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Interrupted Helical Screw Impeller To Characterize
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INTERRUPTED HELICAL SCREW IMPELLER TO CHARACTERIZE FLUID FOODS WITH LARGE PARTICULATES

By

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ABSTRACT

INTERRUPTED HELICAL SCREW IMPELLER TO CHARACTERIZE FLUID FOODS WITH LARGE PARTICULATES

By

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Mixer viscometry is an effective means of characterizing fluids containing particulates. An interrupted helical screw impeller used to determine the flow behavior of fresh concrete was scaled-down to analyze fluid foods with large particulates. The mixer viscometer constant was determined to be 1.6 rad^{-1} by the matching viscosity method. Large particulate food materials successfully investigated in this study were cream corn, salsa, a smooth pasta sauce and a chunkier pasta sauce.

Apparent viscosity curves were constructed for products with moderately sized particulates, or those not exhibiting significant particle-to-particle interaction based on the raw data: torque and angular velocity. Testing materials exhibited shear-thinning behavior and temperature dependence. Regression analysis revealed K and n values ranging from 10.1 Pa s^n to 40.3 Pa s^n and 0.17 to 0.36, respectively. Regression control charts of ln apparent viscosity versus ln average shear rate were constructed for each food product. A protocol was suggested for producing and utilizing these charts as a statistical quality control tool for industry.

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TABLE OF CONTENTS

Table of Contents (cont'd)

LIST OF TABLES

List of Tables (cont'd)

LIST OF FIGURES

List of Figures (cont'd)

NOMENCLATURE

A = constant (dimensionless)

d = spindle diameter (m)

D = container diamter (m)

E_a = energy of activation for flow (cal g^{-1} $mole^{-1}$)

h = impeller height (m)

k' = mixer viscometer constant (rad^{-1})

k'' = mixer coefficient constant (rad m^{-3})

K = consistency coefficient (Pa s^n)

M = torque (N m)

N = rotational speed (rev s^{-1})

n = flow behavior index (dimensionless)

n = number of data points

N_{Po} = Power number (dimensionless)

$N_{Re,I}$ = impeller Reynolds number (dimensionless)

P = power (N m s^{-1})

R = universal gas constant (1.987 cal/(g - mole K))

se = standard error of predicted y

T = temperature (°C)

T_r = reference temperature (°C)

x = independent variable

y = dependent variable

$\dot{\gamma}$ = shear rate (s^{-1})

$\dot{\gamma}_a$ = average shear rate (s^{-1})

η = apparent viscosity (Pa s)

η_r = reference apparent viscosity (Pa s)

μ = Newtonian viscosity (Pa s)

μ_{pl} = plastic viscosity of a Bingham fluid (Pa s)

ρ = density (kg m^{-3})

σ = shear stress (Pa)

σ_a = average shear stress (Pa)

σ_o = yield stress (Pa)

Ω = rotational speed (rad s^{-1})

CHAPTER 1

1. Introduction

1.1. Overall Description

Rheology, or the study of the manner in which materials respond to an applied stress or strain, is widely used for process engineering, product development, and quality control applications within the food industry. Flow behavior information is critical to efficiently design processing operations such as mixing, pumping and heating. Characterizing fluid foods is also needed to standardize and quantitatively evaluate product quality.

Product quality is very important in most industries. Quality is a measure of a product's acceptability to consumers. The food industry successfully utilizes statistical methods such as control charts and regression analysis to monitor and control quality variables. Fill-level, microbiological safety, and shelf life are examples of variables that can be monitored and controlled. Rheological information provides a quantitative measure of the physical material quality for food products.

The utilization of mixer viscometry to evaluate the rheological properties of fluids has been extensive. Mixer viscometry involves the rotation of an impeller immersed in a sample material. Rheological properties are determined from information concerning the system geometry, rotational speed, and resulting torque. An advantage to using mixer viscometry over traditional rotational viscometry, such as concentric cylinders and cone and plate systems, is its ability to assess difficult fluids. Examples of difficult foods are those exhibiting slip, time-dependent behavior, particle settling problems, and those with large particles.

Many prepared foods are essentially coarse solid-liquid mixtures. Examples include salsas, pasta sauces, cream corn and baked beans. Foods that contain large particulates pose problems with effective analysis and therefore, control. Presently, the individual solid and liquid phases that comprise the final product are tested separately, and/or an empirical quality control test is performed. However, the behavior of the separate phases will be different from the final product mixture. Also, empirical test results are very difficult to relate to fundamental rheological properties. No agreed upon means to test for objective, standard characteristics of a final fluid food product with large particulates exists. This research proposes a method to objectively test the rheological properties of these products.

The success of using an interrupted helical screw impeller to determine rheological properties of fresh concrete inspired the experimental technology transfer described in this work. The name of the impeller describes the discontinuous helical pattern of the screw. A scaled down interrupted helical screw impeller has been designed to overcome some of the difficulties presented by complex foods.

1.2. Objectives

The ultimate goal for this research was to develop an impeller for mixer viscometry applications that is appropriate for fluid foods with large particulates, with the potential for use in statistical quality control programs. Specifically, the objectives were:

1) To design, construct and characterize an interrupted helical screw impeller;
2) To evaluate the potential of the interrupted helical screw impeller to characterize the flow behavior of fluid foods with large particulates;

3) To develop regression control charts for typical fluid foods containing large particulates;

4) To develop a statistical quality control protocol for fluid foods with large particulates.

CHAPTER 2

2. Literature Review

2.1. Fluid Food Rheology

Mathematical models aid in the description of the flow behavior of fluid foods. A Newtonian model for fluids,

$$\sigma = \mu\dot{\gamma} \qquad [2.1]$$

illustrates a simple, linear relationship between shear stress and shear rate. Typical food products that exhibit this behavior are water, corn oil, and corn syrup. The power law model,

$$\sigma = K\dot{\gamma}^n \qquad [2.2]$$

represents fluids that are shear-thinning (n < 1) or shear-thickening (n > 1). Common examples of power law fluids are applesauce, orange juice concentrate, and tomato ketchup. Another standard fluid model is the Bingham plastic,

$$\sigma = \mu_{pl}(\dot{\gamma}) + \sigma_o \qquad [2.3]$$

which incorporates a yield stress component, a finite stress required to initiate flow. Peanut butter, cream cheese, and toothpaste are often considered Bingham plastic fluids.

Apparent viscosity is an important quantitative parameter for fluid foods. It is calculated by dividing the shear stress by the shear rate. For Newtonian fluids, the apparent viscosity is a constant value, independent of the shear rate. However, in the case of power law fluids, apparent viscosity changes with shear rate (Steffe, 1996):

$$\eta = K(\dot{\gamma})^{n-1} \qquad [2.4]$$

The above models describe fluids that are considered time-independent. Other fluids will increase or decrease in shear stress over time at a constant shear rate: they are known as rheopectic and thixotropic materials, respectively. Viscosity can also be modeled as a function of temperature:

$$\mu = f(T) = A\exp\left(\frac{E_a}{RT}\right) \qquad [2.5]$$

Using the above equation, apparent viscosities considered at a constant shear rate can be found at any temperature using reference values:

$$\ln\left(\frac{\eta}{\eta_r}\right) = \frac{E_a}{R}\left(\frac{1}{T} - \frac{1}{T_r}\right) \qquad [2.6]$$

This equation assumes that temperature has a negligible effect on the flow behavior index. Larger E_a values indicate a faster change in viscosity with temperature.

