometers. Densities were measured by the pycnometer method, using specially designed pycnometers (Figure 1). A special feature is an upper cup which holds an excess of the sample above the orifices of the capillaries, thus permitting an automatic adjustment of the milk volume when temperature equilibrium is reached. The pycnometers were calibrated with double-distilled water at 0.95, 4.95, and 9.85° C.

Constant temperature baths. Stainless steel water baths equipped with electric stirrers and certified mercury thermometers, and containing distilled water, were controlled to within ± 0.02° C. A Beckman differential thermometer served in estimating the readings to 0.01°. The densities were determined in a room which was held at a constant temperature of 20° C.

Milk samples. A total of 101 samples of mixed raw milk representing all months of the year were tested. Seventy-four were obtained from the U. S. Department of Agriculture herd at Beltsville, Maryland. These samples were mixed morning milk from four to six cows of the Holstein, Jersey breeds and cross-breeds of Holstein-Sindhi and Holstein-Jersey-Red Dane. The samples were cooled promptly to about 40° F. and 60 of them were held for from 4 to 6 hr. and 14 of them for about 24 hr. prior to starting the density determinations.

Eleven samples were obtained from the University of Maryland dairy, nine from the University herd, and two from nearby farms. The University herd milk was mixed morning and evening milk from a herd of 75 cows, which comprised Ayrshire, Holstein, Jersey, and Guernsey breeds. Three samples represented milk held for about 17 hr. and the remainder for about 4 hr. at about 40° F.

Ten samples supplied by the laboratory of the District of Columbia Department of Health came from milk shipped from Maryland and Virginia farms

