

PRESSURE LOSSES AND RHEOLOGICAL
PROPERTIES OF FLOWING BUTTER

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ABSTRACT

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The pressure losses and rheological properties of butter flowing through stainless steel tubing were examined under conditions which were comparable to commercial handling and printing. Pressure is required to overcome the internal resistance of butter to flow. Viscosity is a measure of this internal resistance. An extrusion viscometer was constructed to measure the apparent viscosity of butter since its operation is similar to the actual conditions of flow. The apparent viscosity was calculated from the extrusion viscometer data using the Hagen-Poiseuille equation for flow through tubing.

The butter was found to have an average density of 0.952 g./ml. for 55 to 75° F. under the flow conditions. Since variations are normal in commercial butter this average may be used in power requirement calculations.

Flow profiles were obtained by alternately forcing butters of different colors through the various lengths of tubing at different temperatures. The velocity gradient was small within the butter except near the wall where it was large. As the temperature of the butter decreased from 70 to 55° F. the velocities within the butter became smaller.

A linear relationship was found between the logarithm of apparent viscosity and the logarithm of bulk velocity for a range of 0.001 to 1 ft./sec. The average slope of the regression line was -0.84649. As the length of the tubing increased the average apparent viscosities decreased but at a decreasing rate. Very small differences were found between the apparent viscosities obtained using a 10.5-in. and 14.0-in. length of tubing.

The influence of temperature on the logarithm of the apparent viscosity was found to be linear having a slope of -0.0587 for the range of 55 to 75° F.

A general empirical equation was determined relating the influence of the bulk velocity and temperature to the decrease in apparent viscosity and is:

$$\log \eta = 7.93446 - 0.84649 \log v - 0.0587T$$

Pumping action reduced the apparent viscosity of butter by increasing its temperature and by working. The rate at which the pump operated (52 and 120 r.p.m.) had no apparent influence on the apparent viscosity.

The power requirements for various conditions of temperature, bulk flow and tube diameter were determined.

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LIST OF SYMBOLS

Symbol	Explanation
A	Area
B	A constant
C	Constant of integration
D	Diameter
DF	Degrees of freedom
F	Force
K	A constant
L	Length
P	Pressure
ΔP	Pressure loss
Q	Volumetric flow rate
R	Radius
Re	Reynolds number
S	Rate of shear
SE	Standard error of estimate
T	Temperature
W	Weight
X and Y	Regression equation variables

Symbol	Explanation
a	Intercept in regression equation
b	Slope in regression equation
d	Differential sign
e	Natural logarithm base
f	Friction factor
f'	Yield value
g_c	Dimensional constant relating force and mass (32.2 lb. ft/lb. sec. ²)
h	Loss of head
n	Exponent in power-law equation
t	Time
v	Bulk velocity
x and y	Cartesian-coordinate distances
Δ	A difference
η	Viscosity or apparent viscosity
μ	Symbol for microns
π	3.141593 . . .
ρ	Density
τ	Shear stress

INTRODUCTION

The dairy industry will become more mechanized or automated because of economic necessity. As the trend progresses more dairy products will be handled by equipment during processing and packaging.

Butter has been transferred from the churn to the printer or bulk container mainly by manual methods in the United States. Attempts have been made to develop methods of emptying the churn mechanically in an effort to eliminate the labor involved and to reduce the possibility of contamination. The two main methods are the butter truck and the gear type pump. Both of these methods are utilized with churns incorporating specific designs.

In order to develop better methods of mechanically handling butter a knowledge of the physical characteristics of flowing butter is very important. Butter is usually subjected to empirical tests which evaluate characteristics of immediate interest to the consumer and except in isolated cases little effort has been made to consider the fundamental flow properties.

The science of deformation and flow of materials is often called rheology. Physical properties of materials associated with flow are referred to as rheological properties.

An investigation of the rheological properties of butter has not been attempted under flow conditions. Therefore, the objective of this study is to determine the pressure loss and rheological properties of butter flowing through tubing under normal processing conditions. This knowledge could then be utilized to improve the methods of removing butter from the churn, improve butter printing equipment, design an inexpensive butter patty dispenser and conceivably lead to a sterile system of batch churning and packaging of butter. Other beneficial results may be realized from the improved handling procedures, such as, longer keeping quality.

LITERATURE REVIEW

The importance of rheological properties in butter has long been recognized. Many of these properties were first judged by organoleptic methods. Various attempts to find objective mechanical tests were endeavors to evaluate characteristics of immediate interest to consumers. The initial tests were purely empirical. However, later investigators have applied modern methods of rheological research with some success. Many of the analytical tests used have evaluated the rheological properties separately and under different specific conditions.

I. Viscosity

A material when subjected to a force will deform. Deformation is the process of changing the relative position of the parts of a unit. When deformation is irreversible the materials are called fluids. Fluids include gases and liquids as well as those solids which exhibit continuous flow without separation under certain readily realizable conditions. A certain measurable resistance is encountered in a flowing material. This resistance is due to the internal friction of the molecules moving past each other. Viscosity is the measure of the internal friction of a fluid.

Newton deduced the fundamental law of viscosity more than 250 years ago (6). This concept can be illustrated by a simple model (Fig. 1). Suppose that an inelastic fluid is contained between two parallel planes of area (A) separated by the distance (dy). The lower plane is stationary while the upper plane is moved with a constant velocity (v) by applying of a force (F) so that the flow in the

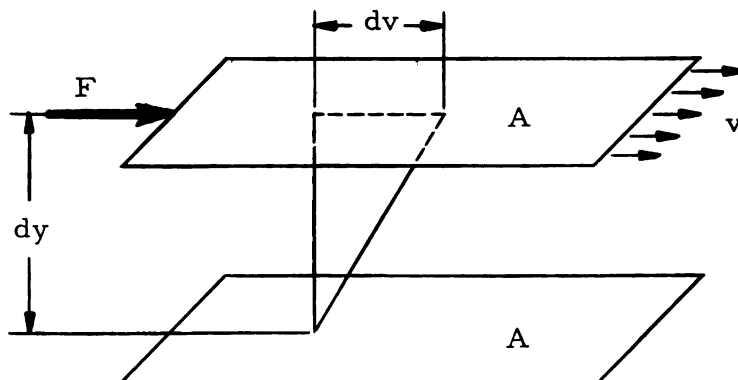


Fig. 1. A model for Newton's theory.

fluid is laminar. The force per unit area (F/A) is called the shear stress (τ) and the change in velocity (dv) over the distance (dy) is called the rate of shear (S). The relationship between the shear stress and the rate of shear defines a proportionality constant (η) called the "coefficient of viscosity" or simply "viscosity." Thus, the equation is:

$$\frac{F}{A} = \eta \frac{dv}{dy} = \eta S$$

which postulates: 1) shear stress is uniform, 2) shear stress is directly proportional to viscosity and 3) viscosity is constant regardless of rate of shear.

II. Newtonian fluids

A plot of shearing stress versus rate of shear is termed a flow curve or rheogram. A linear flow curve passing through the origin is defined by equation 1. A material having such a flow curve is termed Newtonian. Therefore, viscosity is constant and only one other point in addition to the origin is necessary to describe the complete flow pattern of a material as shown in Fig. 2(a).

By rearrangement of equation 1 the absolute viscosity is:

$$\eta = \frac{\frac{F}{A}}{S} = \frac{\text{shear stress}}{\text{rate of shear}} \quad 2$$

A material requiring a shear stress of one dyne/sq. cm. to produce a rate of shear of one reciprocal sec. has an absolute viscosity of one poise. Normally the poise is a rather large unit so that the centipoise (0.01 poise) is used. Pure water at 68.4° F. has an absolute viscosity of one centipoise.

The English system of units (ft., lb., sec.) are also used in which the unit of absolute viscosity is the lb. sec./sq. in. or reyn. A more convenient unit is the Newton which equals one millionth of a reyn. Conversion between the metric and English systems of units can be made on the basis that one reyn is equal to 6,895,000 centipoises.

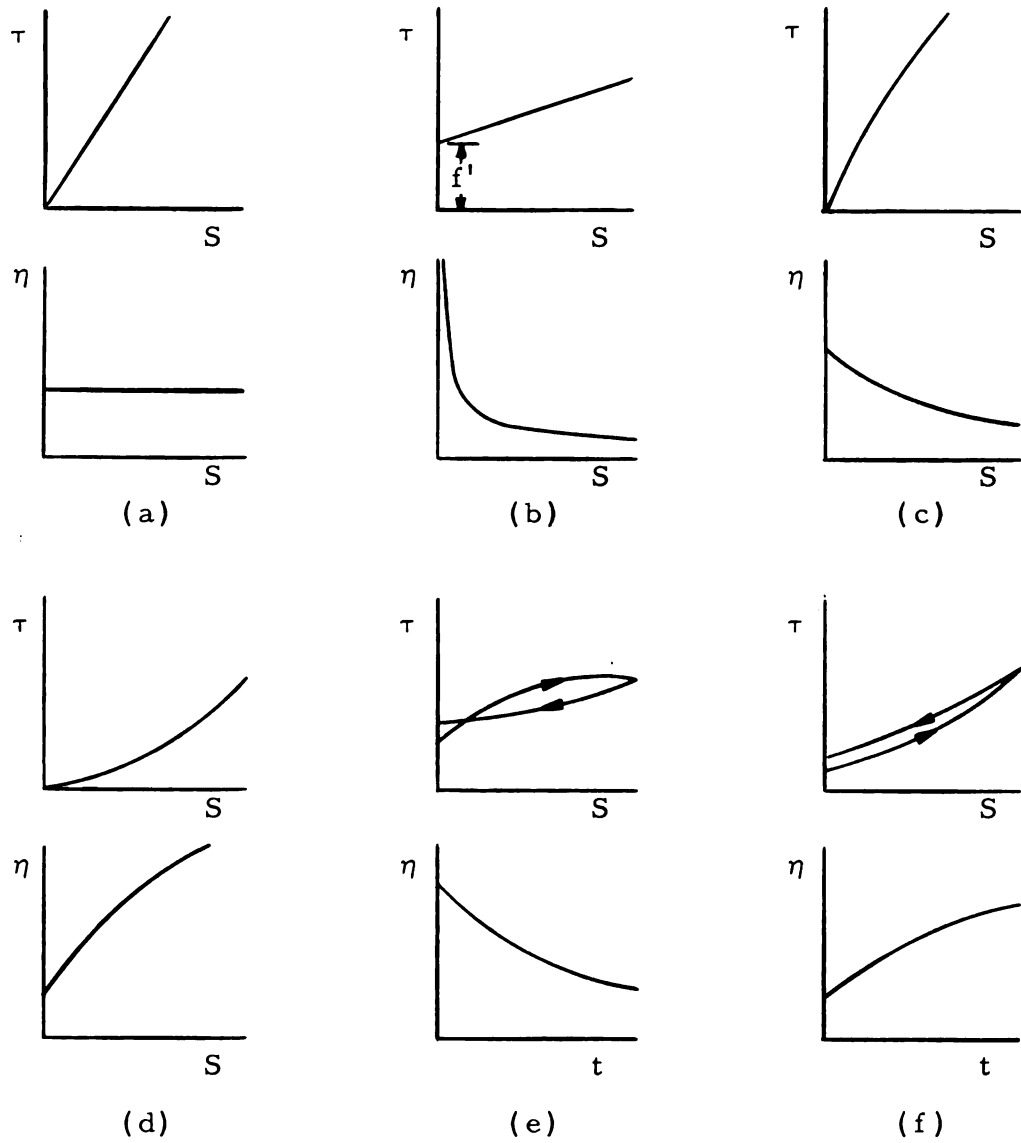


Fig. 2. Characteristic flow behavior of fluids: (a) Newtonian, (b) Plastic (f' = yield value), (c) Pseudoplastic, (d) Dilatant, (e) Thixotropic and (f) Rheopectic.

III. Non-Newtonian time-independent fluids

The viscosities of many materials are influenced by the rate of shear. These materials are termed "non-Newtonian." The viscosity of a non-Newtonian fluid will depend on the rate of shear at which it is measured and will have a number of viscosity values corresponding to various rates of shear. The term "apparent viscosity" is used to describe the viscous property of non-Newtonian fluids. Apparent viscosity is expressed in absolute units and is a measure of the resistance to flow at a given rate of shear. It represents the viscosity of a Newtonian liquid exhibiting the same resistance to flow at the chosen shearing stress or rate of shear (Fig. 3). To have meaning the rate of shear used in the measurement must be provided. The

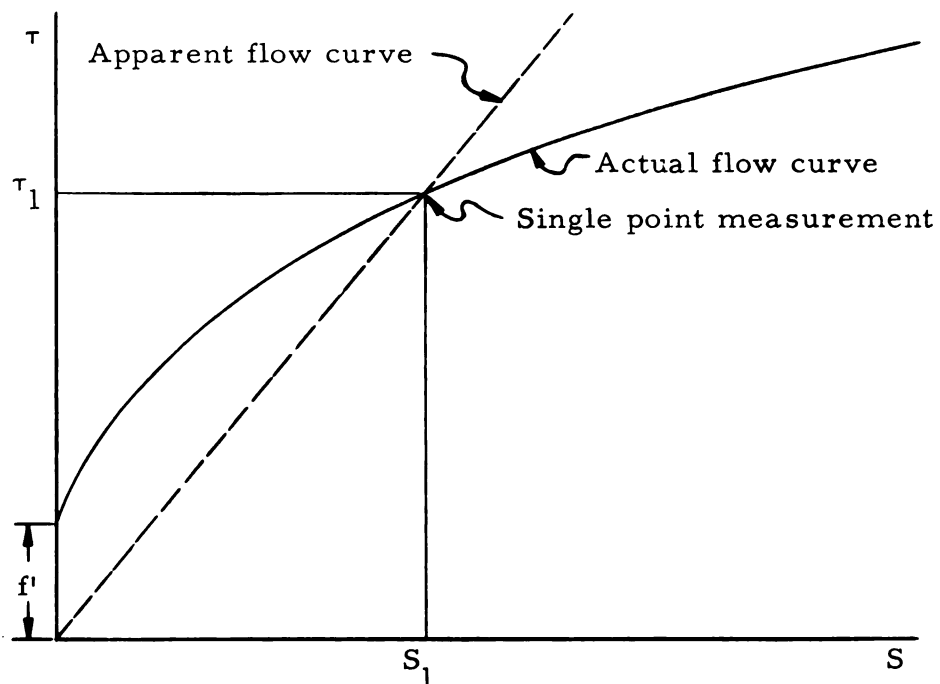


Fig. 3. Actual and apparent flow curves for a non-Newtonian fluid.

apparent viscosity of a fluid is obtained experimentally by measuring the shear stress and dividing it by the rate of shear. A rheogram relating shear stress to rate of shear is frequently used to describe the viscous properties of a non-Newtonian material.

Non-Newtonian materials can be characterized as having three main types of flow -- pseudoplastic, dilatant and plastic (Fig. 2). Fig. 2(c) illustrates a pseudoplastic material. The apparent viscosity decreases with increasing values of rate of shear. A dilatant material shows the opposite effect as illustrated in Fig. 2(d). The apparent viscosity increases with increased rate of shear and will often reach a point where the fluid becomes a solid (25). The shear diagram of pseudoplastic or dilatant fluids when plotted logarithmically is often found to be linear and may be represented by the power-law equation:

$$\tau = KS^n \quad 3$$

Plastics show a decreasing apparent viscosity with increasing rate of shear as illustrated in Fig. 2(b). This type of flow behavior is characterized by a "yield value" since a certain force must be applied to the material before any shear (or flow) takes place. The material will show a viscosity tending to approach infinite values as the rate of shear is decreased.

IV. Non-Newtonian time-dependent fluids

Flow properties of some non-Newtonian fluids are also dependent on the amount of shearing which has occurred and the history of the fluid. These fluids are considered time-dependent. Time-dependency is indicated by hysteresis loops in the shear diagram. If the viscosity value at a constant shear rate decreases with time of measurement the behavior is termed thixotropic as illustrated in Fig. 2(e) and occurs in addition to the plastic, pseudoplastic or dilatant characteristic of the fluid. Thixotropy was first defined by Peterfi (32) as an isothermal, reversible sol-gel-sol transformation. Translated, the word thixotropy means change by touch, indicating that the material decreases in viscosity on shear, but builds up again when at rest. Some fluids revert to their original viscosity almost immediately while others will recover after several hours. Minard (25) mentioned that there is evidence to suggest that a thixotropic material is basically similar to other non-Newtonians differing only in that the time interval of hysteresis in thixotropic materials is of a large enough magnitude to be detected in practice.

If a fluid is subjected to a constant rate of shear for a given period of time and its apparent viscosity increases to some maximum value the phenomenon is called rheopectic. Upon cessation of shearing and resting for a time, its apparent viscosity decreases again. Because time-dependency effects are very unpredictable there are

no mathematical models to describe their shear diagram.

V. Influence of temperature on viscosity

The viscosity of most materials decreases with an increase in temperature. Andrade (3) and Sheppard and Houck (35) showed that when no chemical reaction occurs the change in viscosity with temperature in a Newtonian material may be approximated by:

$$\eta = Ke^{B/T} \quad 4$$

Weltmann (41) mentioned that for some non-Newtonian materials the change in viscosity with temperature can be approximated by:

$$\eta = Ke^{-BT} \quad 5$$

for small temperature ranges.

VI. Composition and structure of butter

The physical properties of butter are influenced by the composition of the cream, the details of the manufacturing process and the storage conditions. The properties mainly affected are the appearance, keeping quality and rheological properties such as body and texture, and spreadability. In controlling the rheological properties, the ratio between the lower and higher melting triglycerides in the milk fat normally predominates over the manufacturing conditions (19).

The rheological properties of butter will be influenced by the volume of both the dispersed phase (fat globules and crystals) and the continuous phase (liquid fat), by the flow properties of the

continuous phase, by the deformability of the dispersed phase and by the proportion, form and arrangement of the dispersed particles.

King (18) made the first estimation of the relationship between the volume of the dispersed phase and continuous phase by counting the fat globules and measuring their size. Mulder (27) stated that this technique is difficult and not very accurate.

Butter made in the conventional method of buttermaking is the result of a two-step concentration; that is, separation of milk (3-4 percent fat) into cream (32-40 percent fat) and the churning of the cream into butter, plus working. The butter consists of 80-83 percent fat with the remainder being water and non-fat-solids. A small volume of air is also occluded during manufacture.

King (19) described the structural elements of the butter as a complicated type of emulsion. The fat globules and crystals, moisture droplets and curd particles are about 0.5 to 20 μ in size. He stated that under the microscope in polarized light the crystalline fraction of free fat in conventional butter can be perceived as minute crystals resulting from an eventual partial crystallization taking place in the free fat.

According to Knoop and Samhammer (20) the main part of the fat in butter is in a liquid or amorphous state with less than 20 percent being in the form of minute crystals. They also maintained that the crystalline fat seemed to be relatively insensitive to

temperature and mechanical treatment in a certain range.

Several authors (10, 12, 27, 37) have stressed the formation of a three-dimensional network from the needle-like fat crystals. The high structural viscosity of butter was explained by Dolby (12) as a crystalline network. Mulder (27) stated that, because milk fat can easily be supercooled and liquid fat often occurs in freshly churned butter in the supercooled state, the increase in hardness is due to the formation of a "skeleton-like structure" as a result of the growing together of the fat crystal. As was pointed out by deMan and Wood (10) the minute fat crystals are responsible for the thixotropic changes in butter because of their anisometric shape (needles) and size (below 1μ). Upon moving, working or stirring of butter, the links between the interlaced crystals, presumably Van der Waal forces, are broken and the system becomes softer. On standing the crystals in the butter rearrange into a continuous pattern and the system becomes harder. This process is known as "setting." Sone et al. (37) connected the recovery of viscosity with the recrystallization of the fat and the formation of a crystalline network.

Polymorphism, the occurrence of unstable crystal modification, has also been suggested as affecting the hardness of butter. According to deMan (9) there is at present no direct evidence to indicate any effect of polymorphism on the rheological properties.

VII. Methods of removing butter from churns

Various mechanical methods of removing butter from churns have been tried. One method utilizes a butter truck onto which the butter is dumped by partially revolving the churn. Hansen (14) reported the successful use of a stainless steel rotary gear pump connected to one of the points of a conical stainless steel churn to fill bulk containers. The successful pumping of butter for temperatures of 56.1 to 65.5° F. have been reported (1). Pedersen and Fisker (29) emphasized the importance of keeping the length of tubing as short as possible. Swortling and Olsson (38) reported the difficulty they encountered in completely emptying the churn due to air pockets. They also emphasized that the butter should not be completely worked when pumping is contemplated. A double-action piston pump utilizing compressed air was reported to have been successfully used for removing butter at temperatures of 57.2 to 59.0° F. from a Kubus butter churn (2).

VIII. Methods used in evaluating the rheological properties of butter

The hardness of butter has been used as a factor in evaluating the rheological properties of butter. Methods, with one or two exceptions, have measured the hardness in arbitrary units under a set of conditions particular to each. The methods of measurement which have been used may be classified as follows: penetrometer, compression, extrusion, sectility and sagging beam.

A. Penetrometer

Mulder (27) reported that the first apparatus to be used in the rheological study of butter was the penetrometer. Brulle (5) rested a vertical rod on a butter sample and loaded it with weights until it penetrated the butter rapidly. A similar device was described by Sohn (36). A rod, ball or cone is pressed by means of weights or is dropped into the butter. One of three variables (depth of penetration, load or time) is measured; the other two are kept constant.

Perkins (30) used a cylinder of metal dropped from a definite height into the butter. The volume of butter displaced by the cylinder was taken as a measure of hardness.

Kruisheer et al. (21) have devised two types of penetrometers. A rod was forced by weights into the sample of butter and after a given time the depth of penetration was measured. The other method utilized a plunger which was forced into the butter at a given rate either by hand or by an electric motor and the resistance measured by a spring balance.

B. Compression

A cube or cylinder of butter is compressed between parallel plates by the action of weights. Two of three variables (load, time or decreased thickness) are kept constant. The third variable is taken as a measure of hardness. Devices utilizing this principle were devised by Coulter and Combs (7), Dolby (11), Hunziker

et al. (15), Perkins (30) and Scott Blair (34).

C. Extrusion

Griffiths (13) used a device in which a cylinder with a sharp-edge orifice was filled with butter. The minimum pressure to produce extrusion indicated hardness. Sargent (33) modified the method by placing the sample under water at constant temperature in a cylinder with a piston at one end and a small orifice at the other. The pressure on the piston was increased until the butter was extruded through the orifice and was then gradually reduced until extrusion almost ceased before the reading was taken.

D. Sectility

Dolby (11) reported a device consisting of a wire which was forced through the sample of butter by weights. Coulter and Combs (7) used a number of wires stretched across a frame to which weights were added. Measurement of force can be taken at constant speed or speed of cutting measured under constant load. Kapsalis et al. (16) incorporated the use of a wire in their "Consistometer" which was used to evaluate spreadability and hardness.

E. Sagging beam

The sagging beam method was developed by Leighton et al. (22) for use with ice cream. Their method was applied to butter by Coulter and Combs (7). A cylindrical sample of butter (13 mm. in diameter) is supported by its ends in a horizontal position at a

temperature of 80° F. The rate of sag is determined by measuring the time necessary for the cylinder to sag 5 mm. The results were used as a measure of the "standing up properties" of butter. The method is applicable only at the temperatures at which butter is soft.

IX. Pseudo-viscosity measurements

The possibility of expressing the data in absolute units has been studied. Davis (8) was one of the first to apply modern rheological tests to butter. Davis (8) loaded a cylindrical piece of butter with different weights. He determined the amount of deformation under the applied stress and after the stress was removed. The permanent deformation was used to calculate a viscosity which was defined as the shearing stress divided by the rate of deformation. This he expressed in absolute units. Davis (8) calculated the modulus of elasticity (relaxation time) from the recovered deformation. The modulus was used as a measure of elasticity and the ratio of the viscosity to the modulus was used to describe "springiness." The viscosity and modulus taken together were considered a measure of firmness. Mulder (27) questioned the correctness of the above.

Kruisheer et al. (21) loaded a "stamp" (4 sq. cm.) with different weights to determine the penetration into butter after 30 sec. From the results they calculated a "yield-value."

An arbitrary viscosity was also estimated by Scott Blair (34) from his compression data. He calculated the pseudo-viscosity

value using:

$$\eta = 0.01896 Wt$$

where η is the viscosity (cp.); W is the load (lb.) and t is the time (sec.). He showed that he was aware of the difficulties involved when he mentioned that even for Newtonian liquids certain standard conditions must be stipulated such as temperature. For a material like butter, a viscosity may be quoted in absolute units provided the conditions of temperature, stress and rate of deformation are specified. When the conditions varied appreciably during the determination, a mean viscosity was reported. Elastic properties and any possible yield value were neglected. Dolby (12) using Scott Blair's apparatus could not obtain reproducible results with sufficient accuracy to detect small differences in firmness.