2.2. Mixer Viscometry

2.2.1. Mixer Viscometer Constant (k')

The original investigators of non-Newtonian fluids using mixer viscometry are Metzner and Otto (1957). They proposed a method based on a matching viscosity assumption (also known as the matching viscosity method), which asserts that the average shear rate for a non-Newtonian fluid is equal to shear rate for a Newtonian fluid when the Newtonian viscosity equals the apparent viscosity of the non-Newtonian fluid. They also assumed that the average shear rate is linearly related to the rotational speed of the impeller by a constant k':

$$\dot{\gamma}_a = k'N \qquad [2.7]$$

A constant value for k' was assumed, although the possibility of variation with the flow behavior index, n, was not dismissed. Table 2.1 contains a listing of k' values and details for studies mentioned in this section.

Table 2.1. Mixer viscometer constants.

Authors	Impeller	D/d	h/d	Method*	k' (rad^{-1})
Briggs and Steffe (1996)	Flag	1.27	2.16	Slope	2.92
Calderbank and Moo-Young (1959)	2 bladed paddle (baffled)	3, 2	n/a	MVM	1.59
	3 bladed marine propeller (baffled)	1.67	n/a		1.59
	4 bladed marine propeller (baffled)	2.13	n/a		1.59
Cantu-Lozano et al (2000)	Helical ribbon screw	1.30	1.57	Slope	2.83
Castell-Perez and Steffe (1990)	5 Paddles	1.41,1.94,3.06	5 (0.56-2.78)	MVM	1.18-5.34
		1.41,1.94,3.06	5 (0.56-2.78)	MVM	0.90-9.86
		1.41,1.94,3.06	5 (0.56-2.78)	Slope	1.56-2.82
Castell-Perez et al (1987)	Flag	1.18	0.59	Slope	9.126
Ducla et al (1983)	Turbine with 2,4,and 6 flat vertical paddles	1.92	n/a	MVM	1.72-1.94
		2.87	n/a		
	Turbine with 4and 6 flat inclined at 45 degree paddles	1.28	n/a	MVM	
		1.91	n/a		
Edwards et al (1976)	Anchor	1.12	1.06	MVM	3.42
	Helical ribbon	1.06	0.85		4.77
	Helical screw 1	1.67	1.48		1.93
	Helical screw 2	1.49	1.32		1.86
Lai et al (2000)	RVA	1.12	0.37	MVM	3.20
Mackey et al (1987)	Flag (with guard leg)	1.82	0.54	MVM	0.91
Metzner and Otto (1957)	6-flat blade turbine (baffled)	1.3-3.7	n/a	MVM	2.07
Nagata (1975)	Ribbon	1.05	0.95	MVM	4.77
	Anchor	0.95	n/a		3.98

Table 2.1. (cont'd)

Authors	Impeller	D/d	h/d	Method	k' (1/rad)
	6-blade Turbine	2.00	n/a		1.88
Qiu and Rao (1988)	Star (6 vanes)	1.785	1.5	MVM	1.85
Rao (1975)	Flag	1.38	0.65	Slope	1.04
Rao and Cooley (1984)	Flag	1.21	0.65	MVM	2.02
	Flag	1.21	0.65	Slope	2.20
	Star (8 vanes)	1.23	0.76	MVM	3.14
	Star (8 vanes)	1.23	0.76	Slope	3.42
Rieger and Novak (1973)	Anchor	1.11	0.89	Slope	2.57
	Pitched blade anchor	1.11	0.89		3.16
	Helical ribbon	1.05	1.0		5.73
Sestak et al (1986)	Anchor	1.11	0.89	MVM	3.63
Steffe and Ford (1985)	MV paddle sensor (15 degree pitch)	1.01	0.65	Slope	4.46

*MVM = Matching Viscosity Method

Rieger and Novak (1973) developed a test that served as an indicator of the suitability of the Metzner-Otto assumption (Eq. [2.7]). The Rieger-Novak method, also known as the slope method, provided an alternative means to determine k'. The authors used several types of agitators to analyze the power consumption in mixing highly viscous, time-independent, inelastic non-Newtonian fluids with pseudoplastic behavior. The accuracy of the k' values for the anchor and pitched blade anchor agitators were best fit as functions of n, rather than constants. The authors compiled a table of k' values for comparison.

Ducla et al (1983) showed that k' for varying turbine impellers was constant when mixing true pseudoplastic fluids over the entire shear rate range tested by using the Metzner-Otto method. The aim of this project was industrial mixing operations. Edwards et al (1976) established k' values of an anchor, helical ribbon, and two helical screw impellers using the matching viscosity method. This was one step in a process to calculate the power consumption with time when agitating a thixotropic liquid. Fluid properties were observed to influence k'; however, the authors chose not to elaborate on these relationships and instead accepted constant values as reasonable.

Sestak et al (1986) developed k' as a function of n for anchor agitators. The function deduced was recommended as a first step of an iterative series to find a converging value for k'. This procedure was considered successful for both pseudoplastic and thixotropic fluids.

The matching viscosity method and slope method were compared for the determination of an average shear rate by Rao and Cooley (1984). The flag impeller in the study done by Rao (1975) was used in this work along with a star impeller that has 8 vanes. k' values for both methods were in good agreement using each impeller. When k' is around 20 1/rev or greater, the slope method must be used with caution because of a greater sensitivity to error. Overall, small errors are magnified because of the log-log relationship required in the slope method. The decided advantage of the slope method was its simplicity.

Briggs and Steffe (1996) found k' for a Brookfield small sample adapter with a flag impeller using the slope and matching viscosity methods. While the slope method resulted in a constant value, the influence of the angular velocity was apparent when using the matching viscosity method. In this investigation, the flow behavior index produced inconsistent, but small, effects on k'. Nonetheless, both methods gave similar results and the use of a constant value was recommended.

Castell-Perez and Steffe (1990) concluded that k' is dependent on n, as well as other variables for paddle impellers. Two versions of the matching viscosity method (power curve and torque curve) and the slope method were evaluated to determine the influence of fluid properties, system geometries and impeller rotational speeds on k'. The authors found that k' is directly related to n and inversely related to K. Above rotational speeds of 20 rpm, k' can be assumed constant. Small gaps between the impeller and the cup were recommended to reduce the influence of fluid properties.

Nagata (1975) produced an exhaustive investigation of mixing principles and applications. Nagata covered power consumption equations for different impellers and fluids and flow regimes, as well as flow models. A straightforward approach was outlined to develop a Power number/Reynolds number curve for pseudoplastic fluids based on work by Metzner and Otto (1957).

2.2.2. Fluid Food Applications

Extensive work has been done with mixer viscometry and fluid food materials. Castell-Perez and Steffe (1992) prepared a complete review of the development of mixer viscometry as related to food applications.

Rao (1975) measured the flow properties of food suspensions using a flag impeller as an alternative to narrow gap and tube viscometers. k' was found using the slope method. Tomato puree, applesauce, and apple pulp were determined to be pseudoplastic in nature. The flow properties for this investigation were valid over only limited ranges of shear rates however. k' was also determined via the slope method by Cantu-Lozano et al (2000) to study the rheological properties of apple suspensions using a helical ribbon screw agitator.

Rao and Cooley's (1984) star impeller along with a 6-vaned impeller was used in another study done by Qiu and Rao (1988). The goal was to evaluate the effectiveness of mixer viscometry when analyzing applesauce for its yield stress and power law parameters. A constant k' was determined for the 6-vaned impeller using the matching viscosity method. The obtainable shear rate testing range was narrower than if using a concentric cylinder.

The k' value of a Haake MV paddle impeller used for the analysis of strained apricots thickened with modified tapioca starch was investigated by Steffe and Ford (1985) using the slope method. Mixer viscometry in this study was applied to thixotropic materials as well as time-independent (after mechanical degradation) materials.