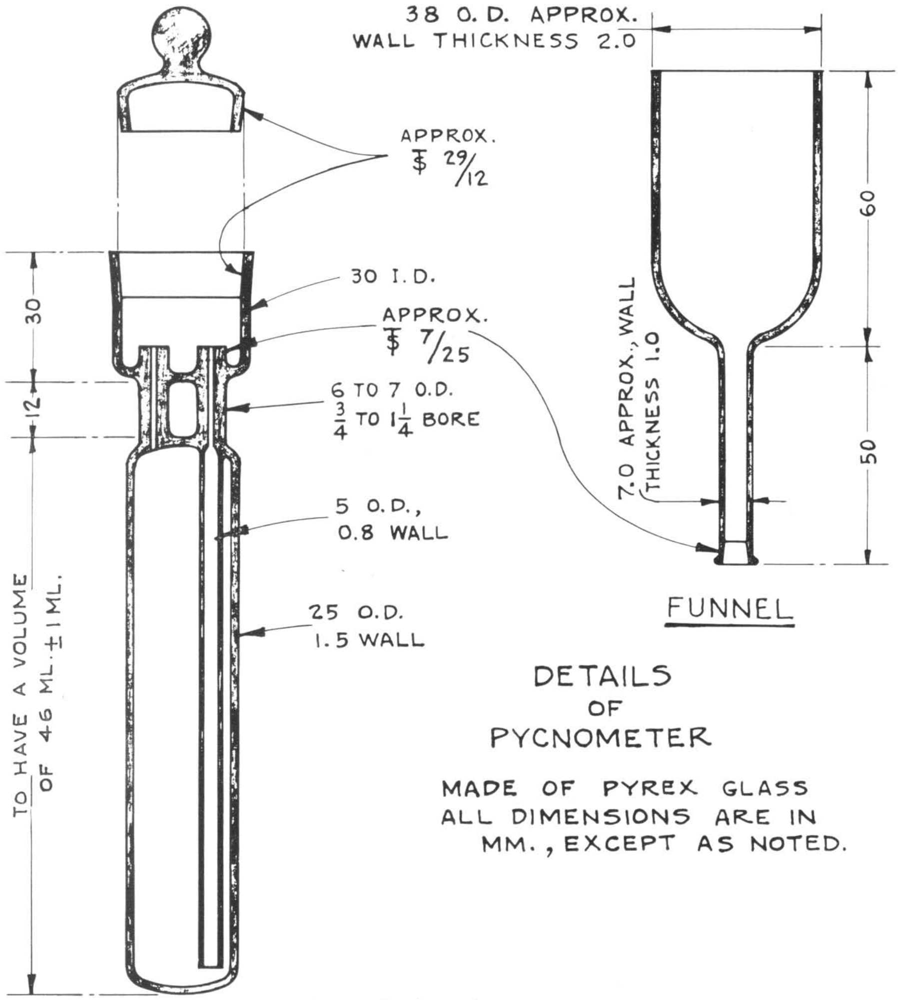

FIG. 1. Design of pycnometer.

within a radius of about 40 miles. The samples represented from 2,800 to 32,000 lb. of farm tank or tank truck milk from two or more producers. These samples represented commercial fluid milk. It may be presumed that they consisted largely of Holstein milk, since it has been reported that approximately 85% of the cows in the District of Columbia milk shed are Holsteins (18). Information was not available for the tank-holding period of this milk.

Six samples of Guernsey milk supplied by two District of Columbia dairies were from tank trucks which contained from about 4,300 to 8,400 lb. of milk. Four samples were from milk held about 24 hr. and two samples from milk held about 2 hr. at 40° F.

EXPERIMENTAL METHODS

Density determinations. Simultaneous density determinations were made in duplicate at two temperatures for each sample of milk: 54 were measured at

0.95 and 4.95° and 47 at 0.95 and 9.85° C. The occlusion of small air bubbles in the pycnometers was avoided by slowly pouring the first portion of milk into the funnel while the pycnometer was in a slanted position. The milk was allowed to overflow from the other capillary, and the level of milk in the cup was adjusted so that the orifices were immersed to a depth of about 2 mm. The cap was placed on the cup and the pycnometer immersed in the bath to the level of the milk in the cup. The design of the pycnometer facilitated rapid chilling of the milk; thus, the volume of milk rapidly attained a state of equilibrium. This arrangement and the gentle agitation of the milk in the cup caused by vibrations of the cooling equipment and stirrers tended to reduce any errors which might be due to the rising of milk fat in the cup during contractions of the milk.

The filled pycnometers were held in the baths for a period of about 1 to 1.5 hr. for the density determinations. Subsidiary experiments indicated that fat in milk which had been previously cooled to about 40° F., and then held for about 1 hr. in the refrigerated baths, was in a state of physical equilibrium; therefore, the milk fat was largely solidified, and its density was at a maximum during the determinations.

After temperature equilibration, each pycnometer was raised slightly in the water baths, the cap removed briefly, and most of the excess milk in the cup withdrawn with a small rubber-tipped suction tube. The surface of the cup was cleaned with small pieces of lintless tissue which had been moistened with distilled water–acetone solution (about 70:30) and wrapped around small bevel-ended wooden sticks, and finally with dry tissue.

All weighings of the pycnometers were made at 20° C. with an analytical balance. The weights were calibrated by comparison with standard weights, certified by the National Bureau of Standards. A correction for the air buoyancy was applied to the apparent densities. A tare pycnometer eliminated any correction for the vessel itself, and the effects of variations in the humidity and temperature.

Determinations of milk fat and total solids. Gravimetric determinations of the percentage of fat were made on the first 16 samples by the Mojonnier method (9), and the Babcock method (1, 8) was employed for the remainder, on which solids also were determined. Accurately calibrated Babcock bottles and pipettes, certified by the Dairy Inspection Service of the State of Maryland, were used. The fat readings were estimated to 0.05 per cent by means of an illuminated reader with a magnifier. The percentage of total solids was determined by the Mojonnier vacuum-oven method (9). The determinations were carried out in duplicate.

RESULTS

The data before analysis are not presented here because of their number. Photostats of the tabulated results can be obtained by writing to the author.