Viscosity values calculated according to Scott Blair's method were also obtained by Mohr and Wellm (26) using a parallel plate plastometer. This instrument was used by Hunziker et al. (15) and van Dam (39) and later by Sone et al. (37).

The viscosities determined by the different methods are essentially different and cannot be compared easily. Even though values of so-called viscosity were reported in absolute terms they may not be the same since the conditions were chosen arbitrarily.

X. Theoretical considerations

Since the apparent viscosity, time dependency and yield stress can be determined from a rheogram, measurements of shear stress and rate of shear over the desired range can be used to reveal the flow properties of a material. However, the selection of equipment to determine these measurements is dictated by the type and magnitude of these properties. Viscometers of the falling ball, rotational, orifice and capillary tube types have been available, but have been either not suited for use with highly viscous, non-homogeneous, non-Newtonian fluids or have been too expensive for the limited applications. Thus, the choice has been restricted to one which uses higher pressures and larger tubes. This type is usually referred to as extrusion rheometers. Fortunately they are easily constructed since they have not been readily available commercially.

Poiseuille (31) derived the equation for laminar Newtonian flow in tubes using a simple force balance (Fig. 4). The force tending to move the cylindrical column is:

$$(P + \Delta P)(\pi y^2) \quad 7$$

The force tending to keep the cylindrical column from moving is:

$$\tau(2\pi yL) + P(\pi y^2) \quad 8$$

For steady state flow these forces must be equal:

$$P(\pi y^2) + \Delta P(\pi y^2) = \tau(2\pi yL) + P(\pi y^2)$$

or

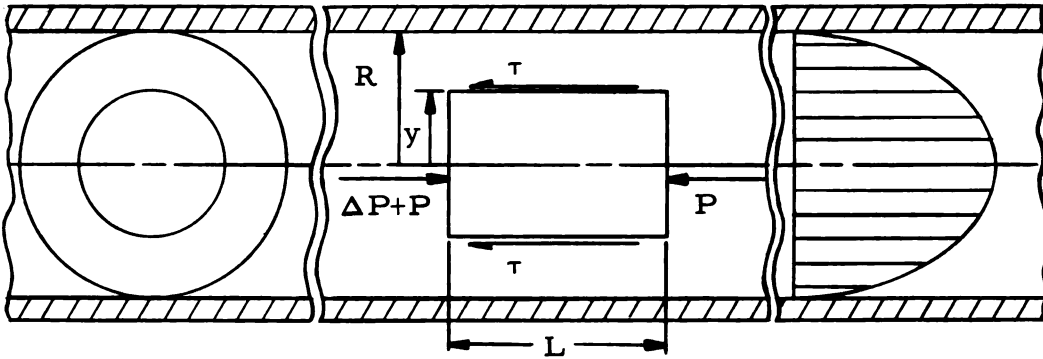


Fig. 4. A model for the Hagen-Poiseuille equation for laminar flow in tubes.

$$\tau = \frac{\Delta P y}{2L} \quad 9$$

Substituting τ from equation 1 into equation 9:

$$\eta \frac{dv}{dy} = \frac{\Delta P y}{2L} \quad 10$$

Rearranging the terms:

$$dv = \frac{\Delta P}{2L\eta} y dy \quad 11$$

and integrating:

$$v = \frac{\Delta P}{2L\eta} \left(\frac{y^2}{2} + C \right) \quad 12$$

The velocity is zero at y equal to R :

$$C = -\frac{R^2}{2} \quad 13$$

or

$$v = \frac{\Delta P}{2L\eta} \left(\frac{y^2}{2} - \frac{R^2}{2} \right) \quad 14$$

or

$$v = \frac{\Delta P}{4L\eta} (y^2 - R^2) \quad 15$$

Velocity is maximum when y equals zero. Therefore:

$$v_{\max.} = \frac{\Delta PR^2}{4\eta L} \quad 16$$

The volume flowing through a parabaloid per unit time of revolution is equal to the base area times half the maximum velocity:

$$Q = 1/2 A v_{\max.} \quad 17$$

The cross sectional area is:

$$A = \pi R^2$$

Substituting A in equation 17:

$$Q = 1/2 \pi R^2 v_{\max.} \quad 18$$

Equating equations 16 and 18:

$$\frac{2Q}{\pi R^2} = \frac{\Delta PR^2}{4\eta L} \quad 19$$

Rearranging the terms:

$$\eta = \frac{\pi \Delta PR^4}{8QL} \quad 20$$

Van Wazer et al. (40) stated that this is the relationship which was first proposed by Hagen and later verified by Poiseuille. It is called the Hagen-Poiseuille law for laminar flow in tubes.

In the derivation the following conditions were postulated:

- 1) the flow was steady;
- 2) the fluid was incompressible;
- 3) there were no external forces;

- 4) there was no slippage at the wall;
- 5) isothermal conditions prevailed throughout;
- 6) there were no radial and tangential components of the velocity;
- 7) the axial velocity was a function of the distance from the axis alone;
- 8) viscosity did not change appreciably with the change in pressure along the tube;
- 9) the tube was sufficiently long that end effects were negligible.

Poisson's ratio is the relative lateral contraction divided by the relative longitudinal strain under unidirectional stress. For incompressible materials Poisson's ratio is equal to 0.5. Scott Blair (34) reported Poisson's ratio for butter to be approximately 0.5.

XI. Pressure losses

A continuous loss of pressure results when a fluid flows in a tube. This pressure loss must be determined in order to design a system which involves fluid flow. Many investigators have experimentally established that for adiabatic flow the pressure loss due to friction is a function of the length and diameter of the tube and of the density and velocity of the fluid (17). Thus, the equation is:

$$h = f \frac{L}{D} \frac{v^2}{2g_c}$$

This relationship is known as the Darcy-Weisbach formula. In flow calculations, L , D and v are usually known, therefore, if the friction factor (f) can be determined the pressure loss or loss of head can be calculated.

The friction factor has been shown to be a function of the Reynolds number (Re). For laminar flow the friction factor is:

$$f = \frac{64}{Re} \quad 22$$

The Reynolds number is defined as:

$$Re = \frac{Dv\rho}{\eta} \quad 23$$

EXPERIMENTAL PROCEDURES

I. Butter

Conventionally churned butter was obtained from three different manufacturers. Each manufacturer supplied a 60-pound sample from churnings of two different days. The bulk boxes of butter were stored at 34^o F. until all were received. Each sample was cut into 2- to 3-pound blocks to facilitate tempering. The blocks were wrapped in regular parchment paper and divided into five groups. The groups were stored at 50, 55, 60, 65 and 70^o F. for at least 48 hr. prior to conducting the test. The composition was determined by the Kohman method (24). The iodine value was determined by the Hanus method (4).

The butter used for the study was considered representative of all conventionally churned winter butter having normal composition and processed under standard commercial conditions.

The density (mass per unit volume) of the butter was determined by collecting a sample extruded from the tubing in a weighed container. The sample and container were weighed on an analytical balance to 0.0001 g. The volume of the containers was determined by allowing water to flow into each container from a burette. The average volume was 7.3 ml. The procedure was checked for

accuracy by repeating the above for larger containers (180 ml.).

An average density was used in the calculations.

The depth of penetration by a conical weight was determined on the samples of butter for different testing conditions as an indication of the relative hardness. The measurements were made with a "Precision" Universal Penetrometer equipped with a cone which weighed 102.5 g. A 5-sec. release time was used. The cone's penetration was observed to 0.1 mm.

Penetration and viscosity values were determined on samples of butter held undisturbed for 48 hr. at the different temperatures. The purpose was to provide maximum pressure limits necessary to overcome the resistance of butter to flow after having been stored for periods of time.

II. Equipment verification

An extrusion viscometer was constructed to determine the apparent viscosity of butter under flow conditions (Fig. 5). The equipment consisted of four interchangeable stainless steel tubings of equal diameter (0.313 in.) and lengths of 3.5, 7.0, 10.5 and 14.0 in. (Table 1). A disc containing a hole in its center was made to fit the tubing. The disc was attached to a sample container by an 1.5-in. stainless steel female fitting. The container (Fig. 5) was made from a 1.5-in. diameter stainless steel tubing. Compressed nitrogen was used as a source of pressure. The pressure on the

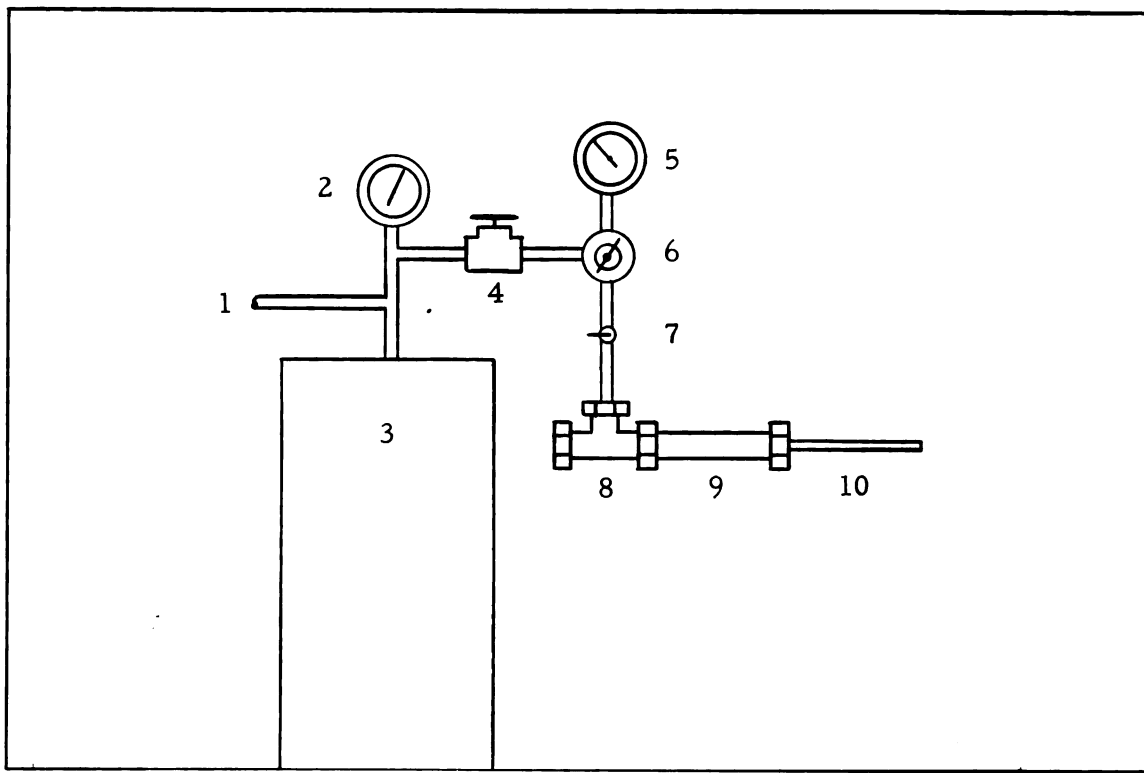
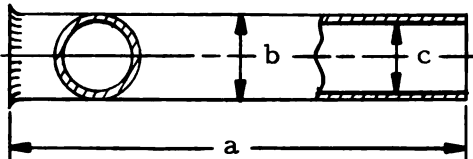
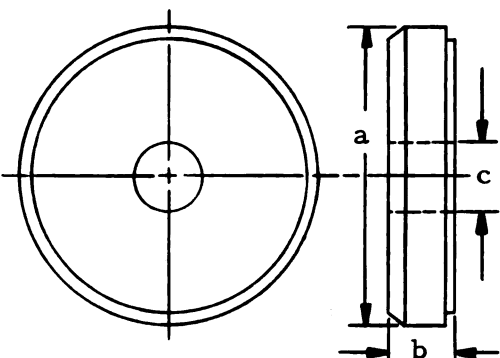


Fig. 5. Extrusion viscometer equipment arrangement.

- | | |
|------------------------------|----------------------------|
| 1. Pressure source connector | 6. Pressure regulator |
| 2. Pressure gauge | 7. Two-way valve |
| 3. Air cylinder | 8. Stainless steel tee |
| 4. Shutoff valve | 9. Sample container |
| 5. Pressure gauge | 10. Stainless steel tubing |

TABLE 1--Tubing and disc specifications

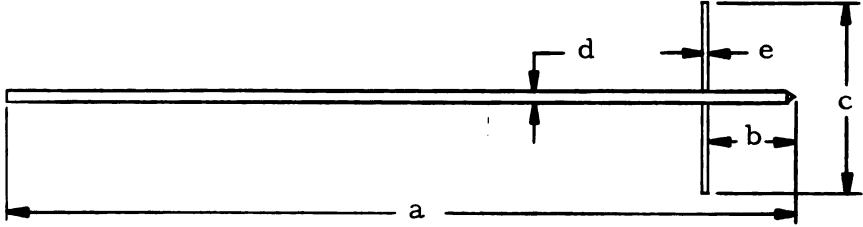
							
Tubing No.	Dimensions in inches			Disc No.	Dimensions in inches		
	a	b	c		a	b	c
A	3.5	0.375	0.313	A	1.875	0.313	0.313
B	7.0	0.375	0.313	B	1.875	0.313	0.375
C	10.5	0.375	0.313				
D	14.0	0.375	0.313				

container was controlled by a Thomas Air Pressure Regulator (Model 911). The pressure applied was measured by one of four Marshalltown gauges having maximum ranges of 15, 60, 100 and 150 lb./sq. in. A two-way valve was inserted in the line between the pressure regulator and the sample container to allow for accurately adjusting the pressure prior to applying it to the sample. The sample container and tubing were positioned horizontally using a

level to eliminate gravitational effects (Figs. 6 and 7).

The extrusion viscometer and the Hagen-Poiseuille equation results were checked for agreement with the Brookfield synchro-electric viscometer (Model HBT) using molasses as the test fluid (Fig. 8). The molasses, a commercial product, was stored at 34° F. for 24 hr. prior to testing. The molasses was stirred with a spoon to simulate conditions similar to extrusion viscometer method. The Brookfield spindle attachments were tempered in the 34° F. room for about 15 min. before use. The spindle was lowered into the molasses from the cross-bar (see Table 2) for 30 sec. using

TABLE 2--Brookfield Helipath stand spindle specifications

					
Spindle	Dimensions in inches				
	a	b	c	d	e
T-A	4.5	0.5	1.894	0.0625	0.0290
T-B	4.5	0.5	1.435	0.0625	0.0290
T-C	4.5	0.5	1.065	0.0625	0.0290
T-D	4.5	0.5	0.804	0.0625	0.0290
T-E	4.5	0.5	0.604	0.0625	0.0290
T-F	4.5	0.5	0.430	0.0625	0.0290

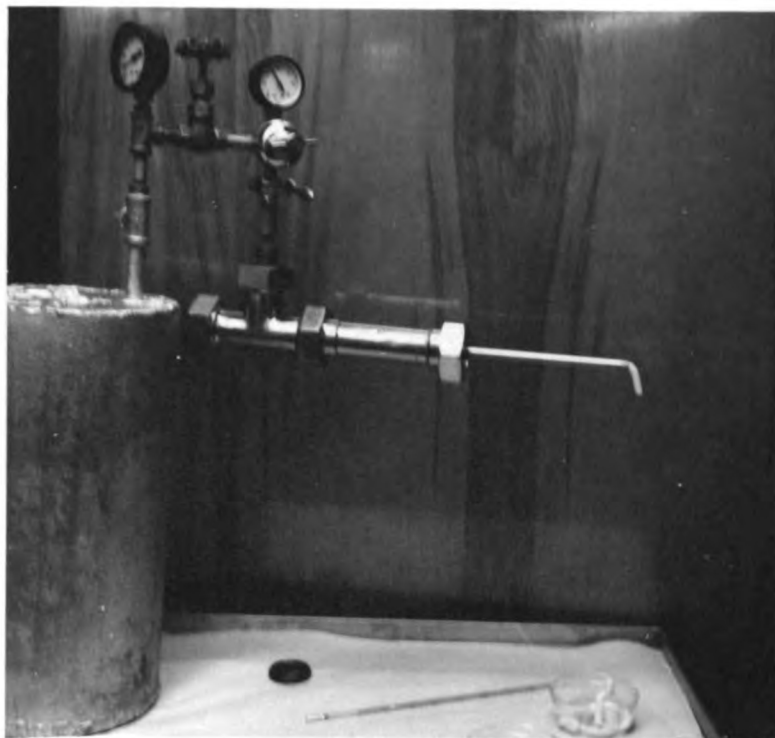


Fig. 6. Extrusion viscometer.



Fig. 7. Extrusion viscometer in operation.



Fig. 8. Brookfield synchro-lectric viscometer, Helipath stand and spindles.



Fig. 9. Brookfield viscometer positioned for viscosity measurements on butter.

the Helipath stand. The stand's lowering action was stopped and the dial reading recorded for the different spindles and spindle speeds. The dial reading was multiplied by a conversion factor corresponding to a particular rotational speed and spindle to obtain the viscosity in centipoises. The conversion factors were supplied on a calibration chart by the manufacturer.

The pressure tube equipment was also tempered in the 34° F. controlled temperature room. The arrangement of the equipment was changed slightly for use with the molasses as shown in Fig. 10 by placing the sample container in the vertical position. The

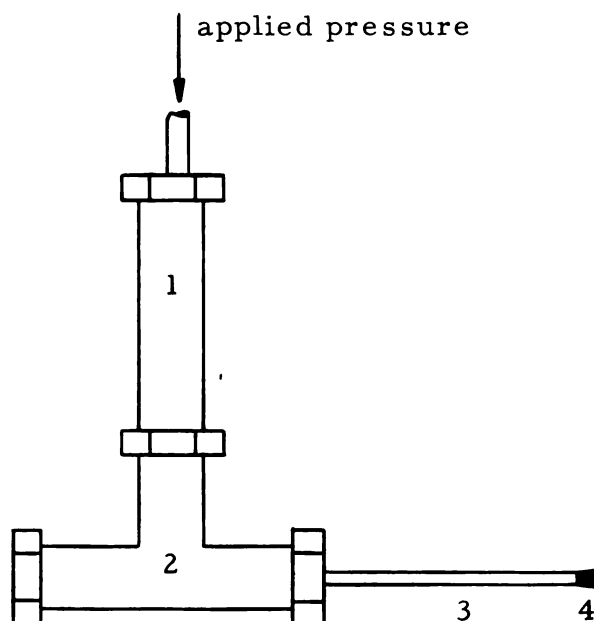


Fig. 10. Arrangement of the extrusion viscometer equipment for use with molasses.

- | | |
|------------------------|---------------------------|
| 1. Sample container | 3. Stainless steel tubing |
| 2. Stainless steel tee | 4. Rubber stopper |

equipment was leveled and the shortest tubing attached. A rubber stopper was inserted in the open end of the tubing to keep the molasses from flowing out. The effect of gravity was found to just overcome the internal resistance of the molasses in the sample container. The two were considered to compensate for each other. The samples were collected for 30-sec. time periods and weighed.

III. Bulk velocity

The bulk velocity is the rate a given quantity of butter will flow from the end of the tubing in 1 sec. In order to determine the apparent viscosity of butter for the desired rate of shear, the bulk velocity was calculated for butter flowing at 10 lb./min. through tubing of various diameters.

IV. Flow profiles

The actual shape of the velocity profile was obtained for moving butter by filling a sample container with butter colored dark blue and a second sample container with butter of normal color. Each sample was alternately used to force the other through the different lengths of tubing at different temperatures. Extreme care was taken to provide a flat surface perpendicular to the center line of the tubing at the entrance for each trial. The resulting cylindrical samples were tempered at a low temperature and cut in half to show the flow profiles.

V. Apparent viscosity of flowing butter

The apparent viscosity of flowing butter was determined from the extrusion viscometer data using the Hagen-Poiseuille equation. The data were obtained from tests conducted in rooms with controlled temperatures. The extrusion viscometer and nitrogen supply were stored in the room at least 24 hr. prior to testing.

The test was conducted by placing the butter in the sample container and attaching it to the pressure equipment. The tubing was connected to the other end. Pressure was applied directly to the surface of the butter. The pressure was changed by increments of 1 or 2 lb./sq. in. at 70° F. and increments of 5 lb./sq. in. at 65, 60 and 55° F. Data were gathered for each length of tubing at 55 to 73° F. All samples of butter were tested before changing to the next temperature.

Prior to each set of tests using a particular tubing, the pressure loss for the sample container was determined by forcing the butter through a disc similar to the disc holding the tubing except that the diameter of the hole in its center was equal to the diameter of the inside of the tubing (Table 1). The pressure loss was determined by slowly applying pressure to the system until the butter started to flow out of the hole in the disc. After several replicates, the gauge pressure noted just before the observed movement was recorded to the nearest lb./sq. in. The sample container loss was

subtracted from the measured pressure loss obtained for each tubing length to obtain the pressure loss along the tubing.

The extruded butter was collected in weighed containers for 15 sec. The rate of flow was allowed to become steady after the pressure was applied before the sample was taken except for the fastest flow rates. For these the sample had to be taken immediately upon applying the pressure. The extruded butter was cut at the exit of the tubing with a spatula and the stop watch started. At the end of 15 sec. the edge of the weighed container was used to cut the butter at the exit of the tubing. Three samples were taken for each pressure. The temperature of the butter was determined by inserting the thermometer into butter in the tubing after each test.

Preliminary graphs of the results of apparent viscosity versus velocity revealed that the data approximated a linear relationship on log-log paper. A regression and correlation analysis were made on the data using the CDC 3600 computer. The data were grouped according to temperature, length of tube and sample of butter.

The regression coefficients and the standard error of estimate were used in the equation:

$$Y = a + bX \pm SE$$

VI. Pressure losses

The pressure loss versus the logarithm of velocity was found to be a linear relationship. A regression and correlation analysis

were performed on the data obtained from the extrusion viscometer.

VII. Reduction in apparent viscosity under mild agitation

The Brookfield viscometer was used to determine the decrease in apparent viscosity of butter under mild agitation. The measurements were conducted in the rooms with controlled temperature. A Brookfield spindle was revolved at a constant speed while positioned at a constant depth in the sample of butter (Fig. 9). The same spindle depth was obtained by lowering the spindle from its cross-bar into the butter using the Helipath stand. The lowering time was 30 sec. Brookfield readings were taken while the spindle revolved continuously.

VIII. Reduction in apparent viscosity due to pumping

A variable speed Waukasha rotor-type pump was used to evaluate the influence of the rate of pumping on the apparent viscosity of butter. The butter was forced manually into the pump on the first pass. The pump speeds used were 52 and 120 r.p.m. Measurements of penetration value, temperature and apparent viscosity (Brookfield and extrusion viscometer methods) were taken after each pass through the pump.

IX. The minimum pressure to initiate flow in tubing, elbows and valve assemblies

The same procedure was used to determine the minimum pressure to initiate flow in the different lengths of tubing at various

temperatures as was used to determine the pressure loss for the sample container (part IV). The minimum pressure was also obtained for elbows (1.5 in. diameter) and for a direction change in three-way valve assemblies (1.5 in. diameter). The length along the center line through the elbows and valve assemblies was 4.5 in. and 5.3 in. respectively. The average minimum pressure obtained for the elbows and valve assemblies was compared to the minimum pressure obtained for different lengths of tubing.

X. Power requirements

The apparent viscosity and bulk velocity data from the extrusion viscometer were used to calculate the Reynolds number and friction factor. Also from the results, an equation for calculating the apparent viscosity at various temperatures and bulk velocities was determined. The above relationships were used to calculate the loss of head and power requirements for various quantities of butter at 55, 60 and 65^o F. flowing through tubing having diameters of 1.5 in. and 3.0 in.

RESULTS

I. Butter

The date of churning along with the cream treatment prior to churning is provided in Table 3 for each sample of butter. The average result of two replicates on each sample from the Kohman analysis and the Hanus test is presented in Table 4.

The results of the density for each sample of butter collected as the butter flowed from the end of the tubing at the different temperatures are presented in Table 5. Each value represents an average of three determinations. The average density was 0.952 g./ml.

The penetration and viscosity results presented in Table 6 were determined on samples of butter held for at least a week at the indicated temperatures prior to conducting the determinations. The apparent viscosities of the samples below 55° F. were beyond the maximum range of the Brookfield viscometer. Fig. 11 shows the average penetration values for butter after flowing through the different lengths of tubing for the four temperatures.