Castell-Perez et al (1987) used a flag impeller with a Brookfield small sample adaptor. k' was found using the slope method. In this study, as well as the work by

Briggs and Steffe (1996) on a flag impeller, the mixing systems were designed for the analysis of power law fluid foods. A flag impeller was also used by Mackey et al (1987) to analyze shear-thinning behavior of food with mixer viscometry techniques. A matching viscosity method was used to define k' because the slope method indicated a dependency on rotational velocity and therefore an increased chance of error in calculations. It was also found that the influence of n on k' decreases with increasing angular velocity. This particular matching viscosity method, later coined the torque curve method by Castell-Perez and Steffe (1990), was also used in Lai et al (2000) to find the k' value of a Rapid Visco Analyser (RVA) system impeller. At speeds of 60 rpm and greater the k' value was considered constant. Applications of the RVA system are primarily for analyzing the rheological behavior of starch slurries during heating and cooling.

2.3. Rheology of Suspensions

The rheological properties of particulate suspensions have been investigated for many purposes such as particle removal from surfaces, fines mobilization in porous media, transport of proppants in fractured reservoirs, and cleaning of drill holes (Patankar and Hu, 2000). Wildemuth and Williams (1984) focused on packing fraction when evaluating the apparent viscosity of concentrated suspensions. These concepts were intended for examining the rheology of dense coal suspensions.

Using a helical ribbon stirrer, the rheological changes of mixing an emulsion with a suspension were studied by Hugelshofer et al (2000). These mixtures are relevant for calorie-reduced food products. Using a model suspension, the slope method and matching viscosity method were both employed to calculate apparent viscosities and shear rates. These results were similar to concentric cylinder data.

2.4. Rheology of Particulate Fluid Foods

There has been much research on the rheological behavior of fine food particles. Schubert (1987) discusses the branch of process engineering associated with particles known as particle technology. Specifically, Schubert's article addresses fine solid particles on the order of micrometers (the largest sector of particle technology) and reviews the properties and characterization of these systems. Examples from food technology were used to illustrate key aspects. Rao (1987) clarified the relationship between composition and rheological behavior of food suspensions of plant origin, such as applesauce and concentrated orange juice. The flow properties of plant food suspensions were put in terms of temperature, concentration, suspending medium and suspended solids. Flow behavior studies pertaining to fluids with larger particulates are less abundant. Currently, there is no agreement on a methodology or instrumentation to investigate these solid-liquid food mixtures.

Particulate food mixtures differ from food suspensions based on the size of the individual solids. Large particulates are generally measured on a centimeter scale, come in a variety of shapes and have only a small difference in density with the carrier fluid. The carrier fluids are most often non-Newtonian, specifically pseudoplastic, and are highly viscous (Lareo et al, 1997). Some studies on the heat transfer of fluid foods with large particulates have been conducted. Sannervik et al (1996), for example, found that the inner heat transfer coefficient increased with increasing food particulate concentration in a tubular heat exchanger.

Bhamadipati and Singh (1990) investigated the flow behavior of frozen thawed peas and dry soybeans in tomato sauce, using tube viscometry. These particulates were used as model foods rather than being an actual, commercial food product. Pressure gradients and volumetric flow rates were used to determine the flow properties. Based on their results, the power-law model best represents the flow behavior of solid-liquid mixtures. Solids and particulate presence increases the consistency coefficient and decreases the flow behavior index. The disadvantage of this technique is the large amount of testing material required.

Rotational viscometry was utilized by Pordesimo et al (1994) to evaluate solid-liquid food mixtures at low shear rates. A very-large-gap parallel plate system was used to determine rheological properties of edible compounds made to imitate liquid food products with large particulates in the range of 0.32 cm to 0.95 cm. Effects of carrier viscosity, particle size, particle concentration, and particle shape were investigated. Pordesimo (1991) reviewed several proposed instruments and procedures to evaluate coarse mixtures. Still, however, not enough is known about large-gap rotational viscometers.

Martinez-Padilla et al (1999) used mixer viscometry to evaluate the physical properties of coarse food suspensions; specifically Mexican sauces. A shear-thinning fluid with pepper and tomato seeds was analyzed using a helical ribbon, a tube viscometer and a wide gap spindle. The helical ribbon best characterized the flow behavior. The ribbon was better able to maintain a pseudo-homogenous flow and required the smallest sample. The disc-shaped seeds were the largest (albeit still on the small side of large particulate systems) particles used in combination with mixer viscometry.

2.5. Concrete Rheology

In the concrete industry, many empirical tests exist to determine the flow properties of fresh concrete (Bartos, 1992). Rheological information about concrete is important because many aspects such as ease of placement, durability and strength depend on the flow characteristics. An obstacle for the analysis of fresh concrete is the complexity of the composition. Particles found in concrete range from 1μm cement grains to 10 mm coarse aggregates to even 100 mm particulates found in dams (Ferraris, 1999).

Tattersall (1973) argues that since it has been accepted that fresh concrete behaves as a Bingham plastic fluid, at least two shear rates are necessary for an accurate characterization of its flow curve. Tattersall and Bloomer (1979), discussed the trials and tribulations of developing an apparatus to test fresh concrete. The authors diverged from historical usage and approached the problem using mixer viscometry. The device developed became the first and most widely known instrument to measure the flow properties of concrete (Ferraris, 1999). A mixer (of interrupted helix form) that allowed concrete to fall back through the gaps and create localized mixing was fabricated. Mathematical relationships were formed translating the raw data to rheological values.

Wallevik and Gjorv (1990) modified the apparatus and testing procedure of Tattersall and Bloomer (1979) to produce more reliable results. The main drawbacks to this apparatus were the required calibration, the large size of the apparatus making it not test-site friendly, and the computations required to find results (Bartos, 1992). Versions of this instrument are now commercially available as the BML Viscometer or the IBB Concrete Rheometer (Ferraris, 1999).

2.6. Statistical Quality Control

Statistical quality control is used in many areas of the food industry, such as product research and development, material control, production quality control and product performance (Hubbard, 1990). When a process is in statistical control, the distribution of data is attributed to stable and repeatable variation inherent in the process (Bafna, 1995).

Dr. Walter A. Shewhart first developed control charts in 1924 as a graphical device for the detection of unusual variation of data resulting from a repetitive process. Control charts can be categorized by the type of application: for variables, attributes, or individual points. Variables encompass any quality characteristic that can be measured, while attributes are classified as either defective or nondefective. Rather than plotting characteristics against time, as in variable and attribute charts; individual charts plot against each specific observation (Puri et al, 1979). Upper and lower control limits are put in place as the boundaries of acceptability. A common method is to use control charts in pairs: one chart for the value of the variable, and one chart for the range or spread of the values.

Bafna (1995) discussed the importance of rheological instruments in statistical control. The variability of the instrument should less than or equal to one tenth of the variability of the process it is monitoring. When monitoring viscosity, Bafna recommended taking values from the highest and lowest shear rates and plotting them on individual charts. The author also outlined six rules when using individual charts to determine whether a process is out of control.

Mandel (1969) combined linear regression and control chart theory to construct regression control charts as a means to analyze postal efficiency. Regression control charts are applicable when controlling a variable that is linearly dependent upon the magnitude of an independent variable. The chart is a linear plot of a variable with upper and lower control limits running parallel with the control line. In the case of several nonlinear relationships, a suitable transformation can make them linear (Chatterjee and Price, 1977). The control limits can be set at any distance from the control line, but are usually kept at 2 or 3 times the standard error of estimate. This decision is based upon economics and experience of the management (Mandel, 1969). The Mandel (1969) method was used in the current research.