The relationships between density and percentages of nonfat solids, fat, and total solids at 0.95° C. are shown in Figures 2, 3, and 4, respectively. Only the results obtained at 0.95° are presented in detail because all of the samples were tested at this temperature; whereas, only about half of them were tested at 4.95°

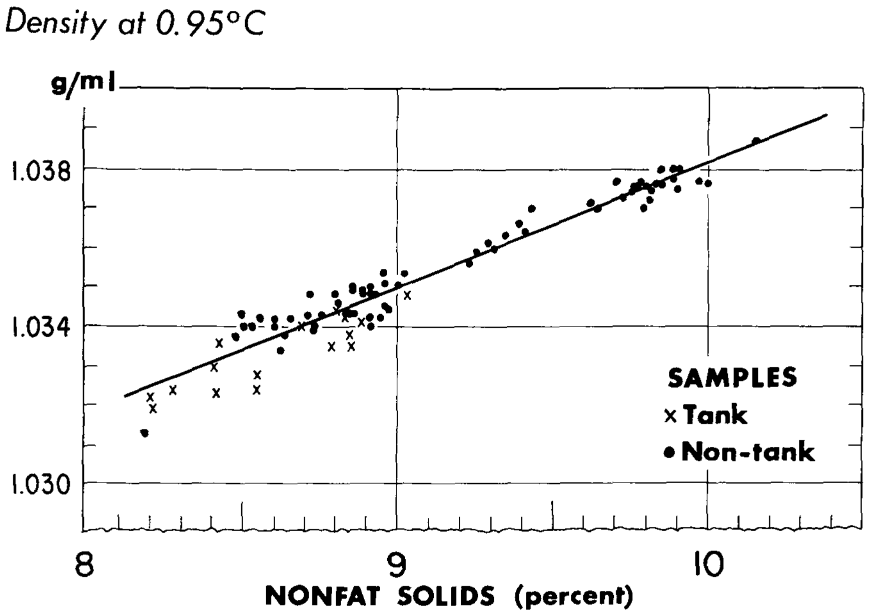

FIG. 2. Relationship of density to percentage of nonfat solids.

and the other half of them at 9.85° C. Furthermore, in general, the results at 4.95 and 9.85 were similar to those obtained at 0.95° C., except for a slight difference due to temperature.

It should be noted that the density values in relation to nonfat solids (Figure 2) are much closer to the line than those in relation to either fat or total

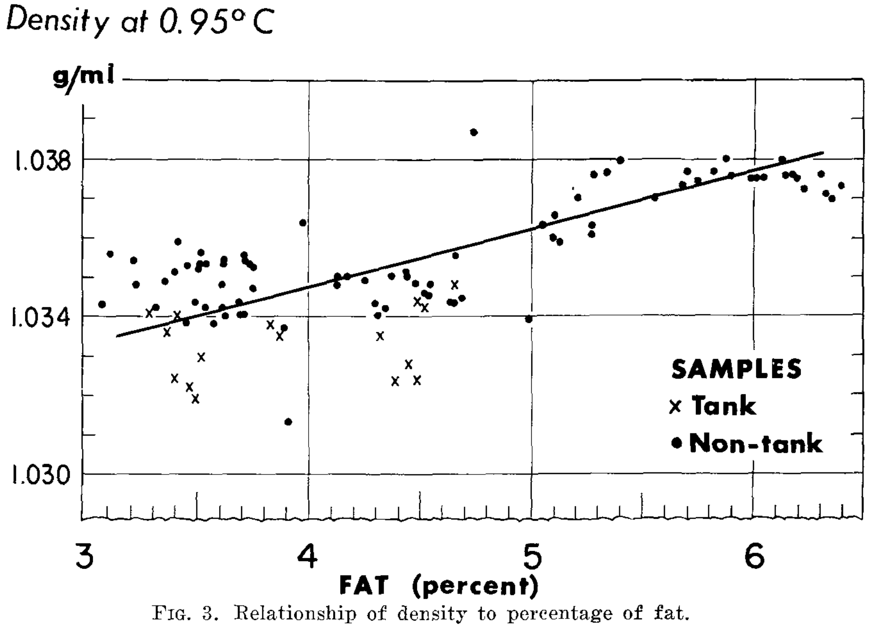

FIG. 3. Relationship of density to percentage of fat.