TABLE 3--Cream treatment prior to churning

Sample	Date churned	Pasteurization temperature (deg. F.)	Holding temperature overnight (deg. F.)
A	1-14-64	165 (30 min.)	40
B	1-13-64	160 (30 min.)	45
C	1-14-64	160 (30 min.)	58
D	1- 9-64	160 (30 min.)	58
E	1-13-64	190 (30 sec.)	46
F	1-12-64	190 (30 sec.)	46

TABLE 4--Composition and iodine number of the butter

Sample	Composition				Iodine number
	Fat (percent)	Moisture (percent)	Salt (percent)	Curd (percent)	
A	80.2	16.0	2.6	1.2	28.1
B	80.7	15.5	2.6	1.2	28.2
C	80.6	16.5	2.0	0.9	28.0
D	80.0	17.0	2.0	1.0	28.7
E	80.0	16.9	2.2	0.9	28.3
F	80.0	17.0	2.2	0.8	27.8

TABLE 5--Densities of butter at various temperatures

Sample	Temperature (deg. F.)	Average temperature (deg. F.)	Density (g./ml.)	Average density (g./ml.)
A	73.2	72.9	0.945	0.948
B	73.2		0.948	
C	72.4		0.947	
D	72.8		0.959	
E	73.4		0.946	
F	72.6		0.944	
A	65.3	65.3	0.953	0.953
B	66.0		0.953	
C	65.6		0.962	
D	64.7		0.953	
E	65.0		0.953	
F	66.2		0.953	
A	62.8	61.9	0.967	0.945
B	63.6		0.922	
C	61.0		0.928	
D	60.7		0.955	
E	60.8		0.941	
F	62.5		0.955	
A	57.2	56.7	0.976	0.961
B	56.8		0.955	
C	56.0		0.956	
D	57.0		0.960	
E	56.6		0.960	
F	56.7		0.956	
Average	0.952			

TABLE 6--Penetration and viscosity of quiescent butter at various temperatures

Sample	Temperature (deg. F.)	Penetration value (mm.)	Viscosity (a) (cp.)
A	72.4	20.7	268,000
B	72.2	18.4	408,000
C	72.2	19.5	406,000
D	72.5	19.9	367,000
E	72.3	19.5	341,000
F	72.4	19.4	296,000
Average	72.4	19.6	349,000
A	59.8	6.1	6,670,000
B	59.5	5.6	7,180,000
C	59.9	5.5	7,060,000
D	60.0	6.1	7,050,000
E	60.0	6.0	7,180,000
F	60.1	5.9	5,700,000
Average	59.9	5.9	6,820,000
A	54.6	4.9	Beyond range of viscometer
B	54.2	4.3	
C	54.0	4.4	
D	54.0	4.5	
E	53.8	4.7	
F	53.8	4.7	
Average	54.1	4.6	
A	48.8	4.0	Beyond range of viscometer
B	47.4	3.2	
C	47.6	3.4	
D	47.2	3.6	
E	47.2	3.6	
F	47.1	3.6	
Average	47.6	3.6	

(a) Brookfield viscometer with Helipath stand using spindle T-C at 10 r.p.m. for 72° F. and spindle T-F at 10 r.p.m. for 60° F.

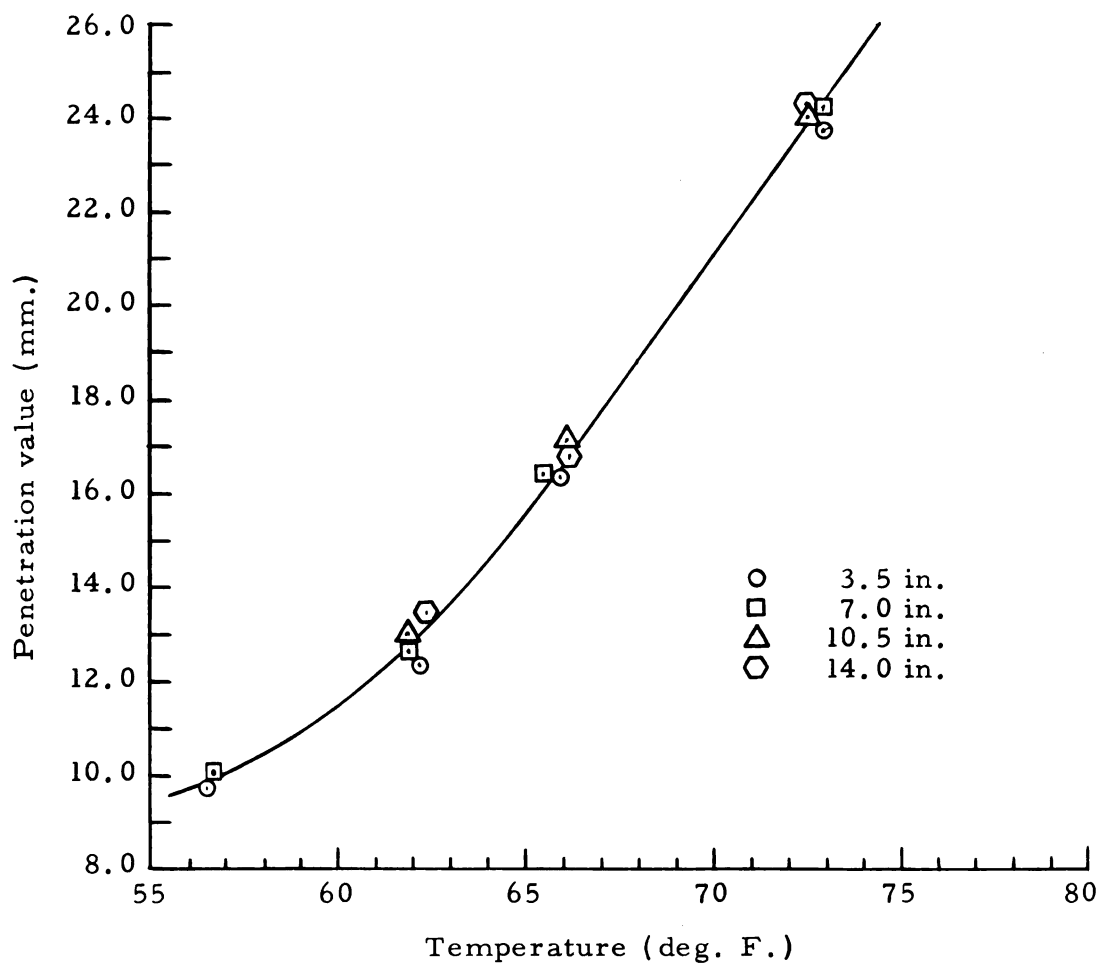


Fig. 11. Average penetration values on butter after flowing through the various lengths of tubing.

II. Equipment verification

The results using the molasses to verify the proper application of the Hagen-Poiseuille equation with the constructed extrusion viscometer are presented in Tables 7, 8 and 9. In Tables 7 and 8 are shown the individual viscosity results from three trials using the extrusion viscometer and the Brookfield viscometer. Pressures and time used with the extrusion viscometer were selected to provide a reasonable size sample for weighing. Spindles and their speeds also were selected to provide adequate torque; however, at the temperature selected the readings were made on the low range of the dial. Approximately 35° F. was selected because preliminary trials revealed that slight changes in temperature had a smaller influence on the viscosity of the molasses than at lower temperatures. Average viscosities obtained using the Brookfield and extrusion viscometer were 11,900 cp. at 36.5° F. and 12,000 cp. at 36.4° F. respectively.

III. Bulk velocity

Fig. 12 illustrates the normal bulk velocities when moving different amounts of butter per min. through the various diameters of stainless steel tubing. The tubing dimensions are presented in Table 10 along with the calculated velocity for moving butter at 10 lb./min. The normal range of bulk velocities expected is between 0.01 ft./sec. to 1 ft./sec.

TABLE 7--Viscosity of molasses by the extrusion viscometer method

Tub- ing (No.)	Pressure (lb./ sq. in.)	Temper- ature (deg. F.)	Viscos- ity (cp.)	Temper- ature (deg. F.)	Viscos- ity (cp.)	Temper- ature (deg. F.)	Viscos- ity (cp.)
2	2	36.0	14,800	36.0	14,200	36.4	12,800
	3	36.0	13,200	36.0	11,900	36.4	10,200
	4	36.1	12,600	36.0	11,900	36.4	11,500
	5	36.1	13,100	36.0	12,800	36.4	12,500
3	3	36.0	12,000	..	..	..	..
	4	36.1	12,100	36.1	11,900	36.5	11,700
	5	36.1	12,600	36.1	12,300	36.5	11,800
	6	36.1	11,000	36.1	11,500	36.5	12,000
	7	36.2	12,000	36.1	11,500	36.5	11,400
4	4	35.9	11,800	..	..	..	..
	5	35.9	12,200	..	..	..	..
	6	36.0	11,300	36.0	12,300	36.3	12,500
	7	36.0	11,000	36.0	11,800	36.3	12,200
	8	36.1	10,800	36.0	11,600	36.3	12,300
	9	..	..	36.0	11,700	36.3	12,000
5	6	36.0	12,250	..	..	..	..
	7	36.0	11,650	..	..	..	..
	8	36.1	12,600	36.2	12,500	36.4	12,800
	9	36.1	12,000	36.2	12,000	36.4	12,200
	10	..	..	36.2	11,800	36.4	11,900
	11	..	..	36.2	11,200	36.4	11,500

TABLE 8--Viscosity of molasses by the Brookfield method

Spin- dle (No.)	Speed (r.p.m.)	Temper- ature (deg. F.)	Viscos- ity (cp.)	Temper- ature (deg. F.)	Viscos- ity (cp.)	Temper- ature (deg. F.)	Viscos- ity (cp.)
T-A	2.5	36.5	13,400	35.9	14,100	34.4	16,600
	5.0	36.5	12,800	35.9	12,500	34.4	16,000
	10.0	36.5	12,500	35.9	12,700	34.4	15,500
	20.0	36.5	12,300	35.9	11,900	34.4	15,400
	50.0	36.5	11,900	35.9	12,400	34.4	14,600
	100.0	36.5	11,700	35.9	12,400	34.4	14,200
T-B	2.5	36.5	..	35.9	..	34.4	..
	5.0	36.5	10,900	35.9	12,800	34.4	14,100
	10.0	36.5	11,200	35.9	12,800	34.4	14,100
	20.0	36.5	11,000	35.9	12,600	34.4	13,900
	50.0	36.5	10,800	35.9	12,300	34.4	13,500
	100.0	36.5	10,500	35.9	12,500	34.4	13,600
T-C	2.5	36.5	..	35.9	..	34.4	..
	5.0	36.5	..	35.9	..	34.4	..
	10.0	36.5	12,800	35.9	13,600	34.4	15,200
	20.0	36.5	12,800	35.9	12,400	34.4	15,600
	50.0	36.5	11,850	35.9	12,300	34.4	15,000
	100.0	36.5	11,800	35.9	12,200	34.4	15,600

TABLE 9--Average viscosity of molasses by the Brookfield and extrusion viscometer methods

	Temper- ature (deg. F.)	Viscosity (cp.)	Range (cp.)	Difference (cp.)
Brookfield	36.5	11,900	10,500 to 13,400	2,900
	35.9	12,600	11,900 to 14,100	2,200
	34.4	15,500	13,500 to 16,600	3,100
Extrusion viscometer	36.0	12,100	10,800 to 14,800	4,000
	36.1	12,100	11,200 to 14,200	3,000
	36.4	12,000	10,200 to 12,800	2,600

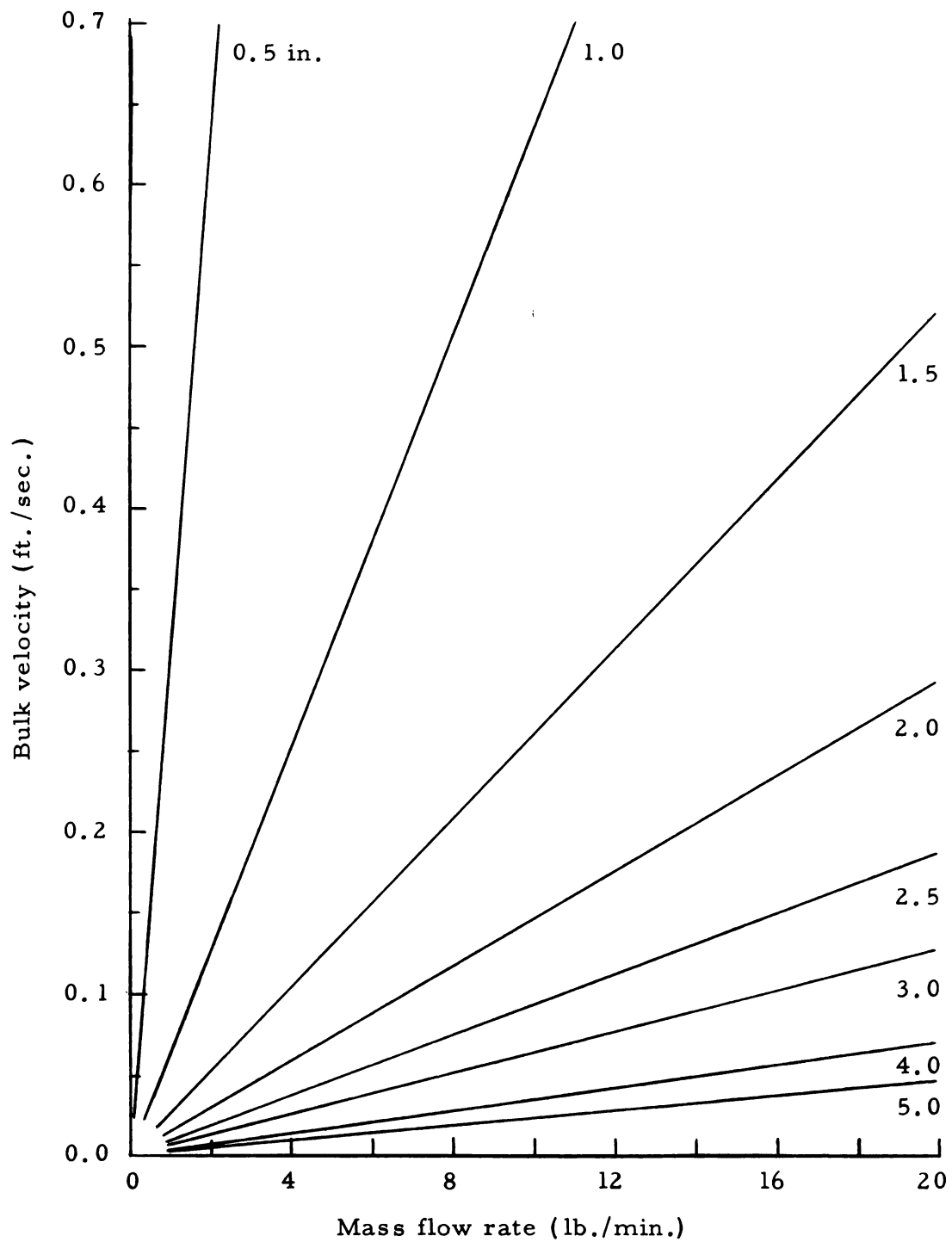


Fig. 12. Velocity of butter flowing through stainless steel tubing of various diameters.

TABLE 10--Dimensions used to determine the bulk velocity of butter flowing in stainless steel tubing of various diameters

Inside diameter (in.)	Bulk velocity (a) (ft./sec.)	Inside diameter (in.)	Bulk velocity (a) (ft./sec.)
0.402	3.1900	2.370	0.0917
0.902	0.6330	2.870	0.0625
1.402	0.2610	3.870	0.0344
1.870	0.1470	4.870	0.0217

(a) Butter flowing at 10 lb./min. with a density of 59.3 lb./cu. ft.

IV. Flow profiles

Figs. 13 and 14 illustrate the flow profiles obtained using the colored butters under different combinations of temperature and length of tubing. The profiles shown were selected from 3 to 8 samples and are representative of all the samples within the group. The samples at 70° F. were soft, making them difficult to obtain without some damage as they flowed from the end of the tubing. Samples from the 14.0-in. tube were also difficult to obtain because the end of the tubing was beyond easy reach while controlling the extrusion viscometer. The depth of field used in taking the pictures and the angle at which the light was placed to illuminate the sample caused minor surface irregularities to be intensified.

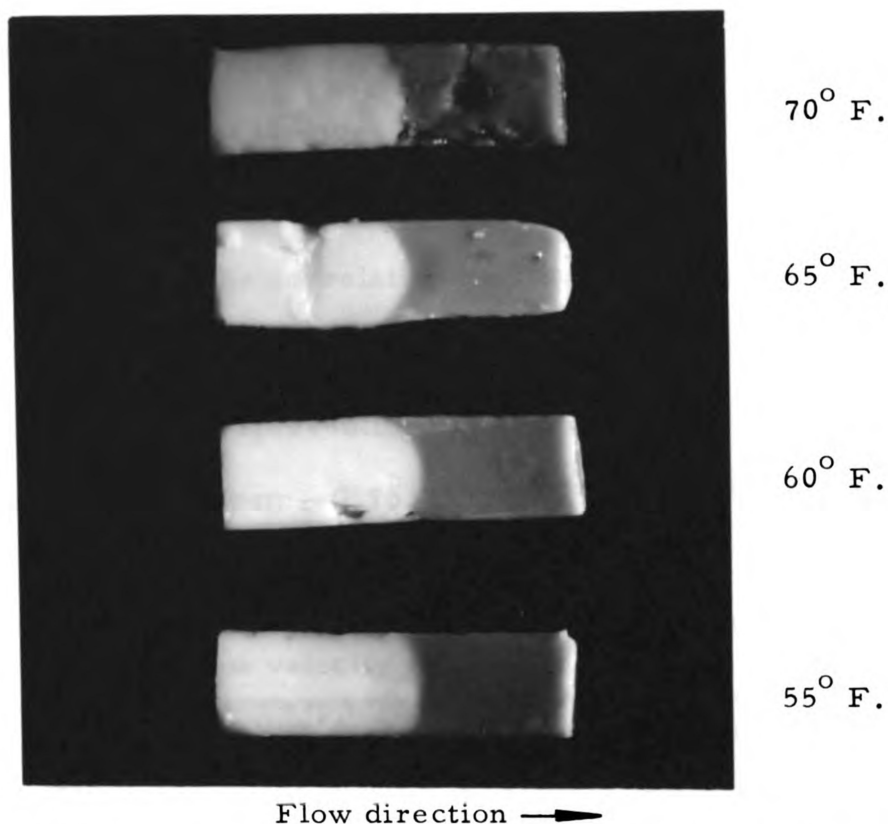


Fig. 13. Flow profiles obtained from the 7.0 in. length of tubing for the various temperatures.

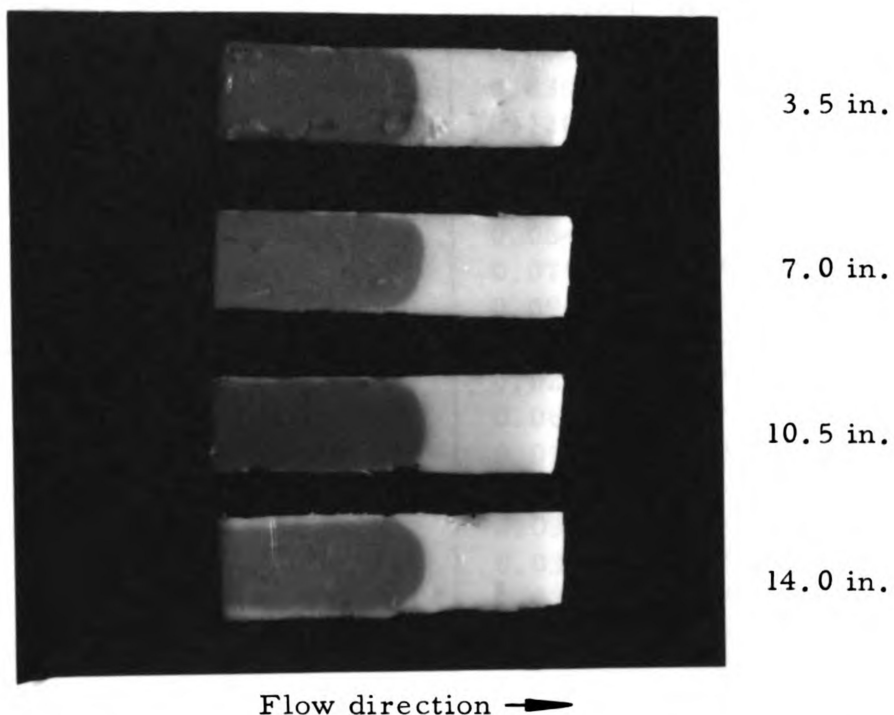


Fig. 14. Flow profiles obtained at 65° F. for the various lengths of tubing.

V. Apparent viscosity of flowing butter

The results of the correlation and regression analysis are presented in Table 11. The correlation coefficients ranged from 0.9738 to 0.9975. Figs. 15 through 21 are the graphs of the resulting equations. The lines representing the regression equations have negative slopes ranging from -0.76375 to -0.92422. The decrease

TABLE 11--Results of the correlation and regression analysis for the apparent viscosity versus velocity

Tube length (in.)	Temperature (deg.F.)	Regression coefficients		Standard error of estimate SE	Correlation coefficient (a)	Degrees of freedom DF
		a	b			
3.5	72.9	3.80550	-0.86124	0.03430	0.9975	88
3.5	66.4	4.29250	-0.81920	0.05509	0.9950	70
3.5	62.3	4.41815	-0.90617	0.08075	0.9902	82
3.5	56.6	4.36642	-0.92422	0.13072	0.9758	67
7.0	72.9	3.65436	-0.86170	0.04359	0.9915	88
7.0	66.4	4.21283	-0.76375	0.06441	0.9839	85
7.0	62.4	4.26132	-0.86374	0.07955	0.9758	88
7.0	57.2	4.26912	-0.88070	0.09431	0.9738	82
10.5	72.6	3.65645	-0.83444	0.02735	0.9973	88
10.5	66.4	4.06036	-0.81467	0.06442	0.9840	85
10.5	62.2	4.18515	-0.87618	0.03112	0.9958	85
14.0	72.9	3.61148	-0.82927	0.03502	0.9934	88
14.0	66.4	4.02311	-0.82536	0.03578	0.9942	88
14.0	62.1	4.12343	-0.89901	0.03695	0.9941	85

(a) DF corrected

in apparent viscosity with an increase in bulk velocity may be illustrated by comparing the results from the 14.0-in. length of tubing at 60° F. for various velocities. The apparent viscosity was 6,510,000 cp. at 0.001 ft./sec. while at 0.01 ft./sec. it had decreased to 866,000 cp. For 0.1 ft./sec. the apparent viscosity is only 115,000 cp.

The effect of the length of tubing on the apparent viscosity for butter flowing at different temperatures is shown in Figs. 15 through 17. As the distance the butter flows increases, the decrease in apparent viscosity becomes less. At a constant velocity of 0.1 ft./sec. and at 60° F. the apparent viscosity is 211,000 cp. for a distance of 3.5 in. For a distance of 7.0 in. the apparent viscosity is 133,000 cp. which is a decrease of 78,000 cp. as the distance increased 3.5 in. Less decrease (18,000 cp.) is found between the 7.0- and 10.5-in. lengths of tubing and only 10,000 cp. between the 10.5- and 14.0-in. lengths of tubing. The graphs in Figs. 18 through 20 are of the same regression equations but grouped according to the length of tubing to show the influence of temperature on the apparent viscosity of flowing butter. The apparent viscosities at 55° F. for lengths of tubes 10.5 in. and 14.0 in. could not be obtained because the pressure required exceeded the capacity of the extrusion viscometer. Fig. 20 illustrates the location of the standard error of estimate for the regression lines obtained from the data using the 10.5-in. tube.