CHAPTER 3

3. Theoretical Development

3.1. Mixer Viscometry

Applying dimensional analysis to mixer viscometry with Newtonian fluids yields the following empirical relationship:

$$N_{Po} = \frac{A}{N_{Re,I}} \qquad [3.1]$$

This relationship is widely accepted when applied in the laminar flow regime, and can be used for non-Newtonian fluids. The Power number and impeller Reynolds number are defined as

$$N_{Po} = \frac{P}{\rho\Omega^3 d^5} \qquad [3.2]$$

and

$$N_{Re,I} = \frac{\rho\Omega d^2}{\mu} \qquad [3.3]$$

Substituting Equations [3.2] and [3.3] into Equation [3.1] yields

$$\frac{P}{d^5\Omega^3\rho} = \frac{A\mu}{d^2\Omega\rho} \qquad [3.4]$$

Using the definition of power,

$$P = M\Omega \qquad [3.5]$$

Equation [3.4] simplifies to

$$\frac{M}{d^3\Omega} = A\mu \qquad [3.6]$$

By replacing the Newtonian viscosity with an apparent viscosity (Equation [2.4]), that is evaluated at an average shear rate given by

$$\dot{\gamma}_a = k'\Omega \qquad [3.7]$$

Equation [3.6] becomes

$$\frac{M}{d^3\Omega} = AK(k'\Omega)^{n-1} \qquad [3.8]$$

The mixer viscometer constant, k', is exclusive to each mixer system.

3.2. Evaluation of Mixer Viscometry Constant (k')

3.2.1. Slope Method

The slope method assumes a constant value for k'. Simplifying Equation [3.8] and taking the logarithm of each side yields

$$\log_{10}\left(\frac{M}{Kd^3\Omega^n}\right) = \log_{10}(A) - (1-n)\log_{10}(k') \qquad [3.9]$$

k' is determined from the slope of the line, $\log_{10}\left(\frac{M}{Kd^3\Omega^n}\right)$ vs. $(1-n)$. Rieger and Novak (1973) argued that if Equation [3.9] was not linear, then the average shear rate assumption expressed by Equation [3.7] is not valid.

3.2.2. Matching Viscosity Method

This technique is a valuable alternative to the slope method for determining the mixer viscometer constant. A power curve is first constructed using Newtonian fluids to determine *A*. Then, a standard non-Newtonian fluid, in which the *K* and *n* values are known, is mixed at a constant rate using the chosen impeller system and the resulting Power Number is measured. Using the matching viscosity assumption ($\eta = \mu$) and Equation [3.1], the apparent viscosity is defined by

$$\eta = \frac{(d^2\Omega\rho)(N_{Po})}{A} \qquad [3.10]$$

Considering Equation [2.4], the average shear rate can be calculated:

$$\dot{\gamma}_a = \left(\frac{\eta}{K}\right)^{\frac{1}{n-1}} \qquad [3.11]$$

When several iterations of the process have been conducted at different speeds, using standard non-Newtonian fluids with well defined flow behavior indices, k'can be calculated from Equation [3.7] as

$$k' = \frac{\dot{\gamma}_a}{\Omega} \qquad [3.12]$$

Using this method allows for k' to be evaluated as a function of angular velocity and the flow behavior index.

3.2.3. Torque Curve Method

To determine k', Mackey et al (1987) developed a method which was later coined the torque curve method by Castell-Perez and Steffe (1990). Rearranging Equation [3.6] yields

$$\mu = \frac{M}{Ad^3\Omega} = \frac{k''M}{\Omega} \qquad [3.13]$$

where k'', the mixer coefficient constant, is dependent solely on the system geometry. Making the matching viscosity assumption and substituting Equation [2.4] into Equation [3.13], yields an equation for k':

$$k' = \left(\frac{1}{\Omega}\right)\left(\frac{k''M}{\Omega K}\right)^{\frac{1}{n-1}} \qquad [3.14]$$

3.3. Determination of Fluid Properties

In laminar mixing, the relationship between torque and angular velocity is found from Equation [3.8]

$$\log_{10}(M) = \log_{10}(d^3 AK(k')^{n-1}) + n\log_{10}(\Omega) \qquad [3.15]$$

where n is the slope of the line. K can be determined by either of two methods. If the values of d, A, k', and n are known, then K can be calculated using the constant term ($\log_{10}(d^3 AK(k')^{n-1})$ of Equation [3.15]. The alternative method is to solve for K using the following equation:

$$K_x = K_y\left(\frac{M_x}{M_y}\right)\left(\frac{\Omega_y^{n_y}(k')^{n_y}}{\Omega_x^{n_x}(k')^{n_x}}\right) \qquad [3.16]$$

where x denotes the fluid with unknown properties and y designates the reference fluid with known properties. This method eliminates the need for determining the value of A.

If the value of k' is known, then rheological parameters may also be determined by assembling a plot of apparent viscosity versus average shear rate. The average shear rate is calculated using Equation [3.7]. Apparent viscosity is found by applying the matching viscosity assumption and substituting the apparent viscosity for Newtonian viscosity in Equation [3.13]:

$$\eta = \frac{k''M}{\Omega} \qquad [3.17]$$

Curve fitting programs can then easily characterize the fluid using an appropriate rheological model.

CHAPTER 4

4. Materials and Methods

4.1. Equipment

The interrupted helical screw impeller was fabricated from stainless steel and consists of 4 triangular blades (0.08 cm thick) joined to the shaft, pointing toward the shaft, in a helical pattern (Figure 4.1 and 4.2). The initial impeller and cup system was a 1/3-scale replica of the design by Wallevik and Gjorv (1990), intended for testing fresh concrete. Through preliminary trials, the cup diameter was increased to improve movement of the particulate foods and reduce slip of particulates against container.

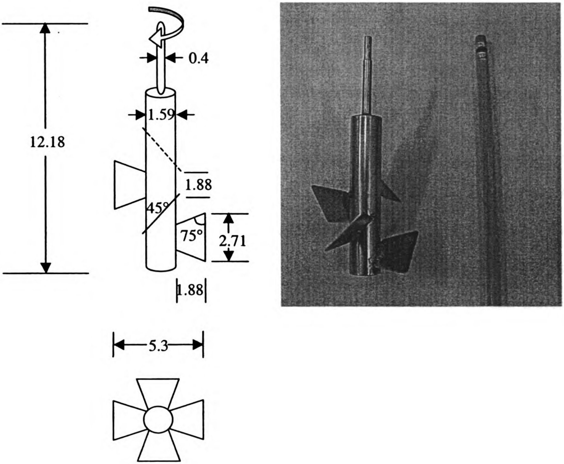

Figure 4.1. Interrupted helical screw impeller (all dimensions in cm).

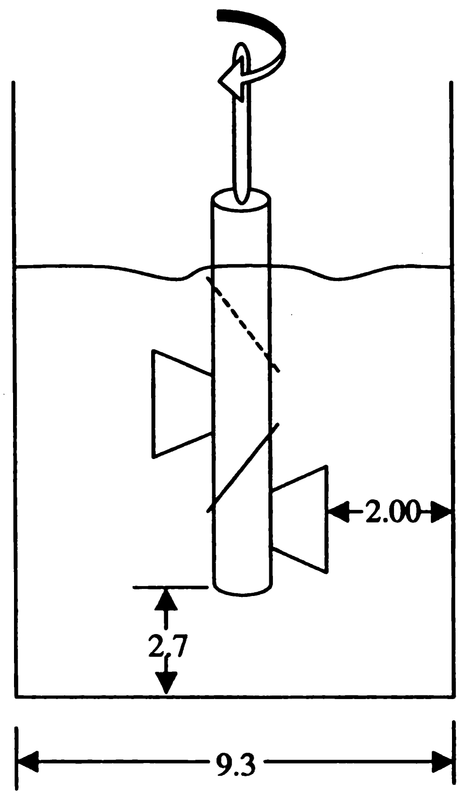

Figure 4.2. Interrupted helical screw impeller and container (all dimensions in cm).

Using an adaptor, the impeller was attached to a Haake VT550 Viscometer (Haake, Paramus, NJ). The torque range of the instrument is 0.1 m Nm to 30 m Nm. A rheological software program, RheoWin2, controlled the VT550 and collected the raw data: angular velocity and torque. The testing material was loaded into an 800ml capacity glass beaker. A foam jacket was used to insulate the beaker and prevent slippage on the test stand. The container was raised into testing position by a scissor jack.