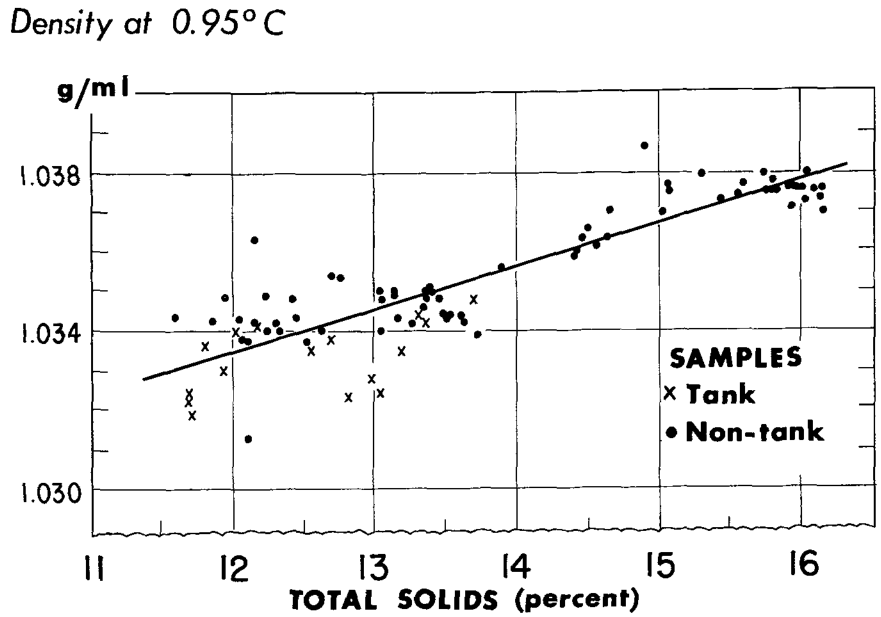

FIG. 4. Relationship of density to percentage of total solids.

solids (Figures 3 and 4). Also, the density was affected as much by a 20% difference in nonfat solids content as by about a 123% difference in fat or by about a 44% difference in total solids over the range of these measurements.

A number of the tank truck samples gave anomalously low values for density and total solids, perhaps indicating the presence of extraneous water.

STATISTICAL ANALYSIS

On the basis that density can be expressed as a linear function of temperature and percentages of fat and nonfat solids over a short range, the best fitting function can be determined by the method of least squares.

If only the percentage of nonfat solids is considered, the function is:

$$D = 1.006830 - .000179\,T + .003144\,N \qquad (1)$$

Where D = density in gram/milliliter

T = temperature in degrees C.

N = percentage of nonfat solids in the milk.

The 95% confidence limits on densities estimated by this formula are $D \pm .000875$. These narrow confidence limits result from a 2.25-fold reduction in the standard error.

When only the percentage of fat is considered, the similar function is:

$$D = 1.028863 - .000195\,T + .001432\,F \qquad (2)$$

Where F = percentage of fat in the milk.

The 95% confidence limits on an estimate of density by this function, used as a formula within the range under investigation, are approximately $D \pm .00198$.

If the percentages of both fat and nonfat are considered, the best fitting function is:

$$D = 1.003073 - .000179\,T - .000368\,F + .003744\,N \tag{3}$$

The 95% confidence limits on densities estimated by this formula are $D \pm .000812$.

It may be observed that there is but slight advantage in the use of the percentage of fat in addition to that of nonfat solids.