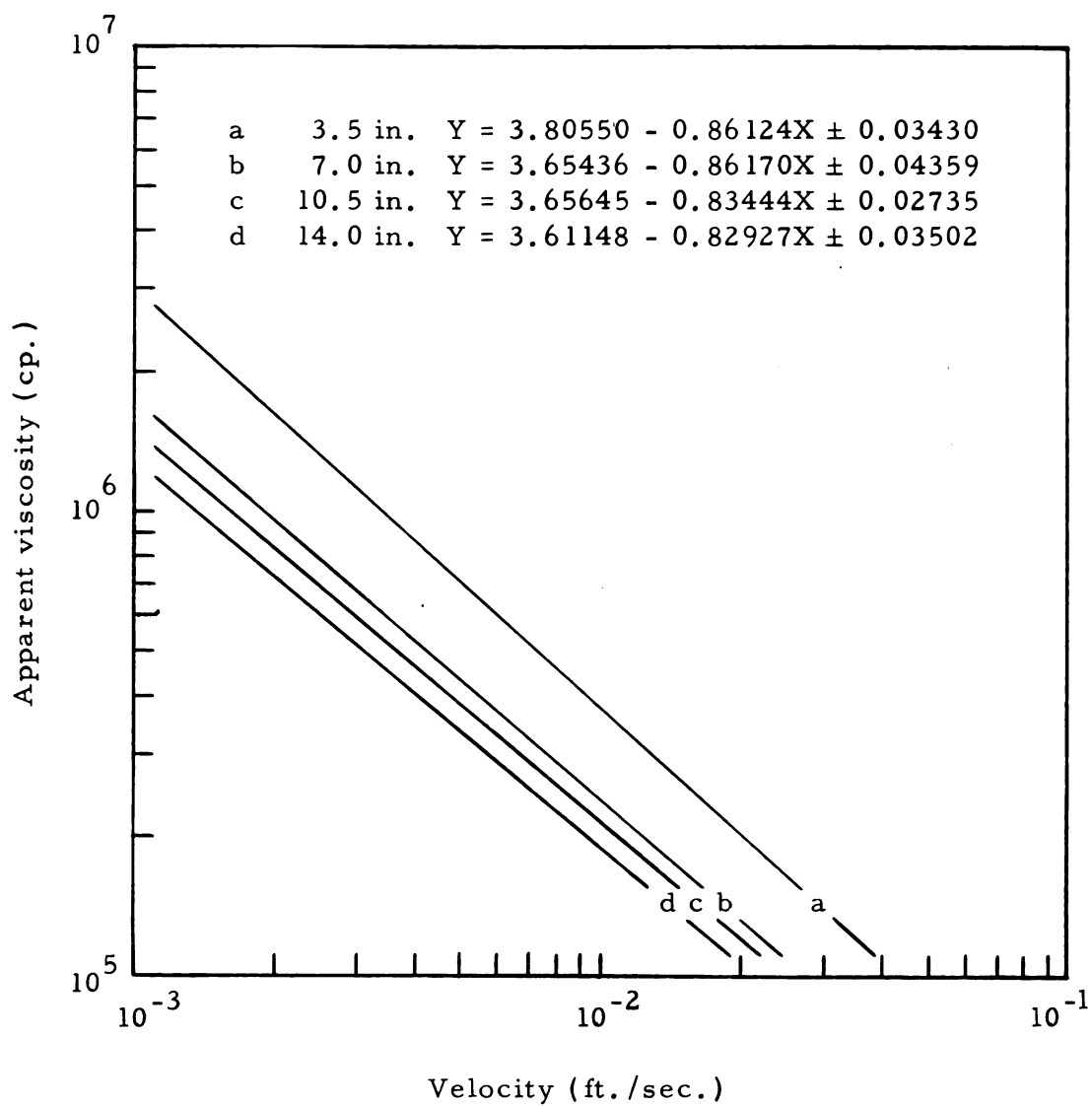


Fig. 15. Effect of tubing length on the apparent viscosity of flowing butter at 70° F.

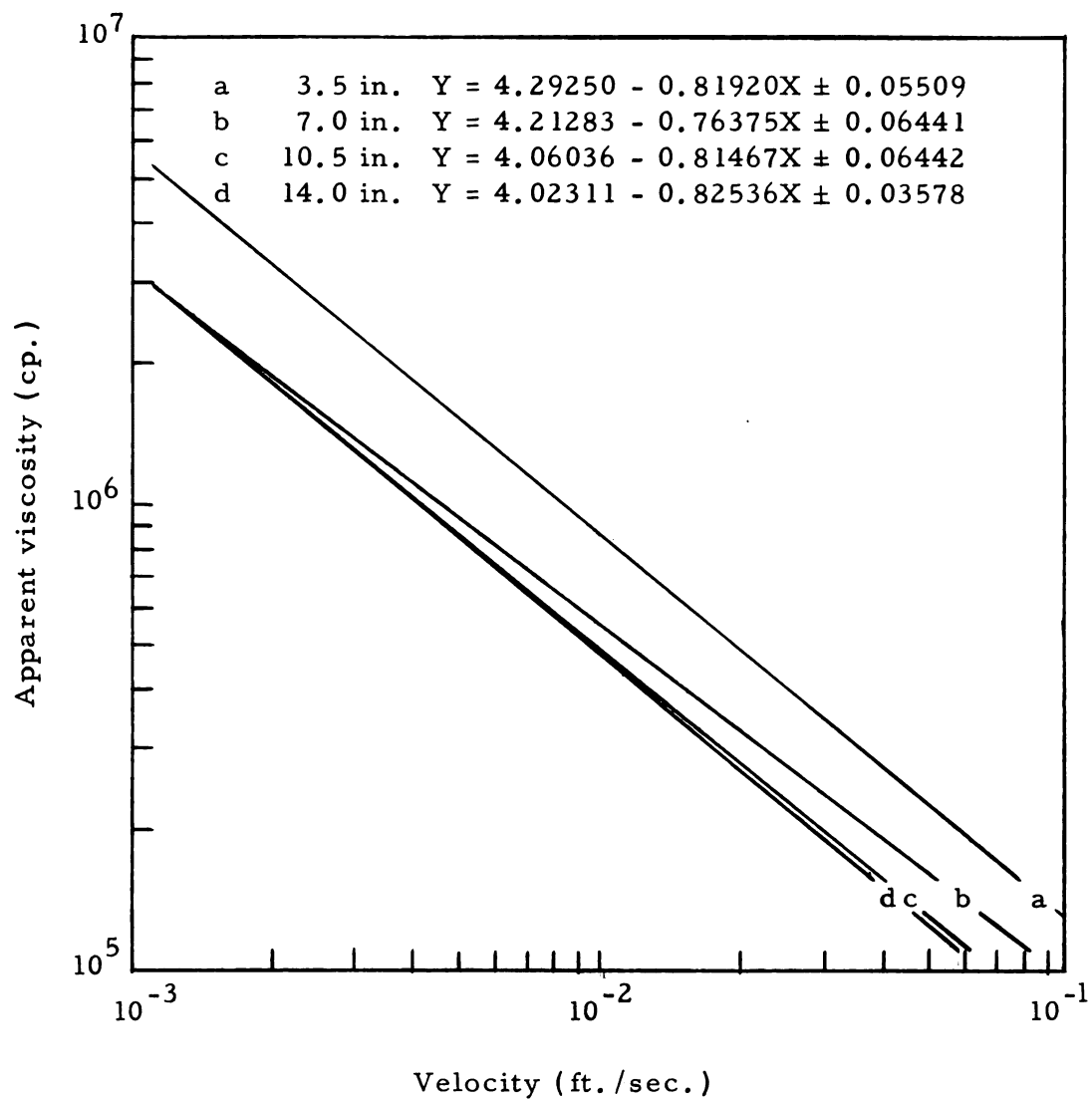


Fig. 16. Effect of tubing length on the apparent viscosity of flowing butter at 65° F.

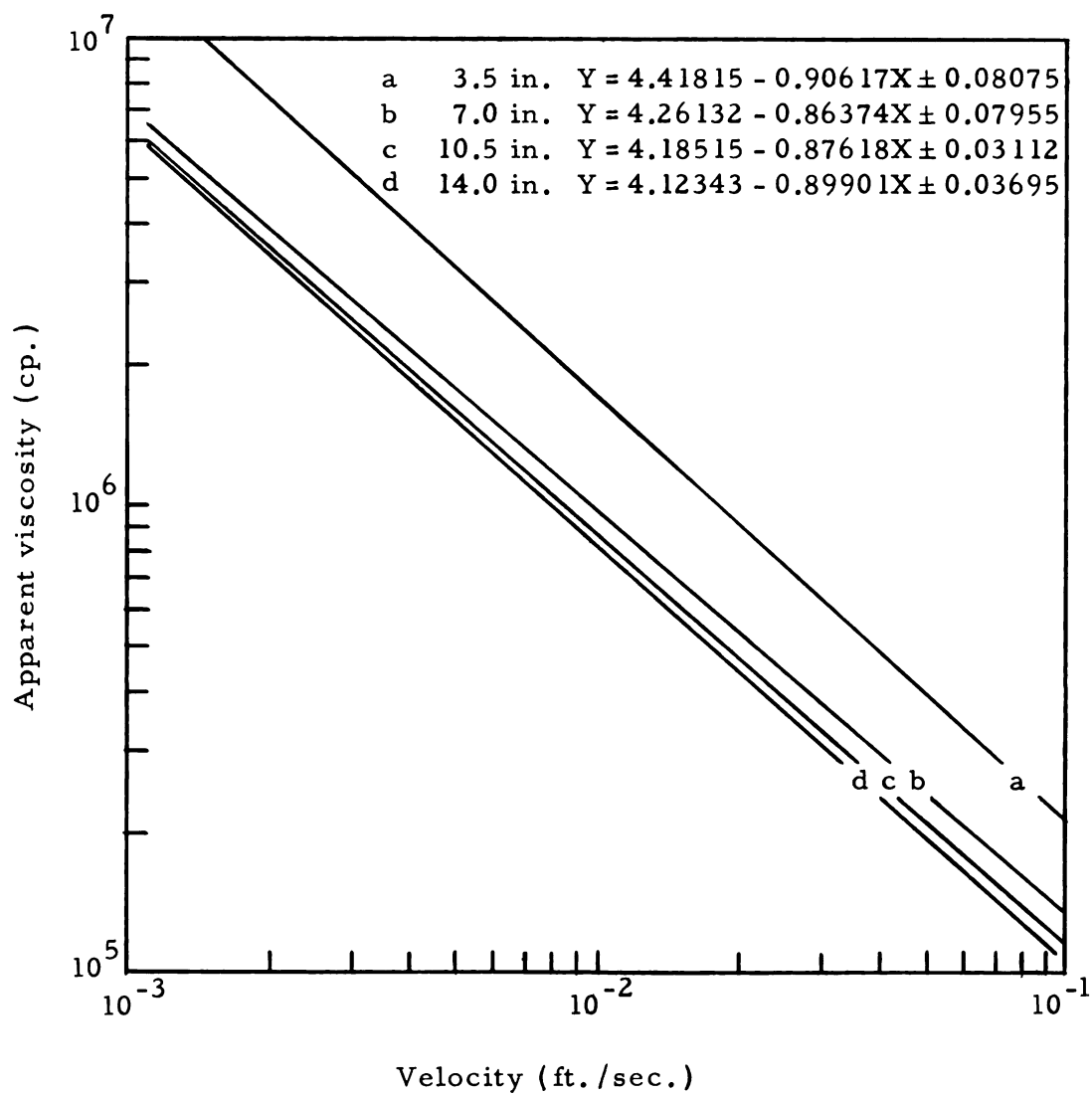


Fig. 17. Effect of tubing length on the apparent viscosity of flowing butter at 60° F.

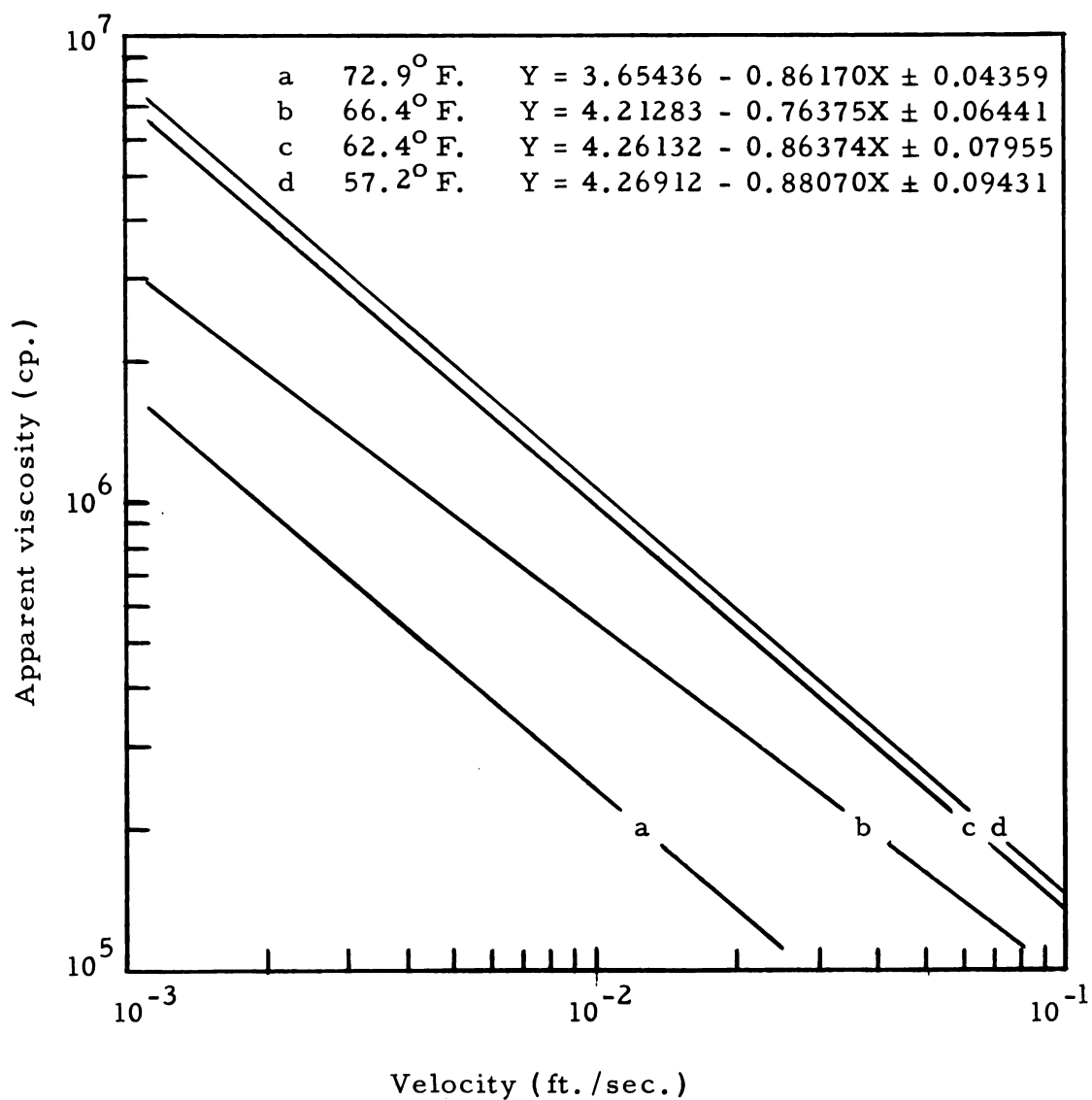


Fig. 18. Effect of temperature on the apparent viscosity of flowing butter (7.0-in. tubing length).

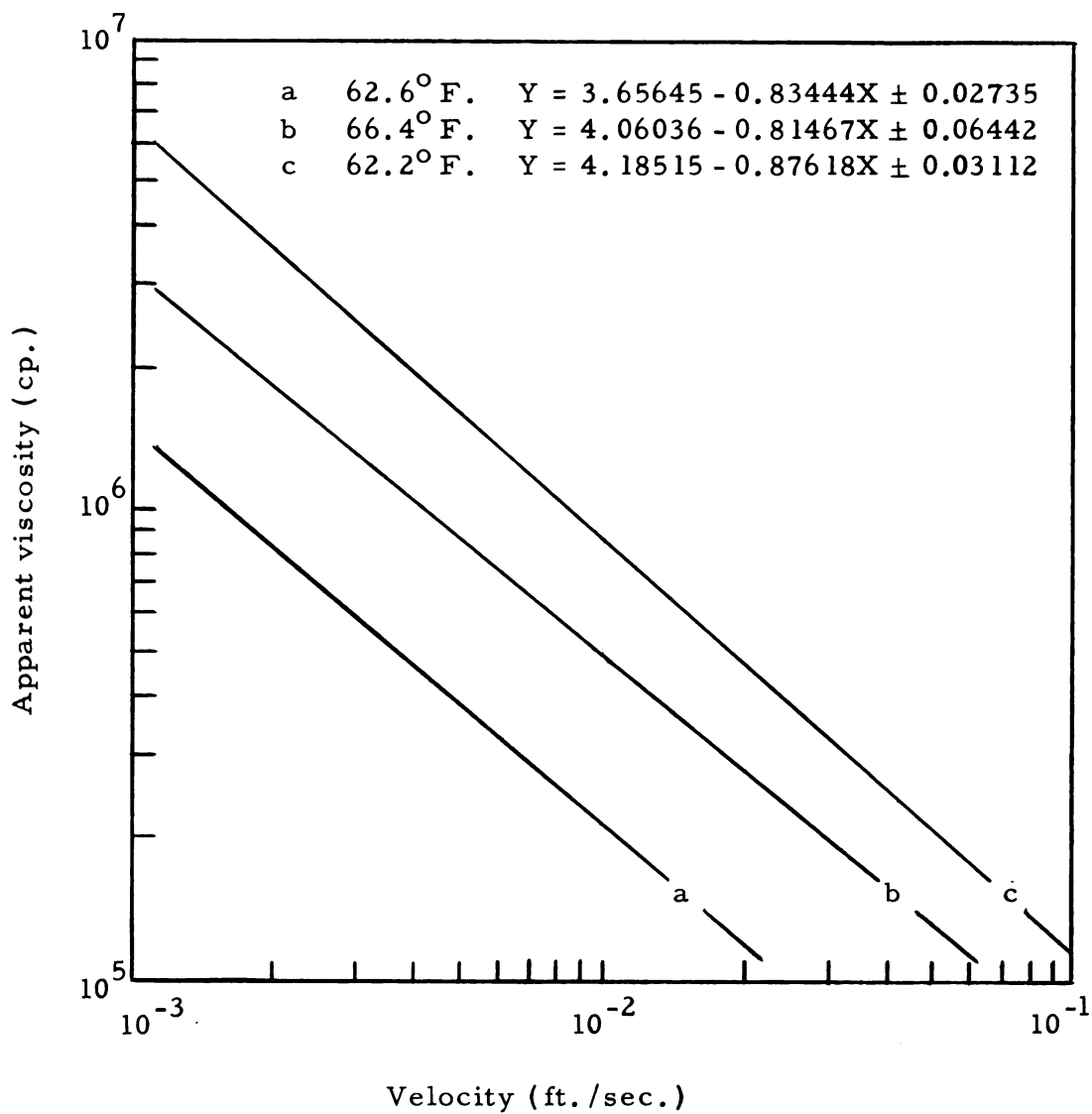


Fig. 19. Effect of temperature on the apparent viscosity of flowing butter (10.5-in. tubing length).

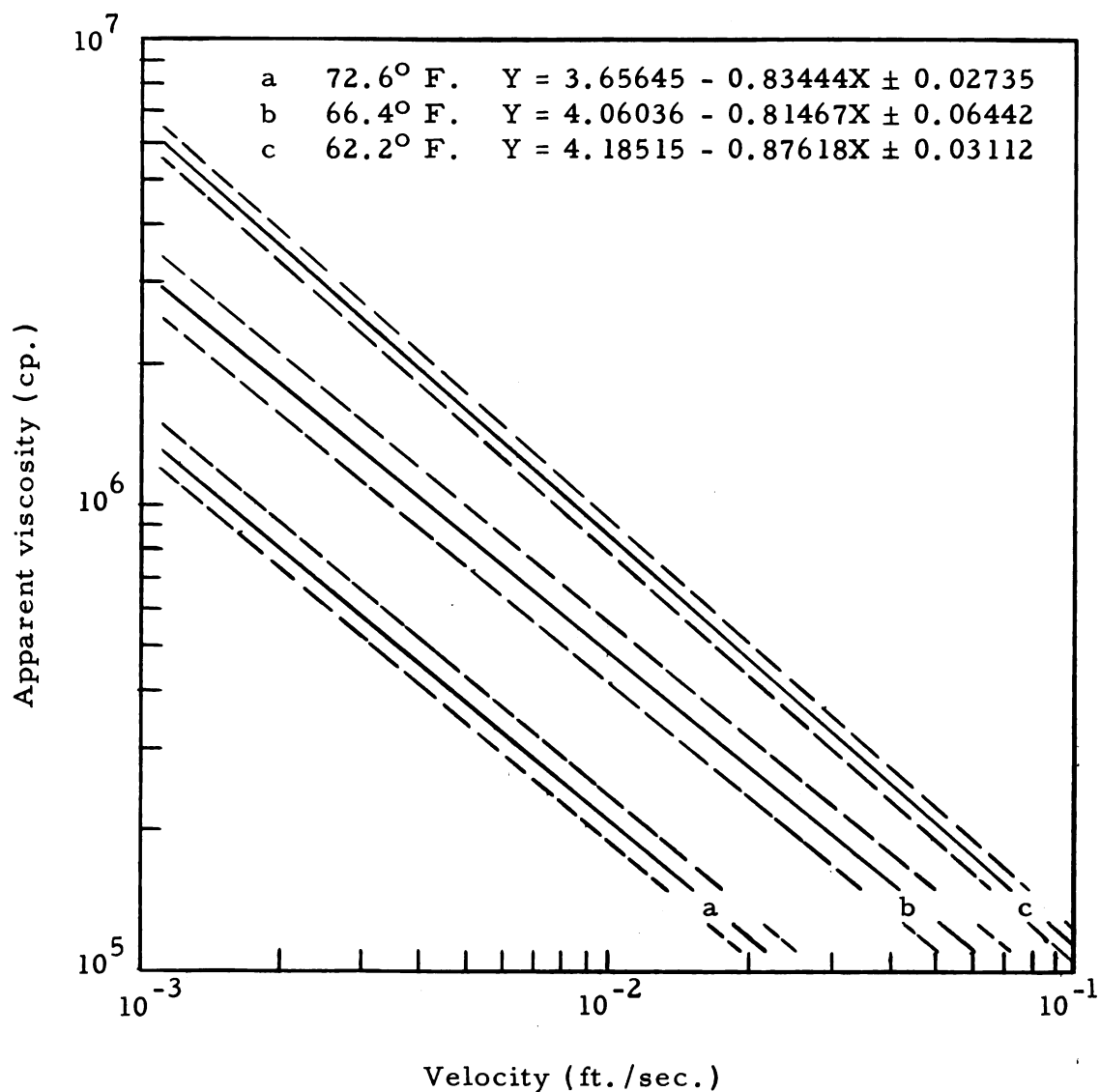


Fig. 20. Effect of temperature on the apparent viscosity of flowing butter with the dotted lines showing the standard error of estimate (10.5-in. tubing length).

The apparent viscosity versus temperature is shown in Fig. 21 for a constant rate of shear of 0.01 ft./sec. The slope of the lines is -0.0587. Thus, apparent viscosity decreases rapidly as the temperature increases. The apparent viscosity using the 10.5-in. length of tubing at 55° F. is 2,250,000 cp. It decreases to 1,150,000 cp. at 60° F. and 590,000 cp. at 65° F.

The results from the regression and correlation analysis are presented in Table 12 on viscosity versus velocity for different samples of butter. The correlation coefficients varied from 0.9935 to 0.9996. The lines representing the regression equations are illustrated in Figs. 22 through 25.

VI. Pressure losses

The results of the correlation and regression analysis on the pressure loss versus velocity for different lengths of tubing and temperatures are presented in Table 13. The number of replicates ranged between 69 and 90 for a given length of tubing and temperature. The correlation coefficients ranged between 0.3506 to 0.9377. The low correlation coefficients were from data obtained using the shorter tubing (3.5 and 7.0 in.) and lower temperatures (55 and 60° F.). Figs. 26 through 28 show the lines representing the regression equations and illustrate the effect of length of tubing on the pressure loss at various flow velocities. The pressure losses increased as the velocity increased. For the 10.5-in. length of tubing

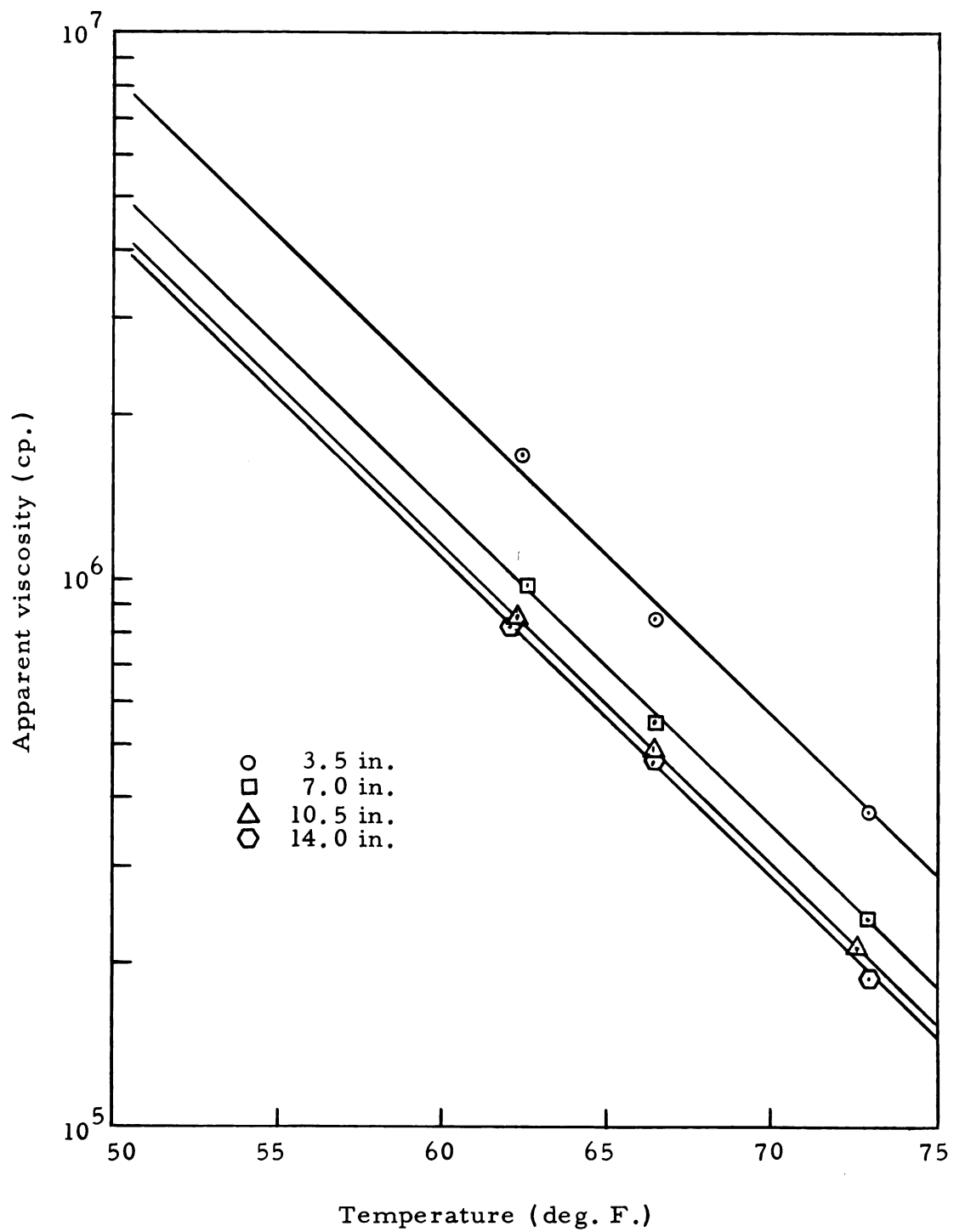


Fig. 21. The effect of temperature on the apparent viscosity of butter flowing at 0.01 ft./sec. for different lengths of tubing.