Samples for cold temperature testing were cooled in a kitchen refrigerator (Kenmore, Hoffman Estates, IL) with temperatures varying by ±1 °C. Heating of the samples for hot temperature testing took place in a drying oven (Isotemp Oven, Fisher

Scientific, Itasca, IL) with a variation of ±1 °C. Thermometers provided temperature verification.

Using the Haake VT550, the MV1 concentric cylinder system with a gap of 1mm was chosen for evaluating non-particulate fluids. Properties were determined using standard rheological methods (Steffe, 1996). The temperature was controlled using a water bath (Haake F6, Paramus, NJ) to within ±0.1 °C. Densities of the Newtonian fluids were determined with a 100 ml specific gravity cup.

A ¼ inch square gap sieving pan was used to separate large particulates from the testing foods. An electronic scale was employed to weigh both solid and liquid phases. Particulate sizes were manually measured using a caliper (±0.02 mm). The liquid phase contained ¼ inch particulates able to pass through the sieve; therefore, a concentric cylinder system was not appropriate to assess the rheological properties because of the small gap size. A helical ribbon and MV1 cup attached to the Haake VT550 was able to successfully evaluate the fluids. The helical ribbon was 3.4 cm in height and 3.3 cm in diameter. Agrawal (2001) determined the k'' and k' values as 12566 rad m^{-3} and 1.38 rad^{-1}, respectively, for this mixer viscometer system.

4.2. Experimental Materials

Home Harvest Pure Honey (United Wholesale Grocery Company, Grand Rapids, MI) and Karo Light Corn Syrup (Bestfoods, Englewood Cliffs, NJ) were the Newtonian fluids used to determine k'' for the interrupted helical screw impeller system. All food samples were purchased at a local grocery store.

Three standard power law fluids were used to determine k': 2.5% and 2.0% (by weight) hydroxypropyl methylcellulose (Dow Chemical Company, Midland, MI) and

1.0% guar gum (Sigma Chemical, St. Louis, MO). The hydroxypropyl methylcellulose solutions were prepared by the hot/cold technique for aqueous media as directed by the manufacturer. The guar gum solution was prepared by directly adding the powder to room temperature deionized water.

The food products with particulates chosen for this investigation were Ragu Old World Style Traditional pasta sauce (Lipton, Englewood Cliffs, NJ), Prego with Fresh Mushrooms pasta sauce (Campbell, Camden, NJ), Chi-Chi's Restaurante Fiesta Thick and Chunky salsa (Hormel Foods, Austin, MN), and Del Monte Sweet Corn Cream Style (Del Monte, San Fransisco, CA). Table 4.1 lists all the ingredients in each food product. Dinty Moore Beef Stew (Hormel Foods, Austin, MN) and Bush's Original Baked Beans (Bush's, Knoxville, TN) were initially explored but rejected as test subjects for reasons to be discussed later.

Table 4.1. Ingredient list of the fluid foods with large particulates selected for testing.

Food	Ingredients
Cream Corn	Corn, water, modified food starch, sugar, salt (for flavor)
Prego	Tomato puree (water, tomato paste), diced tomatoes, corn syrup, vegetable oil (corn cottonseed, and/or canola), mushrooms, salt, spices (Basil, Oregano and other spices), onion powder, dehydrated garlic, citric acid, dehydrated parsley, spice extract.
Ragu	Tomato puree (water, tomato paste), soybean oil, high fructose corn syrup, salt, dried onions, extra virgin olive oil, Romano cheese (cow's milk, cheese cultures, salt, enzymes), spices, natural flavor
Salsa	Tomatoes, Jalapeno peppers, water, tomato paste, onions, vinegar, salt, sugar, garlic powder, onion powder, spices, sodium benzoate (to retard spoinlage after opening), citric acid, natural flavor

4.3. Data Collection Method

4.3.1. Phase Characterization

The particulate foods were emptied onto the ¼ inch sieve in an even layer, enough to cover the entire screen. A collection pan underneath the sieve caught the draining fluid. Gravity and slight manual agitation of the sieve facilitated the separation of solid and liquid components. When the drainage had abated, the two phases were ready for analysis. Each phase was weighed separately. Three sieving trials were run using fresh samples.

The solids portion was divided into the different groups of food present, such as tomatoes, onions, and corn kernels. Ten of each type of food were randomly chosen and measured in three directions: a, b, and c. a is the longest dimension, b is the longest dimension perpendicular to a, and c is the longest dimension perpendicular to both a and b. This method of characterizing the shapes was recommended by Mohsenin (1986).

Rheological properties of the fluid portion were determined at room temperature (23 °C) with the helical ribbon system. A steady-state shear rate ramp up from 1 s^{-1} to 27 s^{-1} and then back down from 27 s^{-1} to 1 s^{-1} was conducted for each sample. Two-second equilibrating times were assigned to each data point. Three repetitions of each fluid food were conducted.

4.3.2. Determination of Mixer Viscometry Constants (k'' and k')

The reference fluids included Newtonian fluids (corn syrup and honey) and non-Newtonian fluids (methylcellulose and guar gum solutions). The flow properties of the reference fluids were evaluated at room temperature (23 °C) using the MV1 concentric cylinder. Shear rates ranged from 10 s^{-1} to 100 s^{-1} for the corn syrup and 3 s^{-1} to 23 s^{-1} for the honey. The differing maximum shear rates were based on the torque capacity of the instrument. The steady state test consisted of increasing and decreasing through the shear rate ranges twice. Each ramp was divided into 10 steps with a 30 second equilibrium time taken before a viscosity reading was recorded. Two repetitions of corn syrup and honey were completed.

Apart from the different shear rate ranges, the Newtonian data collection method was repeated for non-Newtonian fluids. For 1.0% guar gum, the range was 20 s^{-1} – 150 s^{-1}; for 2.0% Methylcellulose, 30 s^{-1} – 250 s^{-1}; and 2.5% Methylcellulose, 10 s^{-1} – 70 s^{-1}. The different shear rate ranges represent the obtainable torque ranges for each fluid. Each fluid trial was duplicated with fresh samples.

The constant, k'', of the interrupted helical screw system was determined using the Newtonian fluids at room temperature (23 °C). Approximately 500 ml of a reference fluid was loaded into the glass beaker. The container was raised into position until the top of the highest blade was just below the fluid surface (Figure 4.2). The impeller was centered in the beaker using a ruler. A bubble balance was used to assure a level testing surface. A steady state ramp up test ran from 1 rad s^{-1} to 30 rad s^{-1} and from 0.5 rad s^{-1} to 12 rad s^{-1} for the corn syrup and honey, respectively. The torque capacity of the Haake VT550 was reached at the respective maximum angular velocity for each fluid. Each test consisted of thirty steps with an acquisition time of thirty seconds for each torque measurement. Two trials were conducted for each fluid.

The procedure to determine k' of the interrupted helical screw system was carried out at room temperature (23 °C). Samples were loaded in the same manner as for the k'' trials. The steady-state test for guar gum and 2.0% Methylcellulose consisted of 25 steps, ramping up from 1 rad s^{-1} to 30 rad s^{-1}, in thirty second increments. While the protocol was identical to the former two fluids, the maximum angular velocity for the 2.5% Methylcellulose was 20 rad s^{-1}. Two tests were executed for each fluid.

4.3.3. Particulate Food Flow Behavior

4.3.3.1. Room Temperature

The food products were tested at three different application temperatures: a cold refrigerated temperature, ambient temperature, and a hot serving temperature. The particulate foods were emptied from their original containers into a large, separate beaker. Since large particulates may settle during storage and shipping, slow and gentle manual mixing with a spoon for approximately 15 seconds was done to create a homogenous mixture. Loading of the samples into the testing apparatus was completed as outlined for k''. Preliminary tests revealed that a pre-shearing phase to eliminate slight time-dependent behavior was necessary for some foods. This pre-shear session consisted of rotating the interrupted helical screw impeller for 100 seconds at 5 rad s^{-1}. Table 4.2 notes which products and temperature settings required the pre-shear test.