If nonfat solids and fat are considered together as total solids (S), then the corresponding fitted function becomes:

$$D = 1.021110 - .000188\,T + .001046\,S \tag{4}$$

The 95% confidence limits on densities estimated by this formula are approximately $D \pm .00154$. It may be observed that this function does not provide an appreciably better estimate than the function which considers fat only.

Comparison of results with published values. Values obtained by the extrapolation of Bearce's data (2) below 20° C., as he suggested, were found to be about 0.3 to 0.4% higher than the densities for 3.5% fat milk calculated by Formula (2) for temperatures of 1, 5, and 10° C. His observed densities for 2.5, 3.5, and 5% fat milks averaged about 0.2% higher over the temperature range of 0 to 10° than densities calculated by Formula (2). Bearce reported that the densities were in most cases somewhat too large.

The density of raw milk containing 4% fat and 9% nonfat solids calculated for 10° C. by the formula of Short (13) was about 0.13% lower than the density calculated by Formula (3).

The average densities of pasteurized, and pasteurized and homogenized milks containing 4% fat and 9% nonfat solids reported by Rutz *et al.* (12) for the temperature range of 0 to 8° C. were about 0.05% lower than densities calculated by Formula (3). Whitnah *et al.* (16) published density values for pasteurized, and pasteurized and homogenized milks containing 3.6 fat and 9.1% nonfat solids at the temperatures of 3 and 5° which were 0.15 to 0.18% lower than densities calculated by Formula (3).

Density values expressed in pounds per gallon in Thomsen's table (14), for 3, 4, and 5% fat milks at temperatures of 40 and 50° F., are almost identical with densities calculated by Formula (2) and converted into apparent weights in pounds per gallon at these temperatures.

The agreement between the density values for milk from various sources is noteworthy, when the variations in milk and its treatment, and the different methods used in determining density, are considered. This is especially true because of unavoidable variations in milk and in sampling it. Rutz *et al.* (12) found that the standard deviations for the density of milk from one herd of cows were large when compared with the estimated precision of measurement. It should be expected that such deviations would be even greater when samples of milk are obtained from various sources and under various conditions of sampling.

DISCUSSION

The literature shows that the density of nonfat solids in milk at 10° C. is approximately 1.6 times that of water, whereas the density of milk fat is 0.93 times that of water. Thus, the density of nonfat solids is 0.6 greater than water, and that of fat is only 0.07 less than that of water. Also, there is usually slightly more than twice as much nonfat solids as fat in whole milk. Thus, the nonfat solids are the most important constituents affecting the density of milk, and this is evident from the results obtained in this study, which show that density is more definitely correlated with the percentage of nonfat solids than with the percentage of either fat or total solids (Figures 2, 3, 4). Obviously, any table involving the volume and weight relationship of milk would have a higher degree of accuracy if the nonfat solids of milk, as well as the fat, were taken into consideration in its preparation and use.

The composition and, hence, the density of the nonfat solids is correlated with the percentage of fat in milk. The density and the percentages of protein and ash increase, but the percentage of lactose decreases, with an increase in the percentage of fat in milk. The ratio of lactose to protein increases about 46% as the percentage of fat decreases from 6.5 to 3.0 (10). Recent studies have indicated that the density of the nonfat solids decreases about 0.02 as the percentage of fat in milk increases from 3 to 6 (17).

The density of milk fat also varies with its composition. The differences between the average maximum and minimum values for the density of milk fat, reported from several sources, varied between about 0.003 and 0.004 (6, 7, 11).

Temperature and its effect upon the physical state of the fat, and particularly the variations which occur in the ratio of the fat and the nonfat solids of milk, are major factors influencing density. Milk fat contracts slightly upon solidification when milk is cooled, and differences in specific gravity may be as great as 0.0002 for each per cent of fat in the milk, depending upon its temperature history (4).

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