TABLE 12--Results of the correlation and regression analysis on the apparent viscosity versus velocity for each sample of butter

But- ter sam- ple	Tem- per- ature (deg. F.)	Regression coefficients		Standard error of estimate SE	Corre- lation coefficient (a)	Degrees of freedom DF
		a	b			
A	72.8	3.64644	-0.87916	0.02246	0.9984	13
B	72.3	3.64242	-0.90014	0.01565	0.9994	13
C	73.3	3.66592	-0.86824	0.01424	0.9991	13
D	72.6	3.70306	-0.80760	0.02720	0.9941	13
E	73.3	3.68582	-0.81527	0.02240	0.9965	13
F	72.8	3.87016	-0.72975	0.01844	0.9940	13
A	65.4	4.24026	-0.81619	0.02797	0.9971	13
B	66.6	4.31262	-0.69145	0.02439	0.9960	13
C	67.5	4.16397	-0.73334	0.01275	0.9991	10
D	65.2	4.15825	-0.77612	0.02629	0.9980	13
E	66.4	4.19921	-0.77474	0.01519	0.9994	13
F	66.0	4.22243	-0.76918	0.01937	0.9983	13
A	62.6	4.41034	-0.75315	0.01978	0.9978	13
B	63.7	4.19529	-0.83903	0.02116	0.9989	13
C	61.7	4.32366	-0.82802	0.02648	0.9965	13
D	61.0	4.38332	-0.85989	0.02146	0.9980	13
E	60.8	4.38396	-0.82075	0.02823	0.9935	13
F	62.4	4.28860	-0.79697	0.01632	0.9985	13
A	56.9	4.43540	-0.85385	0.01507	0.9990	13
B	57.2	4.39406	-0.83464	0.00866	0.9996	13
C	56.6	4.41049	-0.85211	0.01604	0.9985	13
D	57.3	4.20067	-0.86472	0.01967	0.9988	10
E	56.9	4.27915	-0.83498	0.01826	0.9990	13
F	57.1	4.17151	-0.86760	0.02148	0.9991	10

(a) DF corrected

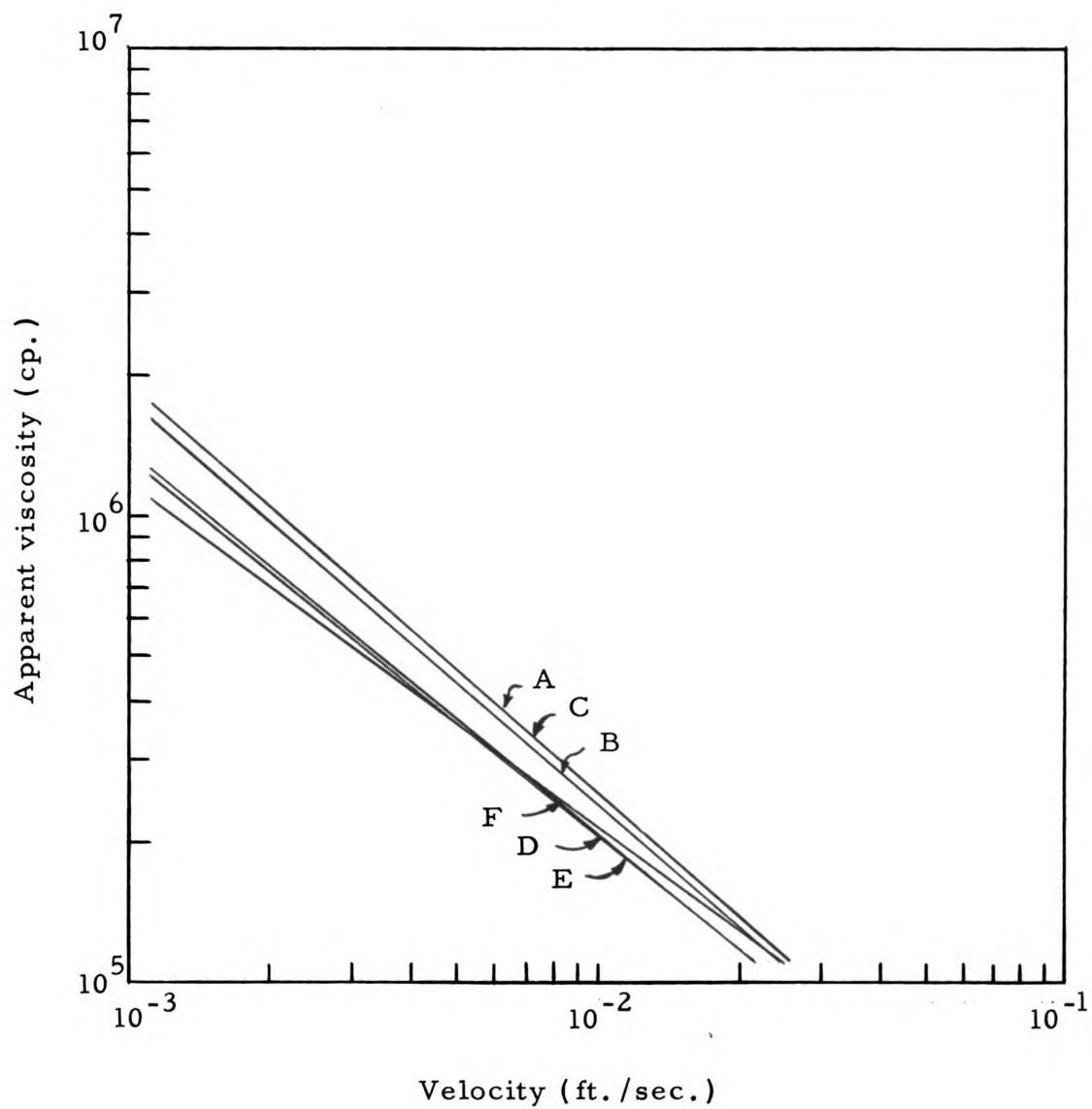


Fig. 22. Effect of sample on the apparent viscosity of flowing butter at 70° F.

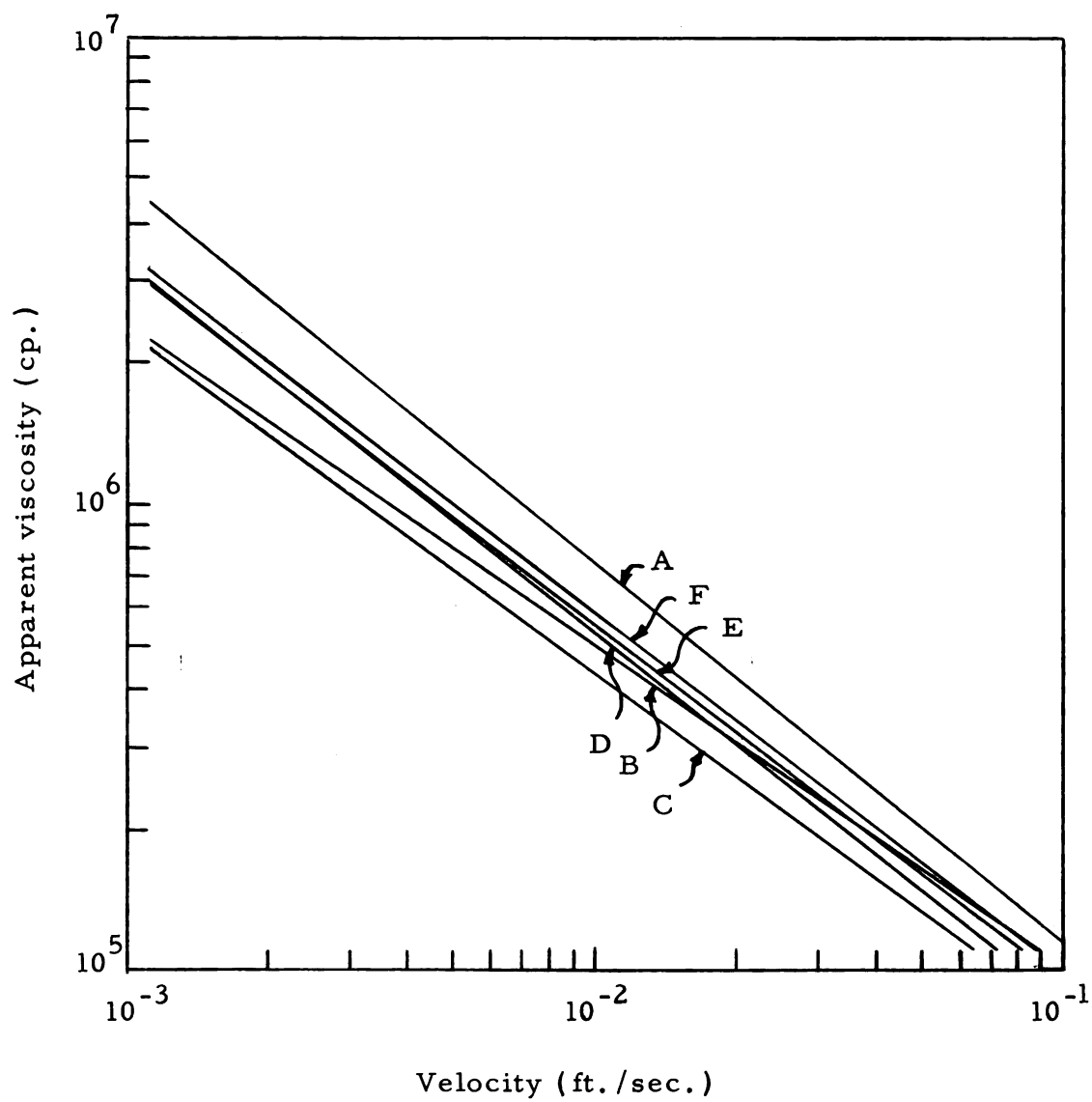


Fig. 23. Effect of sample on the apparent viscosity of flowing butter at 65° F.

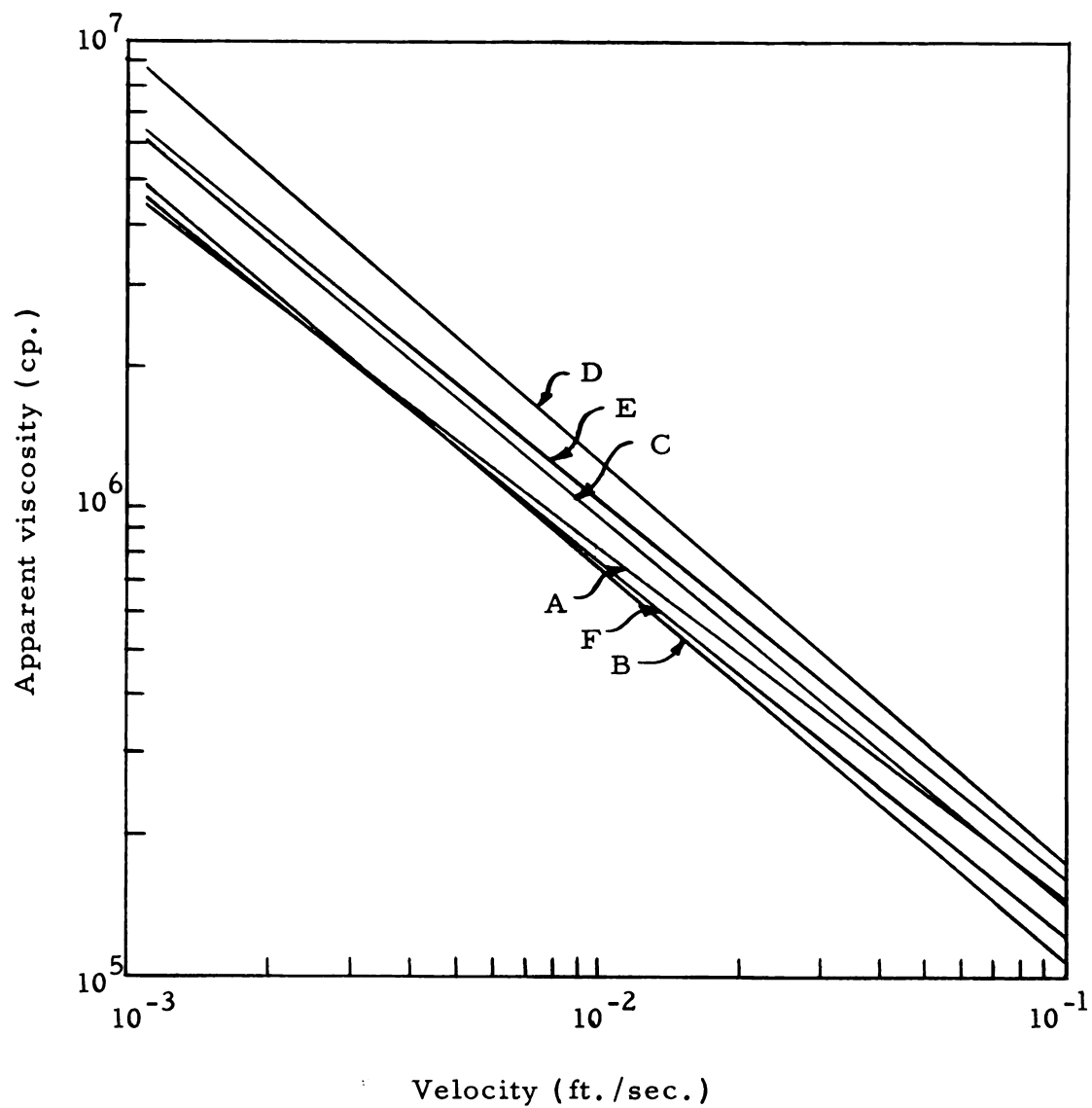


Fig. 24. Effect of sample on the apparent viscosity of flowing butter at 60° F.

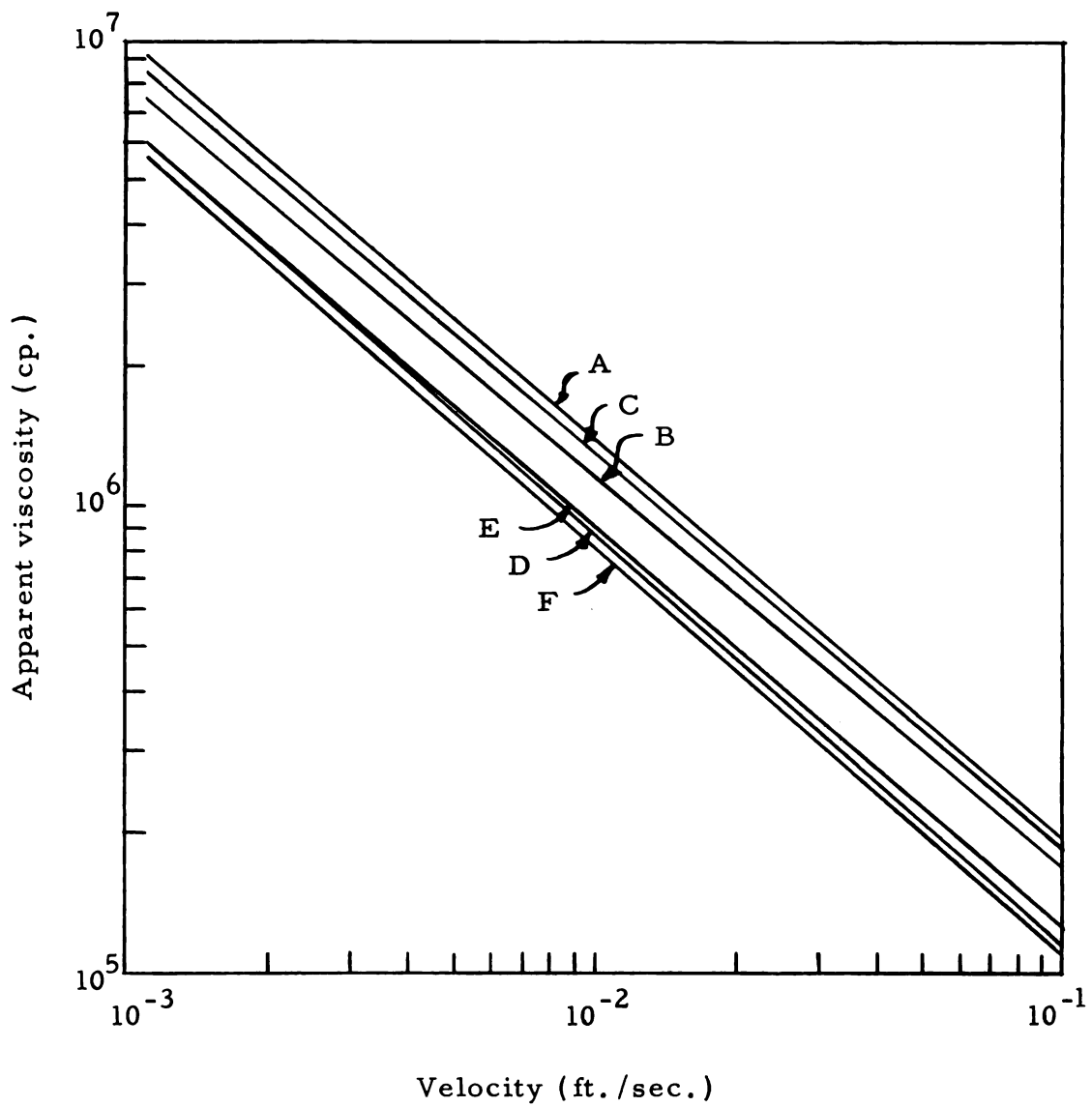


Fig. 25. Effect of sample on the apparent viscosity of flowing butter at 55° F.

TABLE 13--Results of the correlation and regression analysis on pressure loss versus velocity

Tub- ing length (in.)	Tem- per- ature (deg. F.)	Regression coefficients		Standard error of estimate SE	Corre- lation coef- ficient (a)	De- grees of free- dom DF
		a	b			
3.5	72.9	11.64056	2.39662	0.58321	0.9180	88
3.5	66.4	33.94985	8.10970	2.38179	0.9156	70
3.5	62.3	50.36779	7.80264	6.81659	0.5821	82
3.5	56.6	47.39012	6.54752	10.49731	0.3506	67
7.0	72.9	16.43128	3.42433	1.04984	0.7820	88
7.0	66.4	52.36254	14.95041	4.51138	0.8381	85
7.0	62.4	67.56852	13.87937	8.35944	0.5589	88
7.0	57.2	67.61422	11.63275	9.80365	0.4703	82
10.5	72.6	24.59113	5.95443	0.98820	0.9377	88
10.5	66.4	58.66845	14.32616	5.15964	0.7707	85
10.5	62.2	86.09827	16.95727	4.00025	0.8517	85
14.0	72.9	29.07278	7.05309	1.20345	0.9061	88
14.0	66.4	72.76564	17.11135	2.99934	0.9156	88
14.0	62.1	102.00550	17.48606	6.17015	0.7276	85

(a) DF corrected

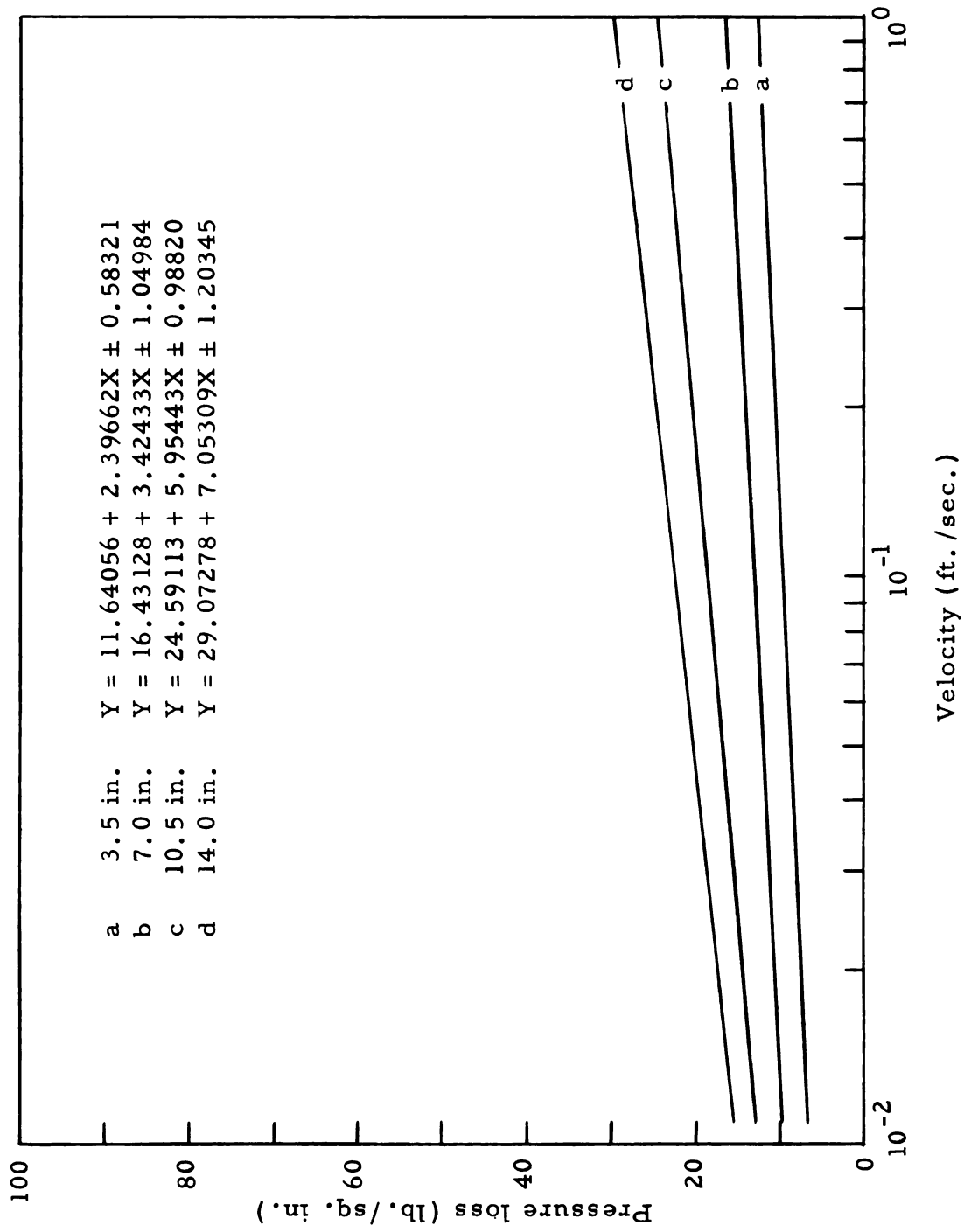


Fig. 26. Effect of tubing length on the pressure loss for butter flowing at 70° F.