Table 4.2. Fluid food products with particulates that did and did not require a pre-shear phase.

Food Product	Cold	Room	Hot
Cream Corn	X	X	-
Prego	X	X	-
Ragu	-	-	-
Salsa	X	X	X

X pre-shear; - no pre-shear

After the pre-shear, the particulate foods were all subjected to a steady state test: 3 rad s^{-1} through 20 rad s^{-1}; and 20 rad s^{-1} through 3 rad s^{-1}. 30 torque measurements were recorded in each direction with a 2 second equilibrating time for every point. The presence of slip and particulate interaction were carefully monitored. Ten repetitions, the minimum number to calculate a standard deviation (Bafna, 1995), were completed for each brand of food using fresh samples each time.

4.3.3.2. Hot Testing

Samples were loaded in the glass beaker containers as done for the room temperature trials and covered. The containers were placed into the oven, set at a temperature of 90 °C. When the samples had reached a temperature comfortably over 80 °C, they were quickly transported to the Haake VT550. The temperature at the time of testing was approximately 80 °C with a temperature drop of 3 to 4 °C throughout the duration of the test. The setup and testing protocol was the same as that described for the room temperature tests. A pre-shearing section was not conducted for cream corn, Prego, or Ragu because no time-dependent behavior was evident from preliminary trials. Ten trials of each food product were completed.

4.3.3.3. Cold Testing

Samples, already loaded into the testing containers, were placed in a kitchen refrigerator. The samples were allowed to equilibrate to approximately 6 °C before being tested. Temperature differences between the beginning and the end of the test were maintained at less than 2 °C. The setup and testing protocol followed the room temperature testing procedure. A pre-shear section was incorporated into the test for cream corn, Prego and the salsa to eliminate time dependency. Ten replicates were made of each product.

4.4. Data Analysis

4.4.1. Phase Characterization

To characterize the solid phase, averages of the measurements in each direction were taken of each food type (onions, peppers, mushrooms, etc.). Torque and angular velocity data from the helical ribbon system were used to evaluate the fluid phase. Apparent viscosity was calculated using Equation [3.17] and Equation [3.7] was used to calculate the average shear rate. The rheological parameters were determined by regression analysis of apparent viscosity versus average shear rate plots using the power law model (Equation [2.4]).

4.4.2. Determination of Mixer Viscometry Constants (k'' and k')

The RheoWin2 software automatically converted the data to viscosity and shear rate readings for the concentric cylinder tests. Averages were taken of the Newtonian viscosity readings for a representative value for each Newtonian fluid. Rheograms of apparent viscosity versus shear rate were made and regression analysis was performed to determine the K and n values of the non-Newtonian fluids.

The raw data used from the interrupted helical screw impeller trials were torque and angular velocity. Based on Equation [3.13], a plot of Newtonian viscosity times angular velocity versus torque was constructed from the Newtonian fluid data. The slope of the line was equal to k''. k' was determined using Equation [3.14] for each of the non-Newtonian standards. A plot of k' versus angular velocity was produced to show any dependency on n and mixing speeds.

4.4.3. Particulate Food Flow Behavior

Using the newly determined mixer viscometer constants, apparent viscosities and average shear rates were calculated with Equations [3.17] and [3.7], respectively. The flow behavior of the particulate foods was characterized by a rheogram of ln η versus ln $\dot{\gamma}_a$. Results were compared for temperature dependence and to the properties of the fluid phase determined using the helical ribbon system.

4.4.4. Regression Control Charts

The general procedure to set up regression control charts is outlined by Mandel (1969). In the current study, a linear plot of $\ln \eta$ versus $\ln \dot{\gamma}_a$ was chosen as the quality control condition. Ten trials of each food type at a certain temperature were averaged to produce one characterizing control line. The standard error based on the predicted y is

$$se = \sqrt{\left[\frac{1}{n(n-2)}\right]\left[n\sum y^2 - \left(\sum y\right)^2 - \frac{\left[n\sum xy - \left(\sum x\right)\left(\sum y\right)\right]^2}{n\sum x^2 - \left(\sum x\right)^2}\right]} \qquad [4.1]$$

Three times the standard error above and below the control line were drawn as the limits of the regression chart.

CHAPTER 5

5. Results and Discussion

5.1. Phase Characterization

The result of separating the fluid and solid phases of the particulate foods is illustrated in Figure 5.1. Ragu pasta sauce contained the highest liquid portion by weight, while salsa had the highest amount of solids. Table 5.1 lists the average measurements of a (maximum dimension), b (maximum dimension perpendicular to a), and c (maximum dimension perpendicular to a and b) for each food type in all the particulate food products. Also included in Table 5.1 is the range of measurements taken for each dimension. The tomato pieces in the salsa were the largest at nearly 2 cm. The largest particulate in each product was close to 1 cm and above. Some of the dimensions of the spices and small onion and garlic flakes were not measured because they were considered insignificant.

Power law models best fit the flow behavior of the particulate food fluid phase. The rheological parameters for each fluid phase measured using the helical ribbon are listed in Table 5.2. The fluids of the cream corn and salsa had similar, low consistency coefficient values. Prego and Ragu fluids had similar flow behavior indices; while the cream corn fluid was the least shear-thinning.

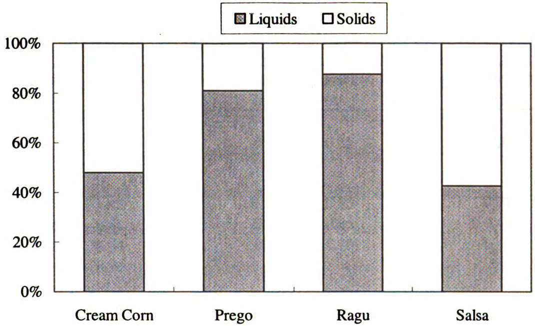

Figure 5.1. Percentage by weight of solid and fluid phases in foods with particulates.

Table 5.1. Measurements a, b, and c and the ranges of each dimension of foodstuffs in the fluid food products.

Food Product	Average a (cm)	Range* (cm)	Average b (cm)	Range* (cm)	Average c (cm)	Range* (cm)
Cream Corn						
-Kernel	1.00	0.33	0.81	0.32	0.44	0.20
Prego						
-Tomato	1.48	0.65	1.23	0.93	0.68	0.77
-Mushroom	0.81	0.34	0.74	0.25	0.61	0.49
-Onion/Garlic	0.64	0.54	0.29	0.30		
-Spice	0.90	1.04				
Ragu						
-Onion	1.24	1.20	0.35	0.22	0.19	0.14
Salsa						
-Tomato	1.94	1.46	1.27	0.61	1.00	0.91
-Pepper	1.09	0.44	0.79	0.60	0.47	0.35
-Onion	0.99	0.36	0.83	0.45	0.36	0.26
-Seed	0.36	0.19	0.14	0.06		

*Highest value - lowest value

Table 5.2. Power law, rheological parameters of the fluid phase of foods with particulates at 23 °C determined by the helical ribbon system.

Food	*K* ($Pa\ s^n$)	*n* (-)	R^2
Cream Corn	3.2	0.43	0.981
Prego	23.8	0.17	0.997
Ragu	18.8	0.19	0.993
Salsa	3.4	0.29	0.987

5.2. Mixer Viscometry Constants (k'' and k')

The property values of the standard fluids are listed in Table 5.3. A graphical representation of Equation [3.13] as Newtonian viscosity times angular velocity versus torque was constructed (Figure 5.2) utilizing the Newtonian standards. The mixer coefficient constant (k''), equal to the slope, was found to be 3047.4 rad m^{-3} with a R^2 >0.99. This value is unique to the specific geometry of the interrupted helical screw/cup system used in this study.