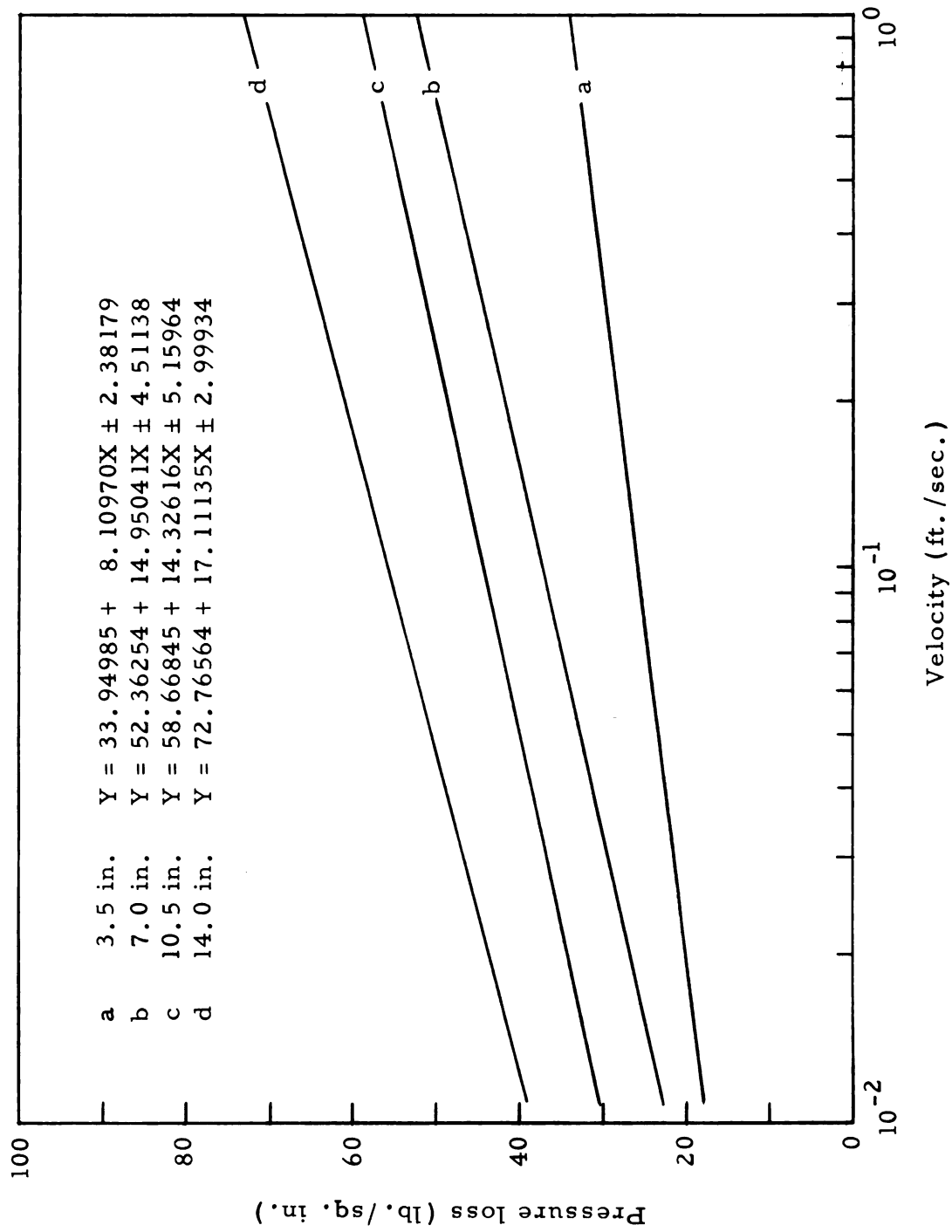


Fig. 27. Effect of tubing length on the pressure loss for butter flowing at 65° F.

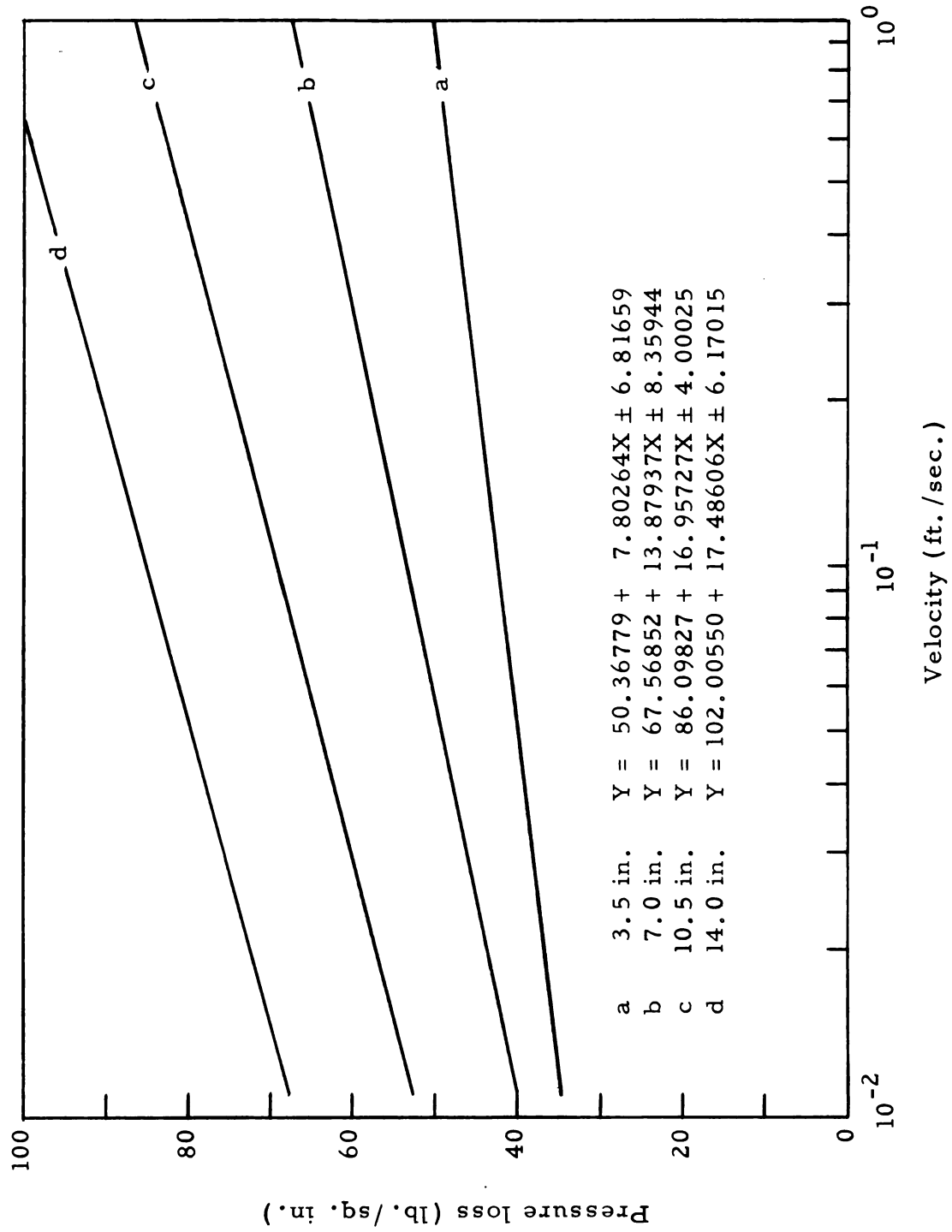


Fig. 28. Effect of tubing length on the pressure loss for butter flowing at 60° F.

at 65° F. the increase was from 22.5 to 37.4 lb./sq. in. as the velocity increased from 0.01 to 0.1 ft./sec. The pressure increased as the length of tubing increased. The increase was from 42.6 to 84.5 lb./sq. in. for lengths of tubing of 3.5 to 14.0 in. at a bulk velocity of 0.1 ft./sec. and 60° F.

Figs. 29 through 32 reveal the effect of the temperature on the pressure loss for butter flowing through different lengths of tubing. The pressure increased from 28.5 to 79.2 lb./sq. in. as the temperature decreased from 72.6 to 62.2° F. at a bulk velocity of 0.1 ft./sec. The standard error of estimate is shown in Fig. 33 for tubing length of 10.5 in. and 72.6, 66.4 and 62.2° F.

The results of the correlation and regression analysis on the pressure loss versus velocity for each sample of butter are presented in Table 14. The correlation coefficients ranged from 0.8659 to 0.9940 which indicated good correlation between data from the same sample. However, greater variations occurred among the samples as shown in Fig. 34.

VII. Reduction in apparent viscosity under mild agitation

The reduction in the apparent viscosity of butter under constant agitation is illustrated in Fig. 35 for four different temperatures. Each point represents the average of 18 trials. The same data are illustrated in Fig. 36 as a log-log relationship.

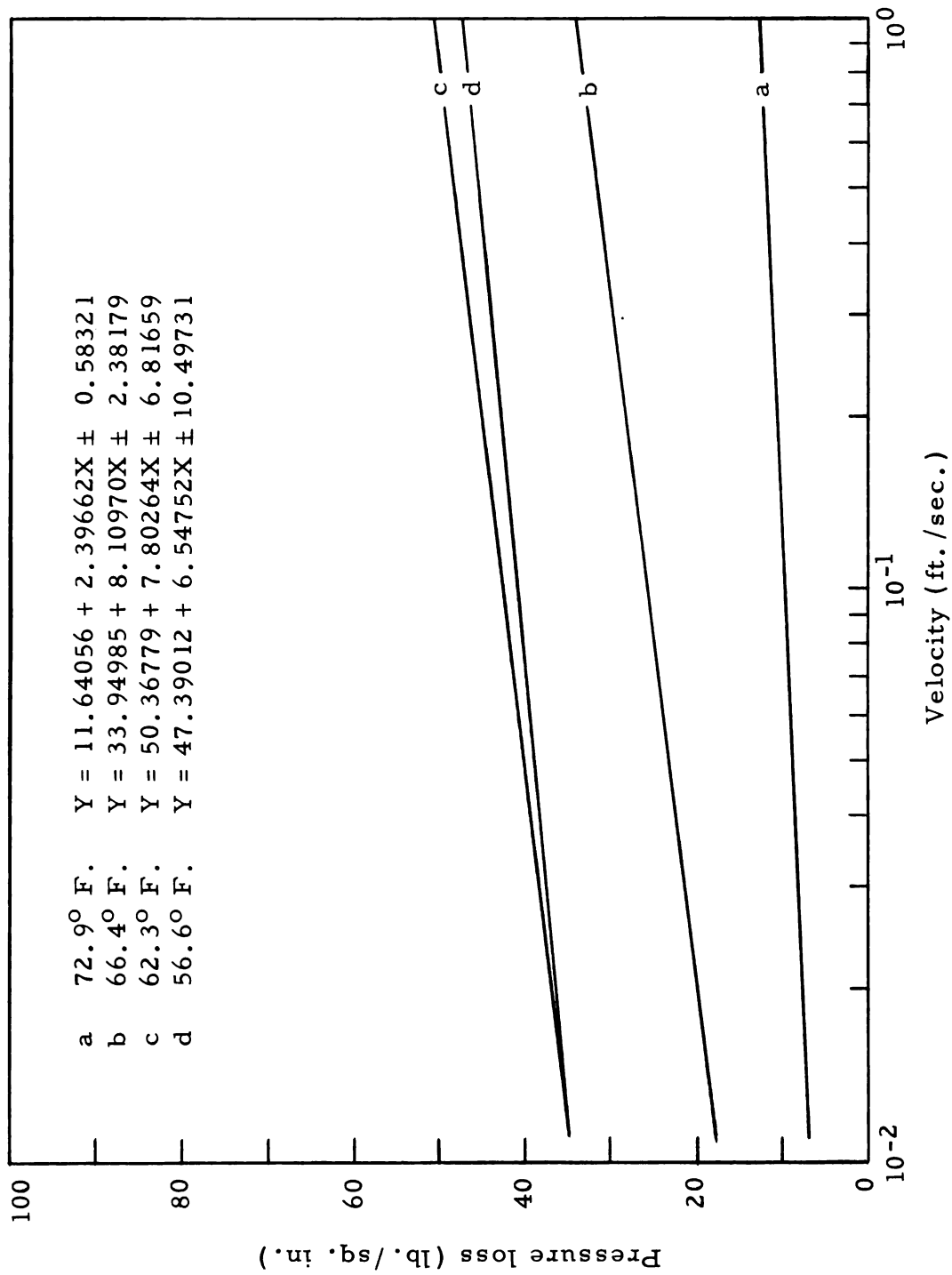


Fig. 29. Effect of temperature on the pressure loss for flowing butter (3.5-in. tubing length).

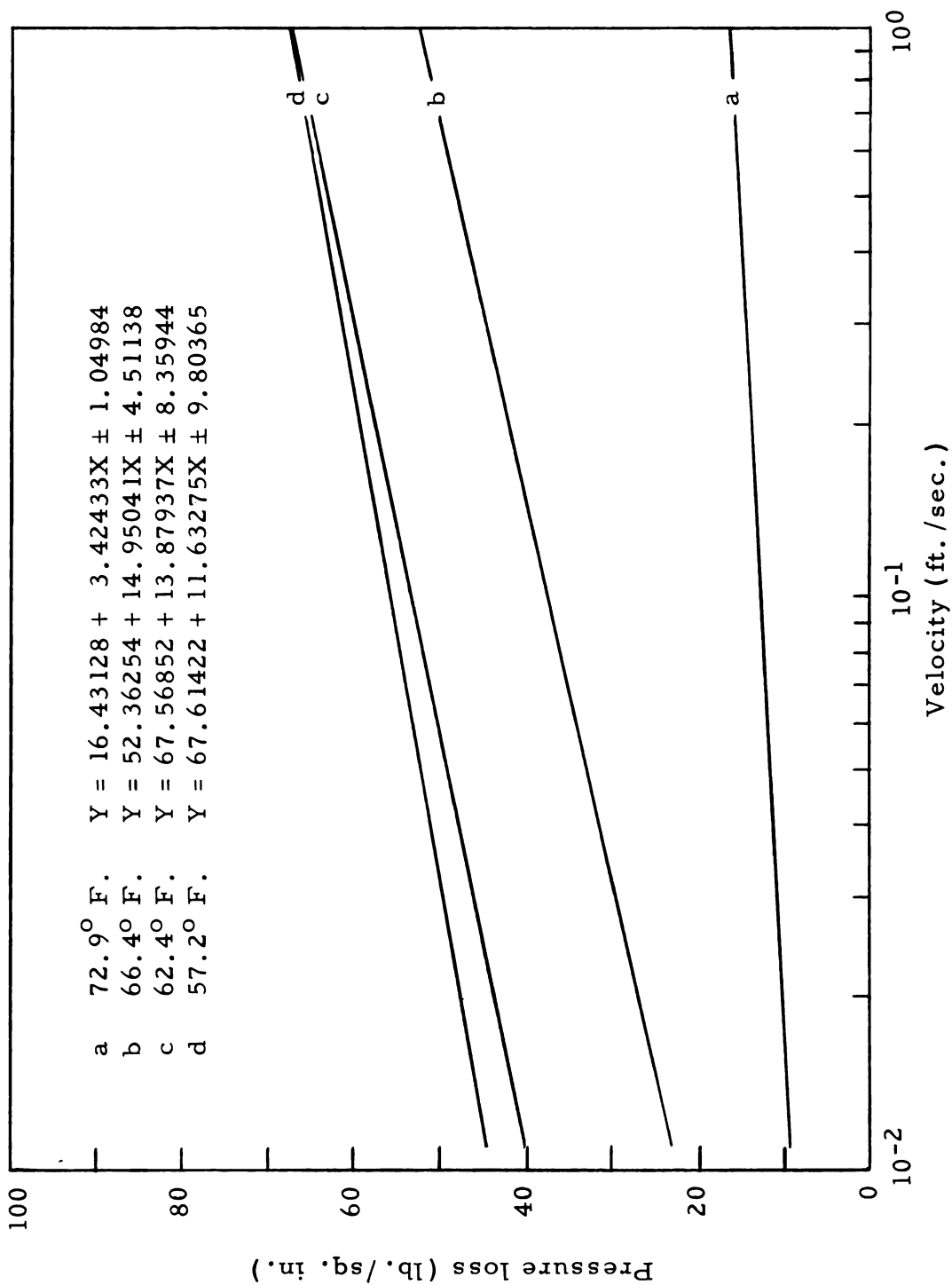


Fig. 30. Effect of temperature on the pressure loss for flowing butter (7.0-in. tubing length).

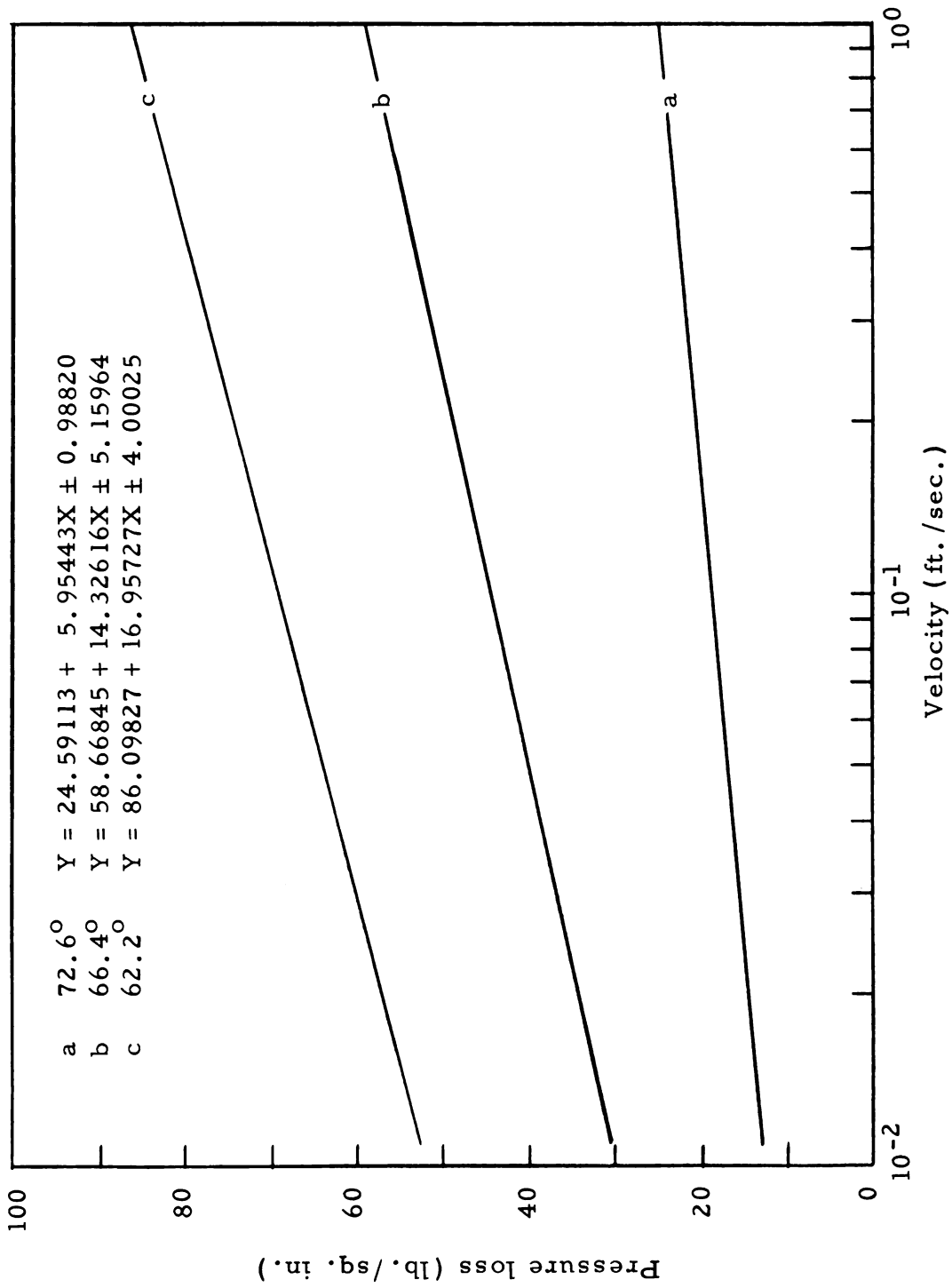


Fig. 31. Effect of temperature on the pressure loss for flowing butter (10.5-in. tubing length).

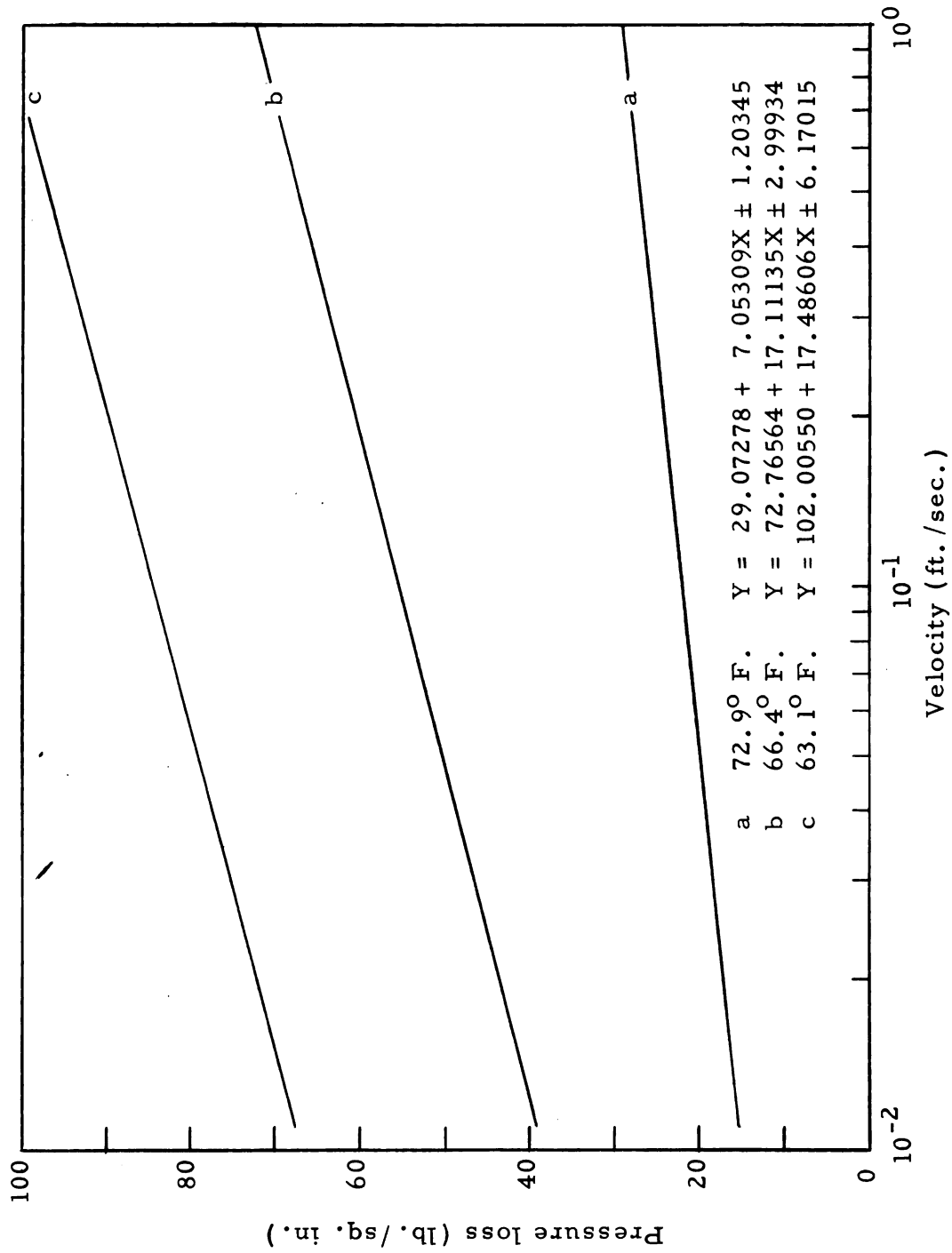


Fig. 32. Effect of temperature on the pressure loss for flowing butter (14.0-in tubing length).

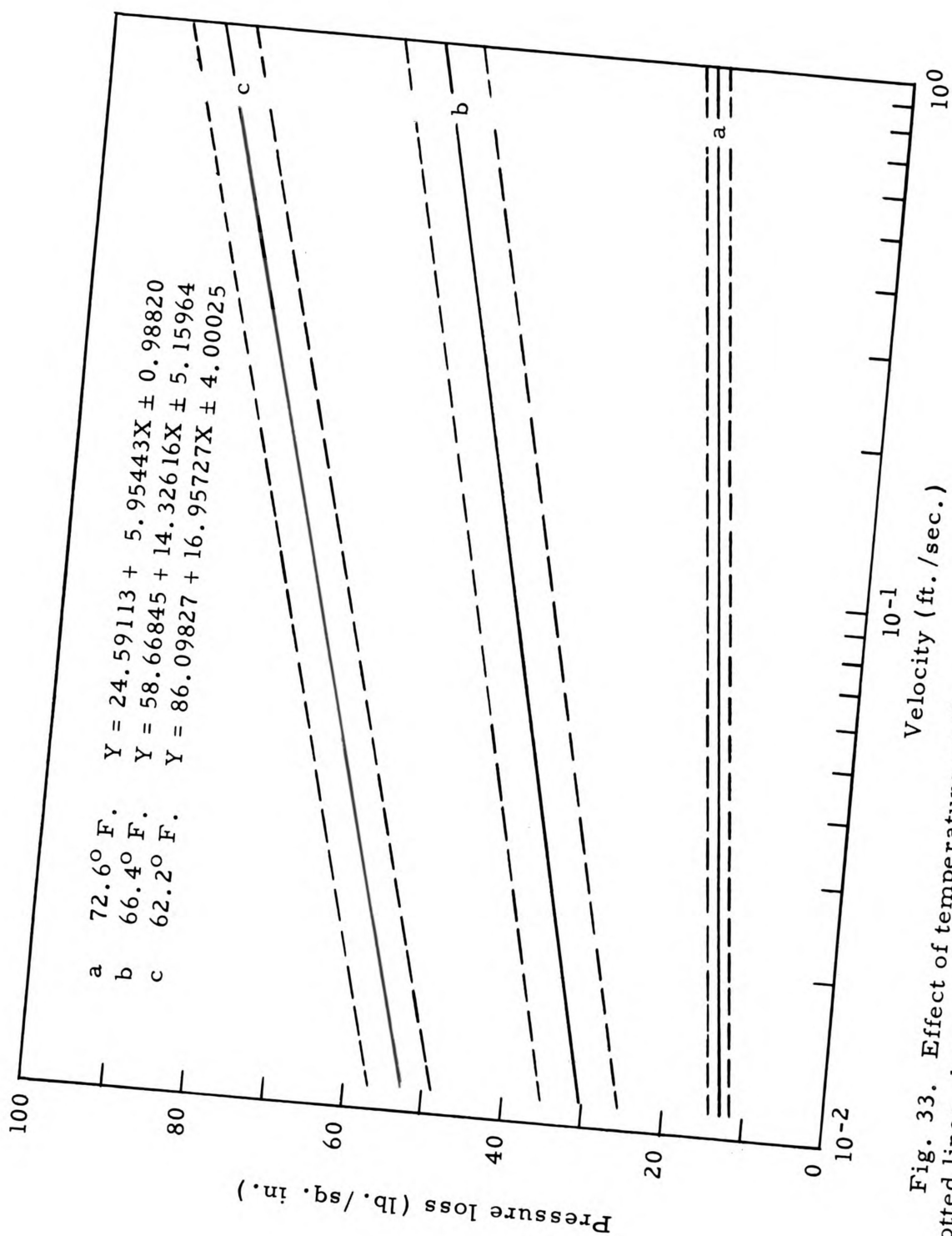


Fig. 33. Effect of temperature on the pressure loss for flowing butter with the dotted lines showing the standard error of estimate (10.5-in. tubing length).

TABLE 14--Results of the correlation and regression analysis on the pressure loss versus velocity for each sample of butter

But- ter sam- ple	Tem- per- ature (deg. F.)	Regression coefficients		Standard error of estimate SE	Corre- lation coef- ficient (a)	De- grees of free- dom DF
		a	b			
A	72.8	16.18960	2.98352	0.60246	0.9114	13
B	72.3	16.66171	2.77435	0.36820	0.9678	13
C	73.3	17.20780	3.59710	0.41260	0.9595	13
D	72.6	16.80197	4.24693	0.68045	0.8854	13
E	73.3	16.49905	4.11626	0.57410	0.9199	13
F	72.8	20.66515	6.05787	0.47424	0.9461	13
A	65.4	60.40789	15.31006	2.70486	0.9292	13
B	66.6	56.76020	18.42651	1.14395	0.9877	13
C	67.5	44.63889	13.96980	0.63935	0.9940	10
D	65.2	47.43741	13.32182	1.80313	0.9692	13
E	66.4	49.62400	13.23481	1.33405	0.9832	13
F	66.0	55.19688	16.25084	1.78659	0.9698	13
A	62.6	86.29430	27.51587	3.13139	0.9604	13
B	63.7	56.80435	13.35821	1.69587	0.9728	13
C	61.7	74.93718	17.99875	2.57551	0.9360	13
D	61.0	86.51364	17.84711	2.30650	0.9490	13
E	60.8	84.52483	21.31428	3.66153	0.8659	13
F	62.4	67.55212	19.33516	0.96292	0.9913	13
A	56.9	92.72694	18.39757	1.73396	0.9715	13
B	57.2	83.99577	18.67517	1.20483	0.9864	13
C	56.6	93.49690	20.50733	2.02376	0.9610	13
D	57.3	58.42069	12.23036	1.56728	0.9633	10
E	56.9	65.66187	14.83491	1.87766	0.9665	13
F	57.1	52.23334	9.77518	1.28330	0.9755	10

(a) DF corrected

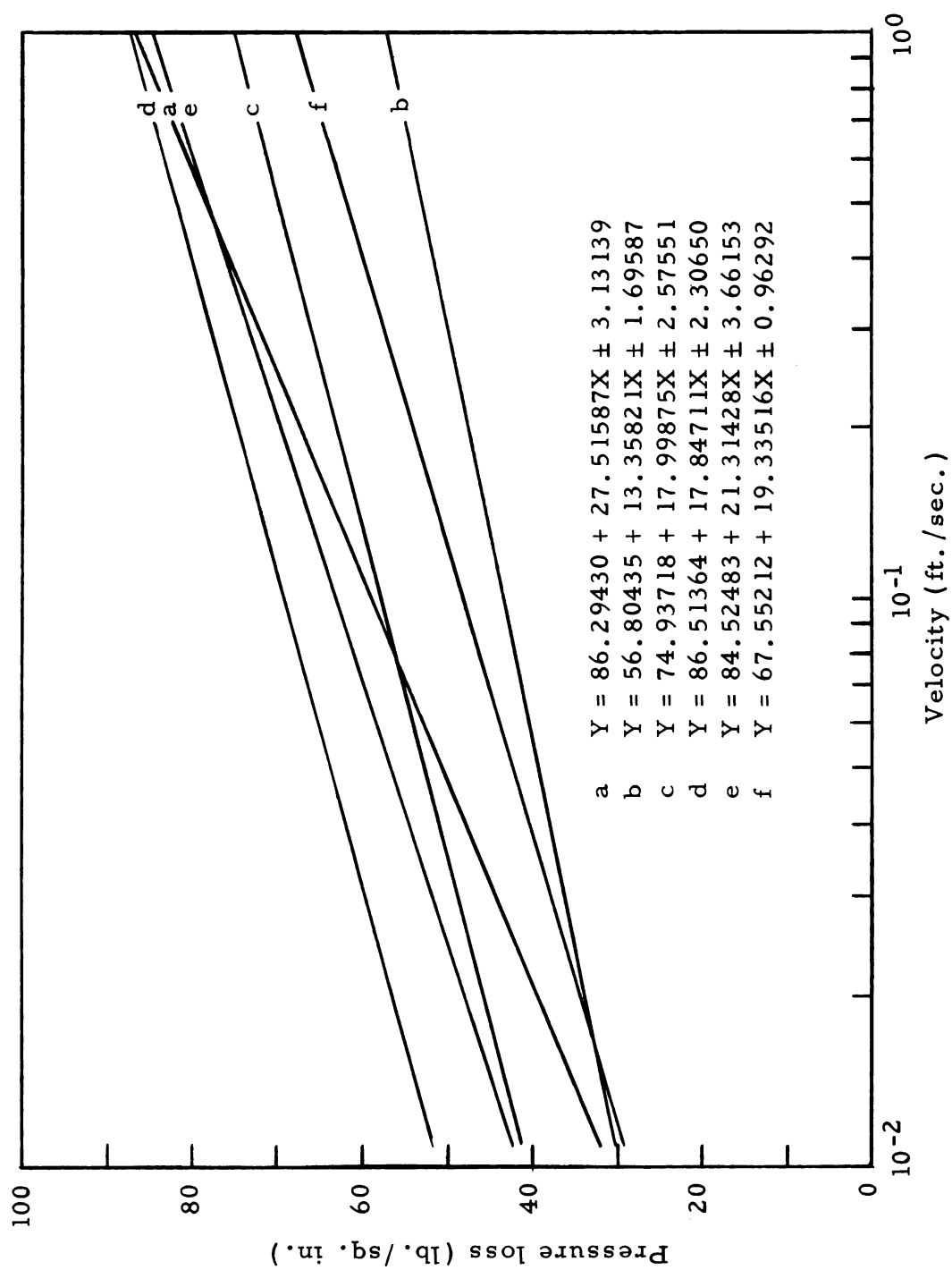


Fig. 34. Effect of sample on the pressure loss of flowing butter at 65° F.

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Apparent viscosity (10^6 cp.)

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is mild

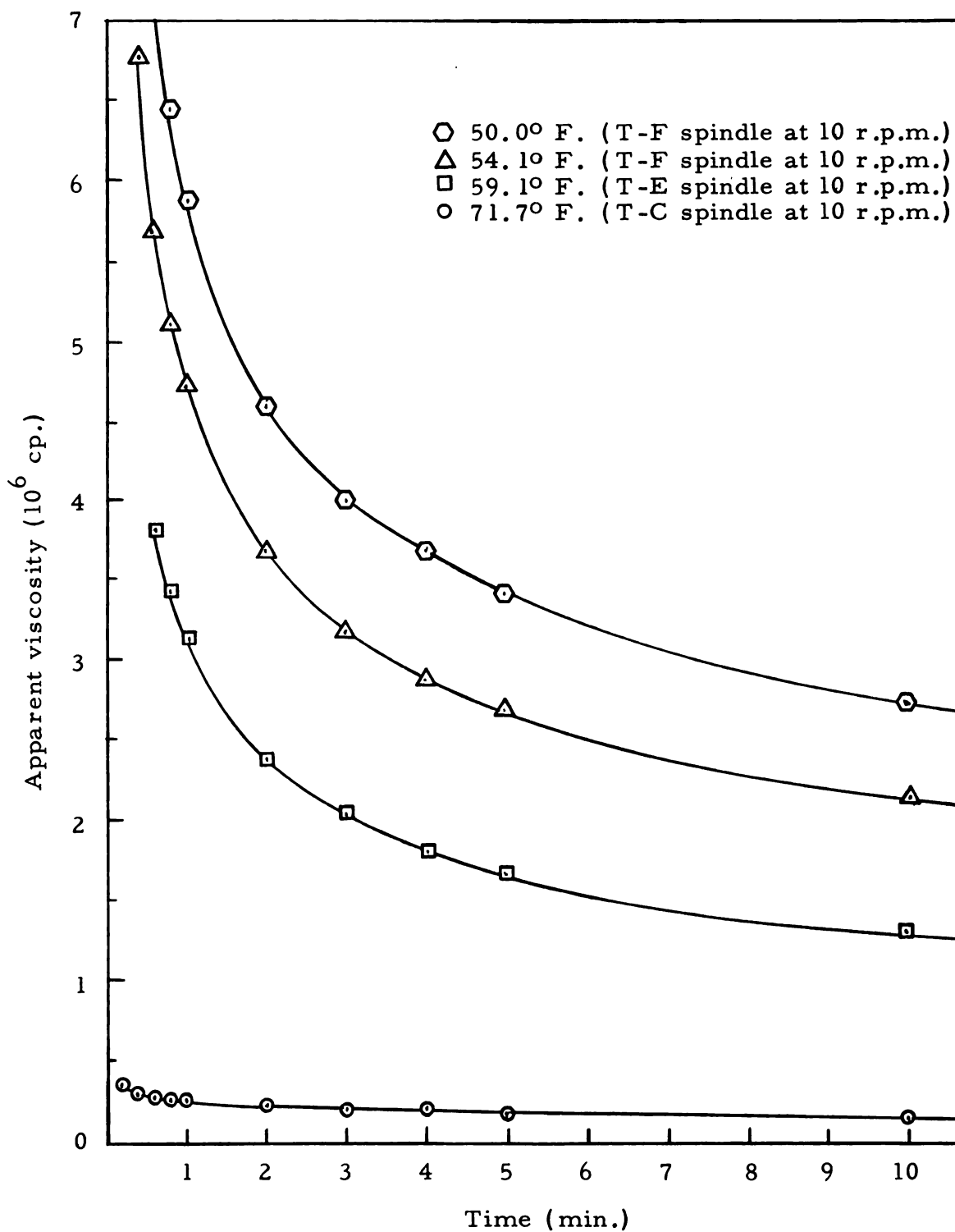


Fig. 35. The reduction in apparent viscosity with time the butter is mildly agitated at various temperatures.

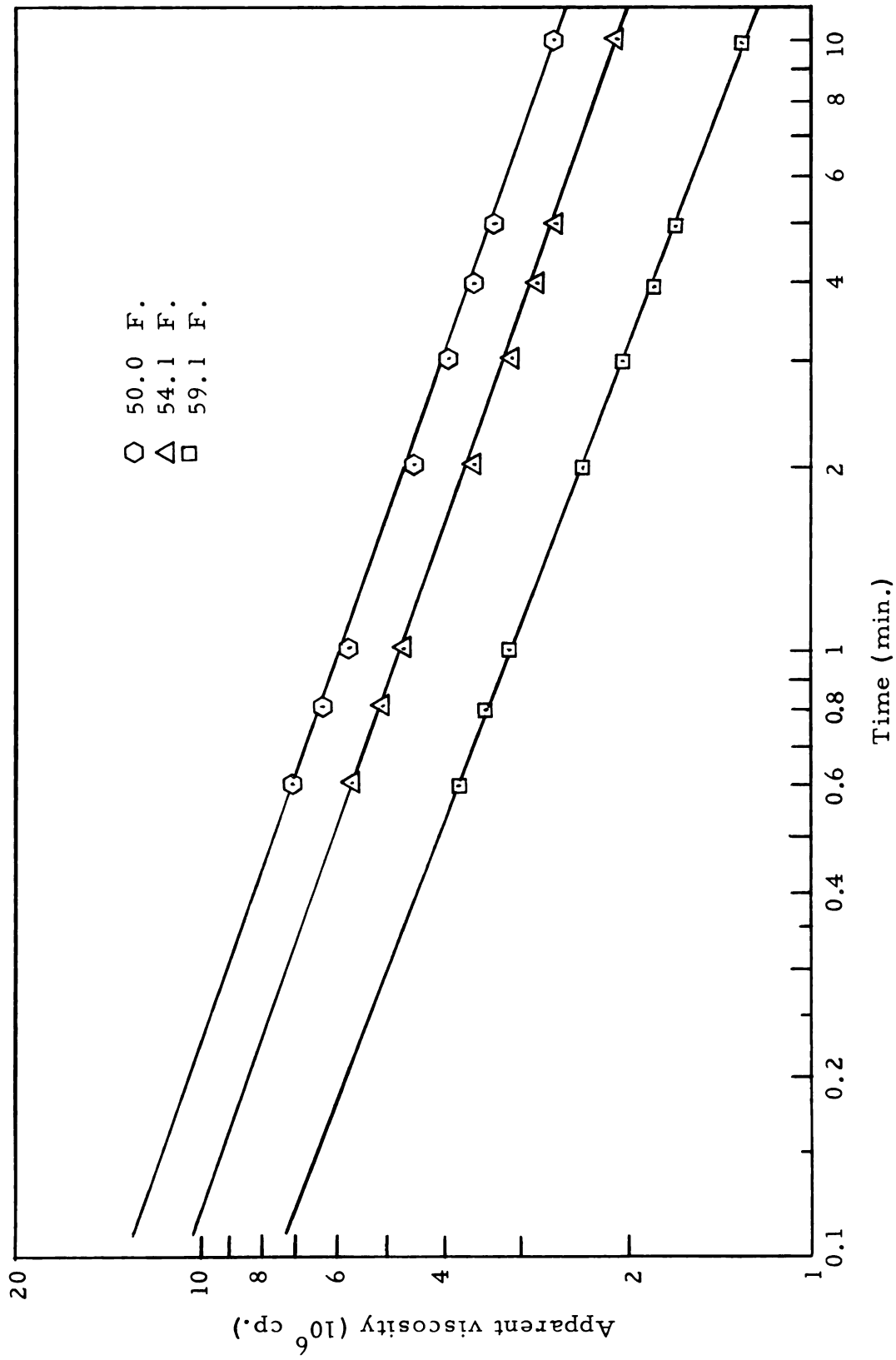


Fig. 36. The linear representation of the reduction in apparent viscosity with time the butter is mildly agitated at various temperatures.

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VIII. Reduction in apparent viscosity due to pumping

The effect of moving the butter through a pump at two different rates is presented in Table 15 for five passes through the pump. The average of three determinations on the apparent viscosity versus the number of passes through the pump at each rate is illustrated in Fig. 37.

The apparent viscosity results from the extrusion viscometer are presented in Table 16 showing the decrease in apparent viscosity with each pass through the pump. Only three passes through the pump could be used because the temperature of the butter became too high to effectively utilize the extrusion viscometer equipment.

IX. Minimum pressure necessary to initiate flow in tubing, elbows and valve assemblies

The minimum pressure necessary just to overcome the inertia of butter in tubing is illustrated in Fig. 38 for different temperatures and lengths of tubing. The lines represent the regression equations determined from the data.

Fig. 39 shows the increase in pressure necessary to initiate flow at different temperatures for various lengths of tubing. The figure was constructed by using the regression equation for the 10.5-in. length of tubing (see Fig. 38). The results of 30 trials at each temperature on the minimum pressure determinations for elbows and valve assemblies are presented in Table 17.

TABLE 15--The influence of pumping on the apparent viscosity of butter

Pump speed (r.p.m.)	Trial (No.)	Passes through pump (No.)	Temper- ature (deg. F.)	Viscosity (cp.)	Pene- tration value (mm.)
52	1	1	66.4	661,000	21.1
		2	66.6	392,000	22.7
		3	67.0	329,000	25.0
		4	67.6	275,000	25.4
		5	68.2	242,000	26.7
52	2	1	67.0	470,000	21.8
		2	67.8	344,000	25.2
		3	68.1	267,000	25.9
		4	68.8	226,000	27.4
		5	69.1	182,000	28.2
52	3	1	64.7	698,000	19.9
		2	68.0	347,000	23.5
		3	68.4	262,000	25.7
		4	68.8	214,000	26.8
		5	68.9	192,000	27.9
120	1	1	65.7	708,000	19.8
		2	67.3	411,000	23.9
		3	67.9	304,000	25.0
		4	68.3	256,000	26.7
		5	68.6	202,000	27.8
120	2	1	65.2	458,000	20.1
		2	67.2	341,000	21.9
		3	68.1	277,000	26.4
		4	68.8	194,000	27.4
		5	69.4	181,000	28.1
120	3	1	65.5	870,000	20.8
		2	67.5	379,000	24.2
		3	68.4	264,000	25.3
		4	68.9	227,000	26.6
		5	69.4	189,000	27.8

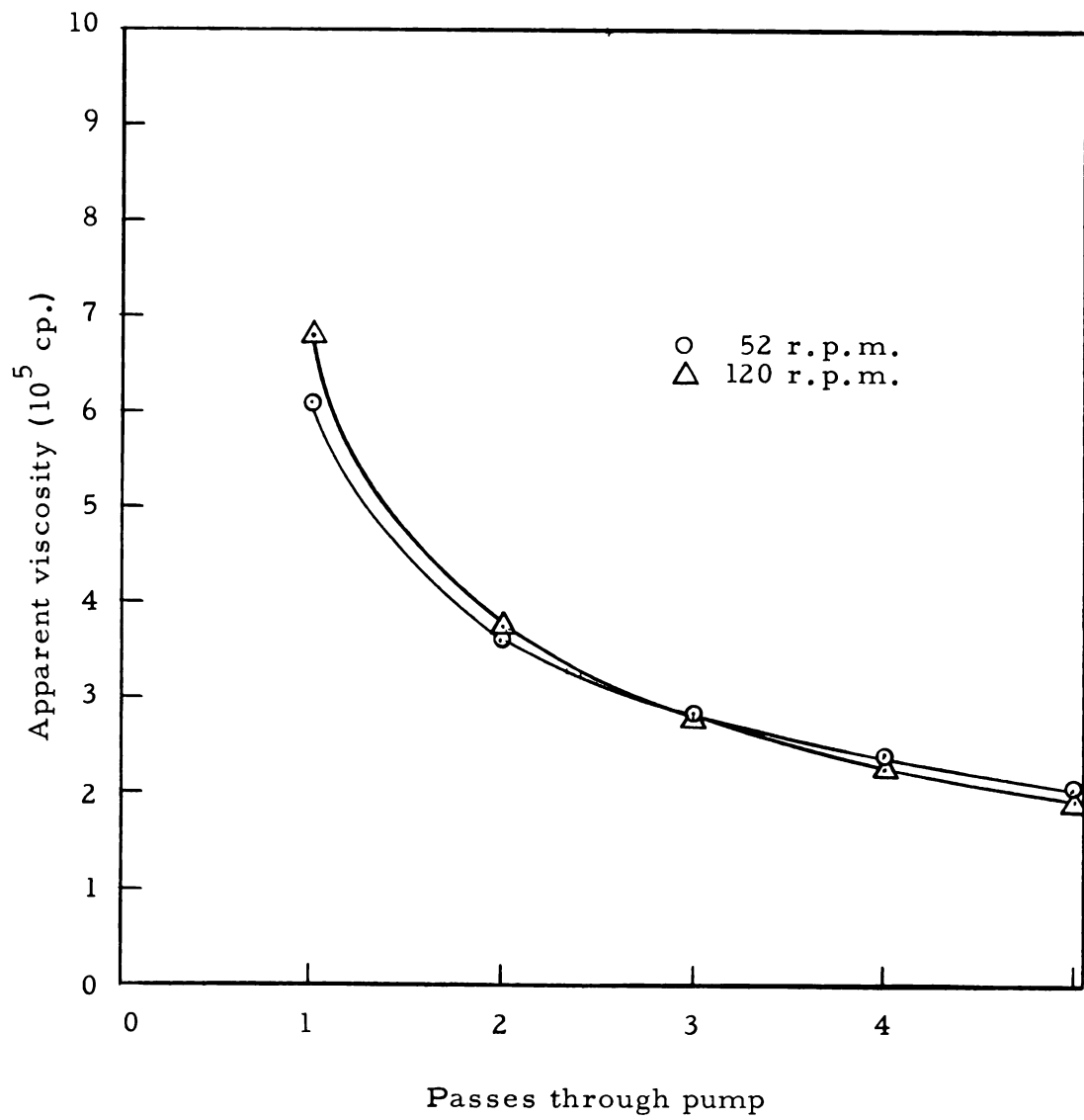


Fig. 37. Effect of pumping rate on the apparent viscosity.

TABLE 16--The influence of pumping on the apparent viscosity of butter using the extrusion viscometer

Pump speed (r.p.m.)	Trial (No.)	Passes through pump (No.)	Temper- ature (deg. F.)	Viscosity (a) (cp.)	Pene- tration value (mm.)
52	1	1	68.5	152,000	22.2
		2	70.0	45,300	25.8
		3	72.6	17,800	33.2
52	2	1	68.1	134,000	21.8
		2	70.3	31,000	25.5
		3	72.4	11,700	35.1
52	3	1	69.7	76,300	23.5
		2	71.0	27,000	27.2
		3	72.9	11,600	36.8
120	1	1	70.0	95,000	23.4
		2	71.8	33,200	27.2
		3	72.3	12,500	33.5
120	2	1	69.5	116,000	22.1
		2	71.0	38,000	27.1
		3	72.5	13,500	34.4
120	3	1	70.0	74,100	26.0
		2	72.4	20,400	29.1
		3	73.0	11,600	34.8

(a) Viscosities determined at constant pressure and variable rate of shear.