Table 5.3. Rheological parameters of the standard fluids at 23 °C used to evaluate k'' and k'.

Standard Fluid	μ (Pa s)	K (Pa s^n)	n (-)
Honey	7.5		1.00
Corn Syrup	2.3		1.00
1.0% Guar Gum		7.6	0.29
2.0% Methylcellulose		9.9	0.54
2.5% Methylcellulose		16.8	0.59

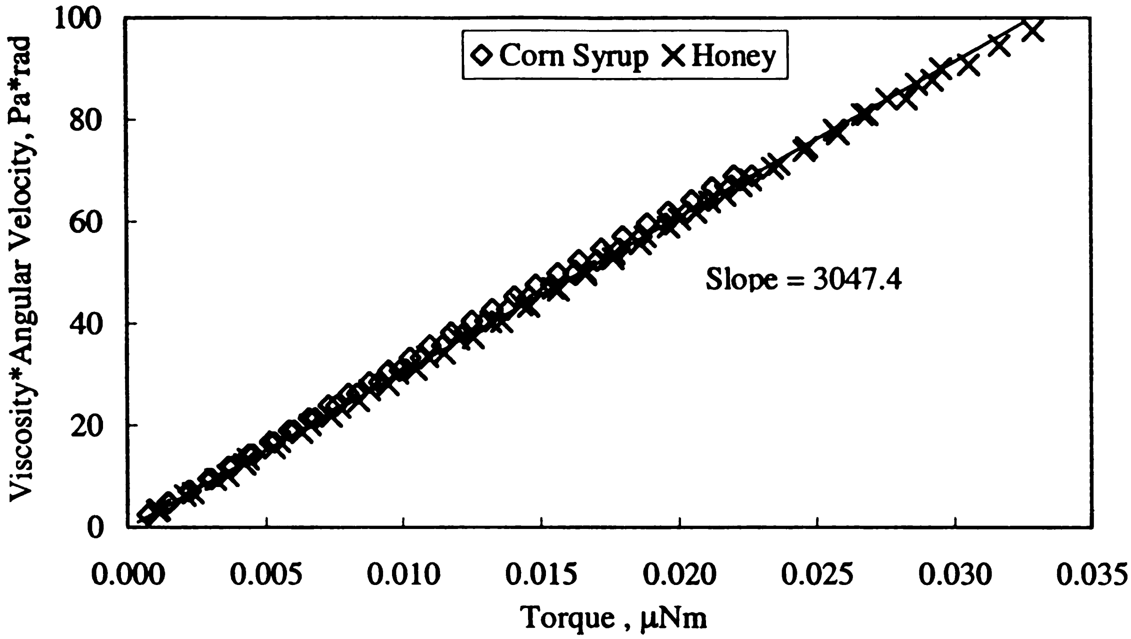

Figure 5.2. Viscosity times angular velocity versus torque for the interrupted helical screw impeller with Newtonian standard fluids for the determination of the mixer coefficient constant, k'' at 23 °C.

k' was determined using Equation [3.14] for each non-Newtonian standard fluid. The data show that k' varies with angular velocity and n (Figure 5.3). However, when focusing on data from 3 to 30 rad s^{-1}, the k' values become relatively independent of angular velocity. A value of 1.6 rad^{-1} was determined for k' by plotting the average shear rate versus the angular velocity for each material. The slope of the regressed line for all the data was taken as the mixer viscometer constant. This finding is comparable to other studies (Qiu and Rao (1988), Rao and Cooley (1984), and Lai et al (2000)). An approximate value of k' is acceptable because it is used to estimate the average shear rate. The actual shear rate varies widely during mixing. The suitability of this value was verified against a conventional rheometer using ketchup. Table 5.4 compares the regression curves of the ketchup data for each instrument. The match is not exact but adequately close because the *k* ' value is an estimate.

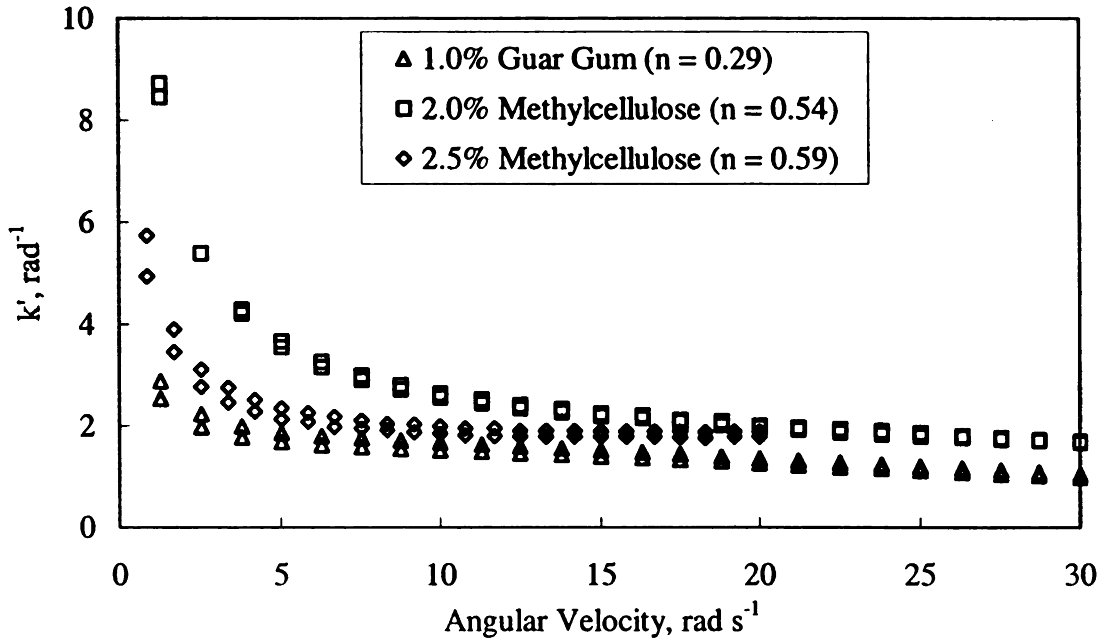

Figure 5.3. Mixer viscometer constant, *k* ', versus angular velocity for the interrupted helical screw impeller using non-Newtonian standard fluids at 23 °C.

Table 5.4. Comparison of the interrupted helical screw impeller and concentric cylinder using ketchup at 23 °C.

Instrument	*K* (Pa s^n)	*n* (-)	R^2
Interrupted Helical Screw Impeller	27.1	0.23	0.979
Concentric Cylinder	23.8	0.22	0.993

5.3. Particulate Food Flow Behavior

Figure 5.4 shows a typical plot of the raw data scatter for one run using the interrupted helical screw impeller and Prego sauce at the cold temperature (8 °C). The resulting trend showing torque to be linearly related to angular velocity was found for all the products with particulates. Each product exhibited a high level of variation in torque response most probably due to the impeller blades coming in contact with different particulates. Variation between tests was attributed to the slightly different composition of particulates in each test batch.