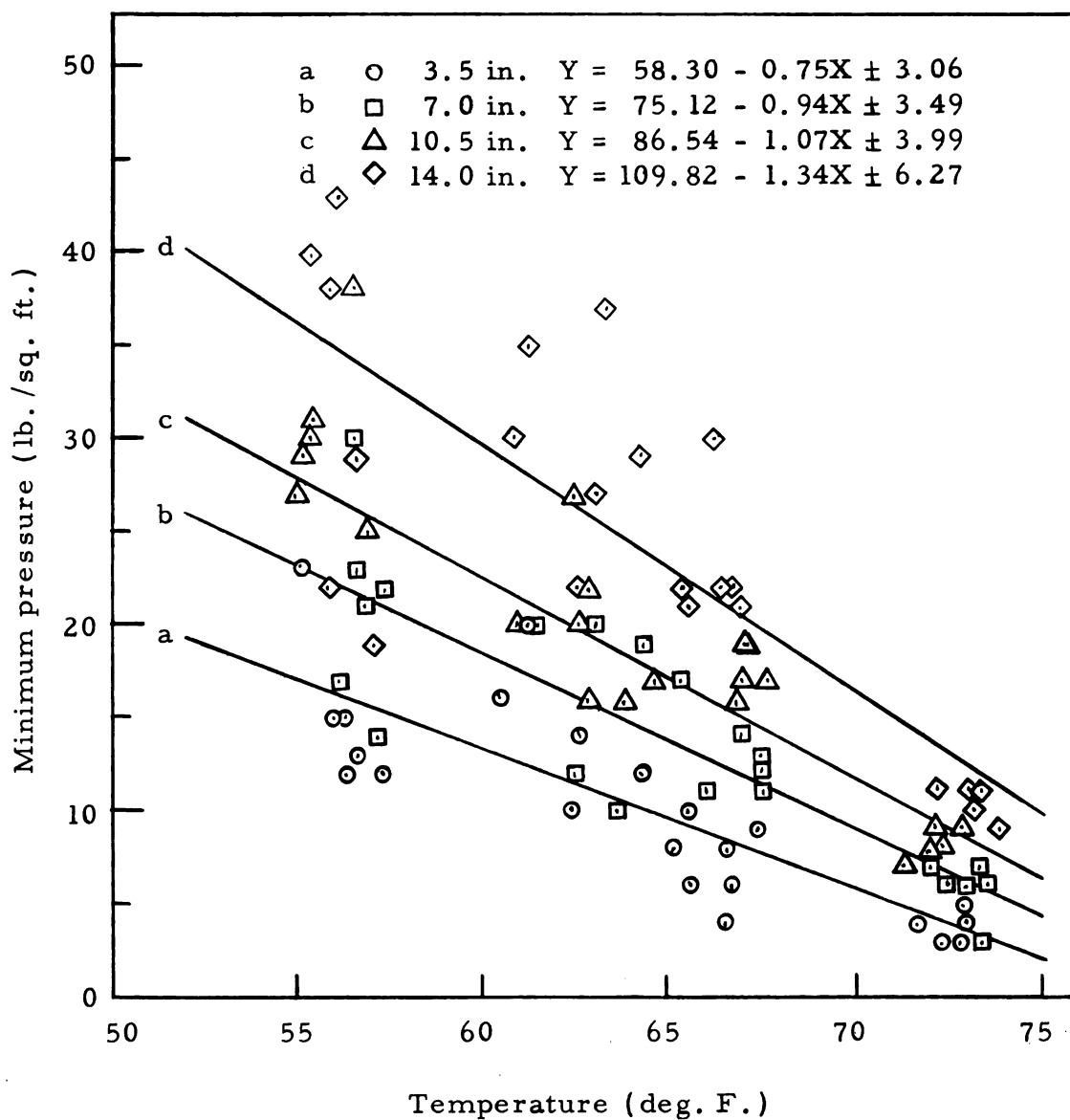


Fig. 38. The effect and regression lines for the minimum pressure needed to initiate the flow of butter in various lengths of tubing at different temperatures.

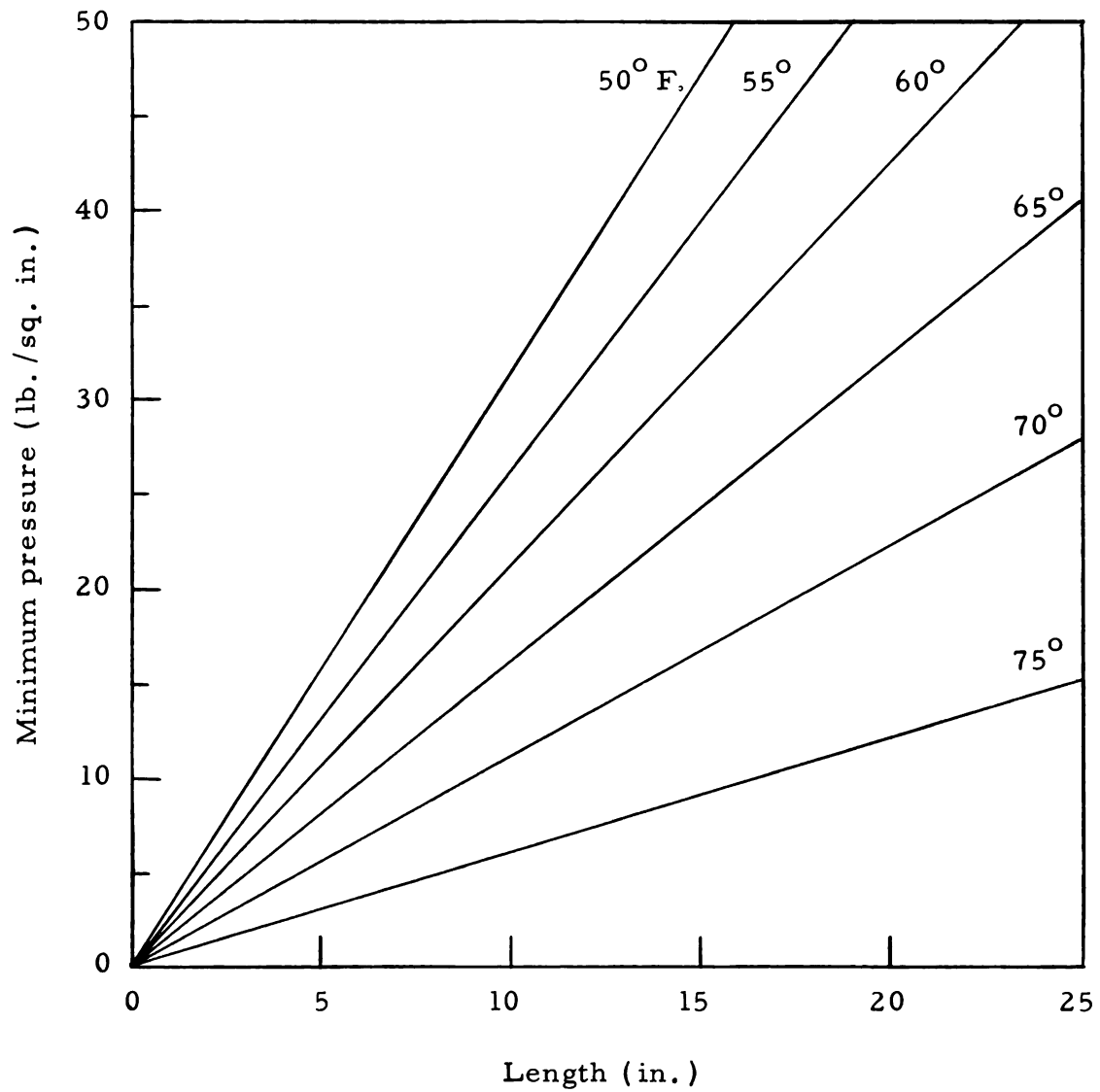


Fig. 39. The minimum pressure needed to initiate flow through tubing at various temperatures.

TABLE 17--Average minimum pressure losses for elbows and valve assemblies of 1.5-in. diameter

	Temper- ature (deg. F.)	Minimum pressure (lb./sq. in.)	Range (lb./sq. in.)	Differ- ence (lb./ sq. in.)
Elbows	72.0	1.95	1.50 to 2.25	0.75
	65.1	2.99	2.50 to 4.00	1.50
	57.0	5.11	4.50 to 5.75	1.25
Valve assemblies	71.3	1.94	1.50 to 2.25	0.75
	65.5	5.55	4.25 to 6.00	1.75
	56.8	9.43	8.75 to 10.25	1.50

X. Power requirements

A plot of the calculated friction factor versus the calculated Reynolds number is illustrated in Fig. 40. Since the data were determined for laminar flow, a logarithm scale was used for the friction factor to show a wider range of values.

The general relationship for the apparent viscosity versus the bulk velocity and temperature for flowing butter is:

$$\log \eta = 7.93446 - 0.84649 \log v - 0.0587T \quad 24$$

which is considered valid for temperatures between 55 and 75^o F.

The following is an example of the calculations for determining the power requirements. A printer operating at 50 lb./min. is supplied with butter at 55^o F. through a 2.0-in. stainless steel tubing (Fig. 41).

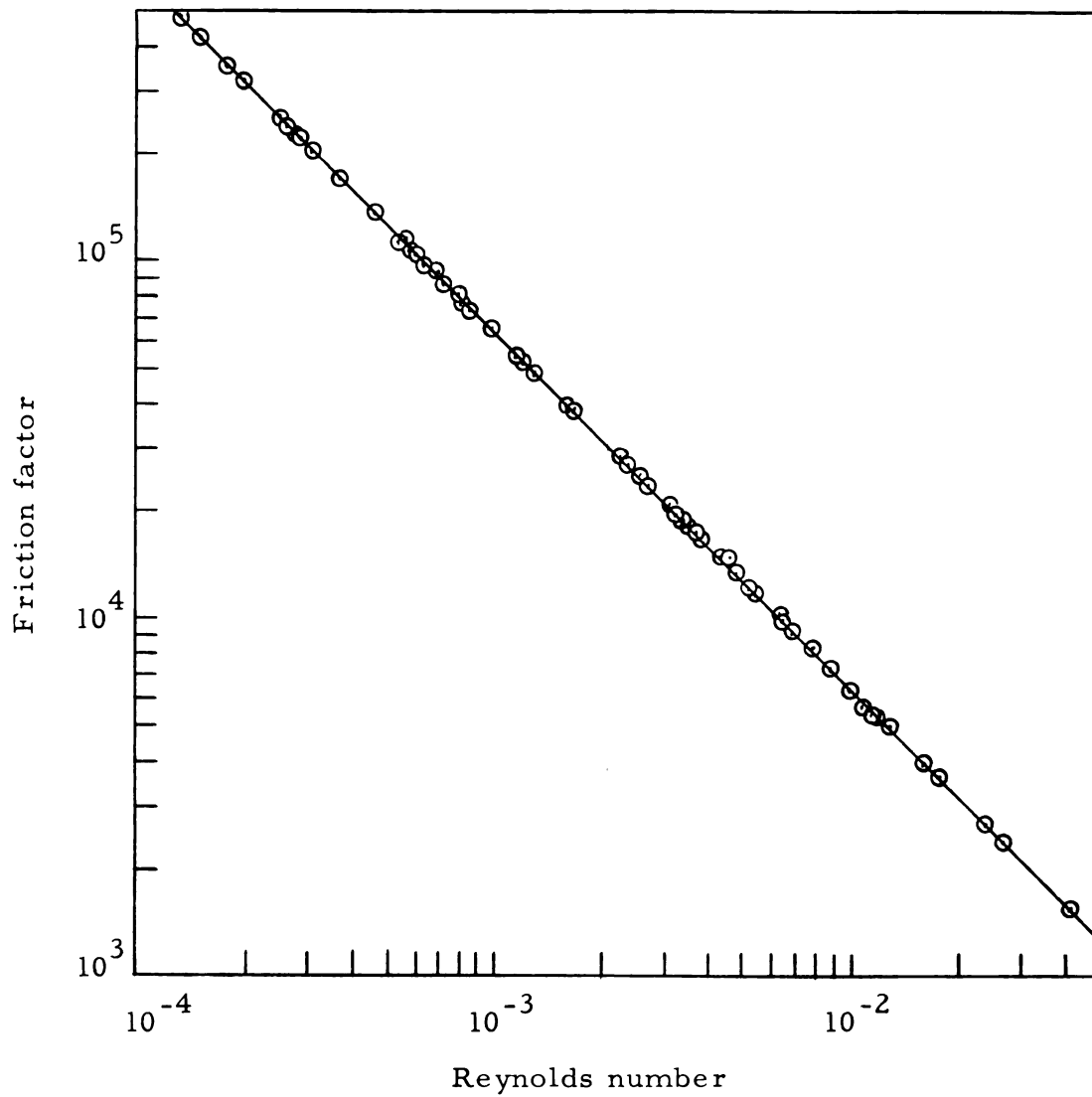


Fig. 40. Friction factor versus Reynolds number for butter flowing through stainless steel tubing.

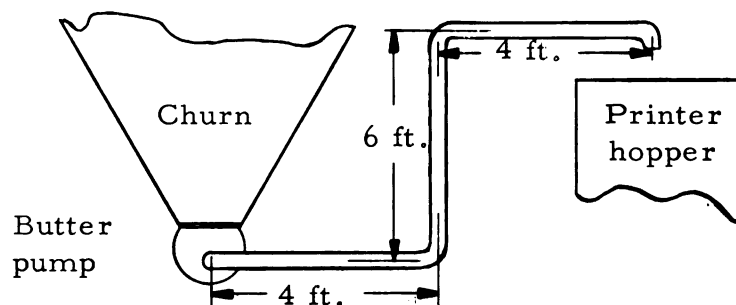


Fig. 41. Arrangement of stainless steel tubing for the calculations of the power required to pump butter at 50 lb./min.

Given: $W = 50 \text{ lb./min.}$
 $T = 55^\circ \text{ F.}$
 $\rho = 59.3 \text{ lb./cu. ft.}$
 $D = 1.87 \text{ in.}$
 $L = 15.5 \text{ ft. (includes 1.5 ft. for the four elbows)}$

Bulk velocity:

$$v = 5.16 \times 10^{-2} \frac{(50)}{(1.87)^2} = 0.738 \text{ ft./sec.}$$

Apparent viscosity:

$$\log \eta = 7.93446 - 0.84649 \log v - 0.0587T$$

$$\log \eta = 7.93446 + 0.11169 - 3.17900$$

$$\eta = 73,700 \text{ cp.}$$

Reynolds number:

$$\text{Re} = \frac{(1.87)(0.738)(59.3)}{(12)(6.72 \times 10^{-4})(7.37 \times 10^4)} = 0.138$$

Friction factor:

$$f = \frac{64}{0.138} = 465$$

Loss of head:

$$h = \frac{(465)(15.5)(12)(0.738)^2}{(1.87)(64.4)} = 391 \text{ ft.}$$

Horsepower:

$$Hp = \frac{(50)(391 + 6)}{(0.8)(0.8)(3.3 \times 10^4)} = 9.4 \text{ hp. (includes 80\% motor efficiency and 80\% pump efficiency)}$$

The loss of head and power requirements is presented in Tables 18 and 19 for butter flowing under various conditions. The calculated power requirements revealed that a 5^o F. decrease in temperature about doubles the horsepower required (0.18, 0.35 and 0.69 hp. at 65, 60 and 55^o F.) to move the butter. Increasing the diameter from 1.5 to 3.0 in. reduced the power required from 1.81 to 0.35 hp. for moving butter at 60^o F. through 20 ft. of tubing at 10 lb./min. This reduction is even greater as the quantity of butter increases.

TABLE 18--Loss of head and power requirements for various quantities of butter at different temperatures flowing through tubing of various lengths

Inside diameter (in.)	Temperature (deg. F.)	Weight (a) (lb./min.)	Length (ft.)	Bulk velocity (ft./sec.)	Apparent viscosity (cp.)	Reynolds number	Friction factor	Loss of head (ft.)	Horsepower (hp.)
1.402	65	10	10	0.262	44,100	0.0613	1,045	10	0.05
		10	20	0.262	44,100	0.0613	1,045	19	0.09
		10	30	0.262	44,100	0.0613	1,045	29	0.14
		50	20	1.310	12,000	0.1130	567	1,974	46.80
		100	20	2.620	6,700	0.4030	159	2,900	137.00
1.402	60	10	10	0.262	85,800	0.0315	2,030	191	0.91
		10	20	0.262	85,800	0.0315	2,030	382	1.81
		10	30	0.262	85,800	0.0315	2,030	764	3.62
		50	20	1.310	23,300	0.0580	1,100	5,020	119.00
		100	20	2.620	13,000	0.2080	308	5,620	226.00
1.402	55	10	10	0.262	167,000	0.0162	3,950	358	1.70
		10	20	0.262	167,000	0.0162	3,950	716	3.39
		10	30	0.262	167,000	0.0162	3,950	1,074	5.08
		50	20	1.310	45,300	0.0298	2,150	9,800	232.00
		100	20	2.620	25,400	0.1060	603	11,000	521.00

(a) Density of butter: 59.3 lb./cu. ft.

TABLE 19--Loss of head and power requirements for various quantities of butter at different temperatures flowing through tubing of various lengths

Inside diameter (in.)	Temperature (deg. F.)	Weight (a) (lb./min.)	Length (ft.)	Bulk velocity (ft./sec.)	Apparent viscosity (cp.)	Reynolds number	Friction factor	Loss of head (ft.)	Horsepower (hp.)
2.870	65	10	10	0.0626	157,000	0.0084	7,000	19	0.09
		10	20	0.0626	157,000	0.0084	7,600	39	0.18
		10	30	0.0626	157,000	0.0084	7,600	60	0.27
		50	20	0.3130	40,000	0.1640	390	50	1.17
		100	20	0.6260	22,400	0.5900	108	55	2.60
2.870	60	10	10	0.0626	306,000	0.0043	14,800	38	0.18
		10	20	0.0626	306,000	0.0043	14,800	75	0.35
		10	30	0.0626	306,000	0.0043	14,800	113	0.53
		50	20	0.3130	78,300	0.0843	760	98	2.31
		100	20	0.6260	43,500	0.3030	211	107	5.07
2.870	55	10	10	0.0626	595,000	0.0022	28,800	73	0.35
		10	20	0.0626	595,000	0.0022	28,800	146	0.69
		10	30	0.0626	595,000	0.0022	28,800	220	1.04
		50	20	0.3130	152,000	0.0435	1,470	187	4.43
		100	20	0.6260	84,700	0.1560	411	209	9.90

(a) Density of butter: 59.3 lb./cu. ft.

DISCUSSION

Small variations in the density of the butter flowing from the end of the tubing were expected since variations in composition occur normally. The average density at the different temperatures increased from 0.948 g./ml. at 72.9° F. to 0.961 g./ml. at 56.7° F. which is normal for materials decreasing in temperature. However, at about 62° F. the average density was slightly out of order with densities at other temperatures. Densities at about 62° F. showed the greatest variation among samples (0.922 to 0.967 g./ml.). The possibility of more air being trapped in the containers may be a cause. The range of densities given by McDowall (23) for butterfat was 0.91 to 0.95 g./ml. at 94° F. When the non-fat portion of the butter is considered, the average density of 0.952 g./ml. is reasonable. Since variations are unavoidable in commercial butter the average density was used in the calculations.

The average minimum penetration values were found to be 3.6, 4.6, 5.9 and 19.6 mm. at corresponding temperatures of 47.6, 54.1, 59.9 and 72.4° F. respectively. After the butter had flowed through the various lengths of tubing considerable softening had occurred as indicated by the increased penetrations values (Fig. 11). However, no significant differences in the penetrations values were found for

butter after it had flowed through the various lengths of tubing. The lack of differences may be a result of the method of collecting the samples of butter from the end of the tubing which masked any other effects. But it could also suggest that the softening occurred before the butter entered the tubing or during the first 3.5 in. This softening may occur very rapidly followed by little or no softening. Another possibility could be that most of the softening occurs within a small distance from the wall and the bulk of the sample remains at about the same hardness for the different distances moved.

The results from measuring the viscosity of molasses revealed that similar values can be obtained from the Brookfield and extrusion viscometers on a time-independent fluid. The temperature of the molasses increased about two degrees when poured into the sample container in the extrusion viscometer method but was the same for all trials (about 36.0°F.). The temperature of the molasses was constant during each trial by the Brookfield method but varied from 34.4 to 36.5°F. among trials. When the influence of temperature is considered, the average viscosities obtained from each method seemed to be about the same.

The flow profiles (Figs. 13 and 14) revealed a variation in velocity does occur in the butter across the diameter of the tubing. The velocity gradient is small in the butter except near the wall. Here the velocity gradient is large. The parabolic flow profile

becomes flatter as the temperature is lowered from 70 to 55° F. due to the increase in the viscous properties of the continuous phase. As the distance the butter flowed increased the parabolic profile became more pronounced (Fig. 14) indicating that the velocity gradient even though small is still present. Mulder et al. (28) using colored butter in their moisture dispersion studies concluded that the gradient of velocity was large in the butter near the walls of a perforated disc through which it was forced and small for the remainder.

The relationship between the logarithm of apparent viscosity and the logarithm of velocity was found to be linear. The average slope of the regression lines was -0.84649. An increase in the velocity from 0.01 to 0.1 ft./sec. resulted in a decrease in apparent viscosity of 751,000 cp. at 60° F. This linear relationship is in agreement with the results obtained by Sone et al. (37) using a parallel plate plastometer at lower rates of shear and for 68 and 77° F.

Temperature increases resulted in very rapid decreases in the apparent viscosity of butter (Figs. 18 and 19). The similar apparent viscosity results obtained for 55 and 60° F. are probably due to the extrusion viscometer method in that the butter is softened considerably as it is forced into the tubing. Attempts to plot the apparent viscosity versus the temperature as an Arrhenius function

did not result in a straight line. A plot of the logarithm of the apparent viscosity versus the temperature did suggest a linear relationship having a slope of -0.0587 . This relationship is in agreement with the equation given by Weltmann (41) for some non-Newtonian materials (see equation 5).

The results on the apparent viscosity from the different samples of butter showed a variation but no definite pattern. The variation was small within given sample of butter as indicated by the high correlation coefficients (0.9935 to 0.9996). However, the variations among the samples of butter were greater (correlation coefficients ranged from 0.9738 to 0.9915). The variations among the results from different samples of butter also became greater at 55 and 60° F. (Figs. 24 and 25). The variations within the same sample are probably due to temperature fluctuations and small differences in the amount of softening which occurred just prior to flowing through the tubing. The variations between the samples of butter are probably due to the presence of triglycerides having different melting points and to the effects of the processing conditions.

Large variations in pressure losses were found among the various samples of butter (correlation coefficients ranged from 0.3506 to 0.9377). However, no pattern could be found for composition or processing influences to explain the variations. The variation within the same sample was small as indicated by the

correlation coefficients which ranged from 0.8659 to 0.9940.

The results on the reduction of the apparent viscosity of mildly agitated butter were shown to be a linear relationship between the logarithm of apparent viscosity and the logarithm of time. This suggested a similar relationship between the apparent viscosity and the distance butter moves through tubing for a given velocity. Such a relationship was not found. The relationship may exist and was simply masked by variation in other factors, such as, differences in the samples of butter or temperature.

Pumping reduced the apparent viscosity of butter by increasing its temperature and by working. The rate of pumping had no apparent influence on the apparent viscosity (Fig. 37). The use of the extrusion viscometer is not recommended for studying effects of pumping since the rate of shear has been shown to be a factor in measuring the apparent viscosity and also because additional softening will occur as the butter is forced into the tubing.

The average minimum pressure loss for elbows and valve assemblies per unit length was less than the average minimum pressure for straight tubing per unit length. This lower pressure loss was probably due to differences in the softness of the butter during the trials. Since softening of the butter does occur in butter pumping systems, the actual center line distance may be used in determining the total length of tubing in loss of head calculations.

SUMMARY

The butter had an average density of 0.948 g./ml. at 72.9° F. and 0.961 g./ml. at 56.7° F.

The average minimum penetration values for the butter used were 3.6, 4.6, 5.9 and 19.6 mm. at corresponding temperatures of 47.6, 54.1, 59.9 and 72.4° F. respectively. Penetration values increased after the butter had flowed through the various lengths of tubing (3.5, 7.0, 10.5 and 14.0 in.) but no significant differences in the penetration values were found for butter after flowing the various distances.

The velocities of the butter flowing in the tubing were shown to vary by using two different colors of butter. The velocity gradient was small within the butter except near the wall where it was large. As the temperature of the butter decreased from 70 to 55° F. the velocities within the butter became smaller.

A linear relationship was found between the logarithm of apparent viscosity and the logarithm of bulk velocity for a range of 0.001 to 1 ft./sec. The average slope of the regression line was -0.84649. The average correlation coefficient was 0.9887. As the length of the tubing increased the average apparent viscosities decreased but at a decreasing rate. Very small differences were

found between the apparent viscosities obtained using a 10.5-in. and 14.0-in. length of tubing.

The influence of temperature on the logarithm of the apparent viscosity was found to be linear having a slope of -0.0587 for the range of 55 to 75° F.

A general empirical equation was determined relating the influence of the bulk velocity and temperature to the decrease in apparent viscosity and was:

$$\log \eta = 7.93446 - 0.84649 \log v - 0.0587T$$

The pressure loss increased from 18.5 to 24.2 lb./sq. in. as the bulk velocity increased from 0.1 to 1.0 ft./sec. at 70° F. for butter flowing through a 10.5-in. length of tubing (0.313 in. diameter). An increase in the length of tubing from 3.5 to 14.0 in. resulted in an increase in pressure loss from 26 to 56 lb./sq. in. at 0.1 ft./sec. and 65° F. A decrease in the temperature of the butter from 72.6 to 62.2° F. increased the pressure loss from 18.5 to 69.5 lb./sq. in.

Pumping reduced the apparent viscosity of butter by increasing its temperature and by working. The rate at which the pump operated had no apparent influence on the apparent viscosity.

The center line distance through an elbow or valve assembly may be used in determining the total length of tubing in calculating the loss of head.

The calculated power requirements revealed that a 5° F. decrease in temperature about doubles the horsepower required (0.18, 0.35 and 0.69 hp. at 65, 60 and 55° F.) An increase in the diameter of the tubing from 1.5 to 3.0 in. reduced the power required from 1.81 to 0.35 hp. for moving butter at 60° F. through 20 ft. of tubing at 10 lb./min.

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