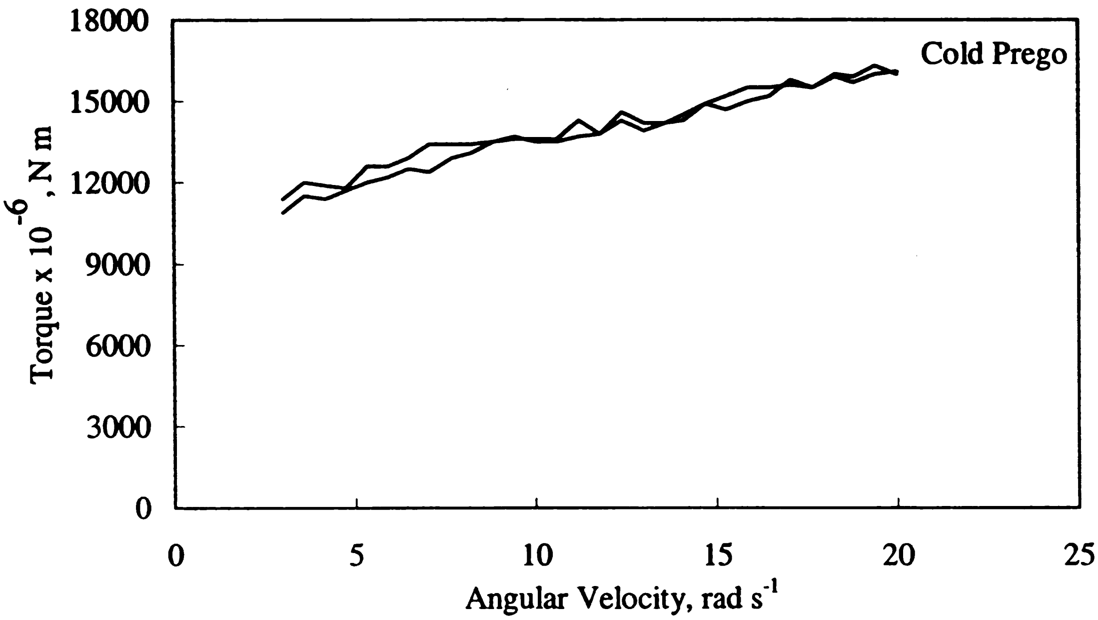

Figure 5.4. A typical raw data set from one trial using the interrupted helical screw impeller with Prego sauce at 8 °C.

Using the value of k' and Equation [3.7], the average shear rate range for testing the fluid foods with particulates was 4.8 s^{-1} to 32 s^{-1}. By taking the logarithm of each side of Equation [2.4], a linear relationship between apparent viscosity and average shear rate is formed:

$$\ln \eta = \ln K + (n-1)\ln \dot{\gamma}_a \qquad [5.1]$$

ln η versus ln $\dot{\gamma}_a$ was plotted for cream corn, Prego, Ragu, and salsa (Figures 5.5 – 5.8). The regressed lines for all three temperatures appear on each figure. The upper range of the angular velocity (17.1 rad s^{-1} – 20 rad s^{-1}) for the salsa trials at hot temperature was eliminated from analysis because excessive slip (a violation of a basic assumption) was observed at the wall of the container. Data results were no longer linear for those conditions.

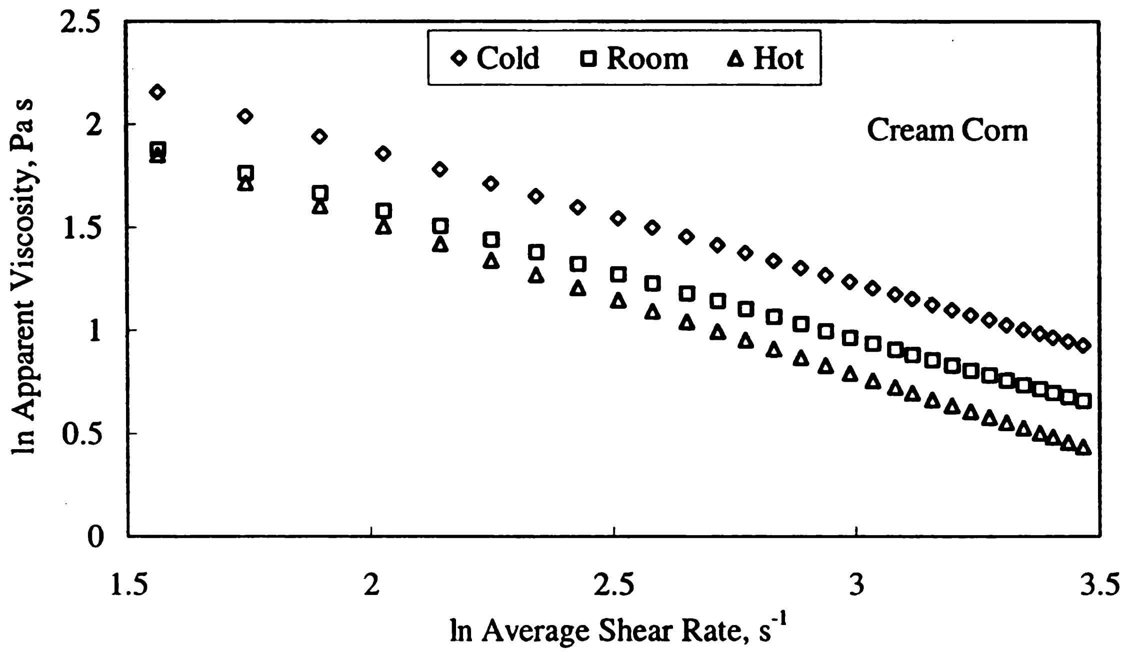

Figure 5.5. ln η versus ln $\dot{\gamma}_a$ for cream corn at cold (5 °C), room (23 °C) and hot (80 °C) temperatures using the interrupted helical screw impeller.

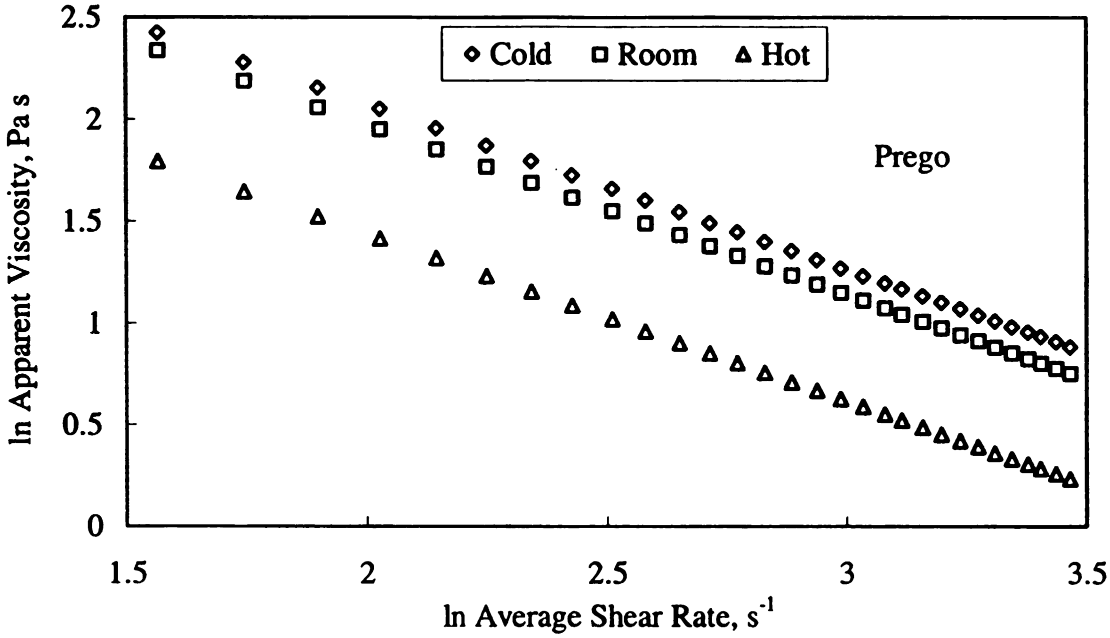

Figure 5.6. ln η versus ln $\dot{\gamma}_a$ for Prego at cold (8 °C), room (23 °C) and hot (80 °C) temperatures using the interrupted helical screw impeller.

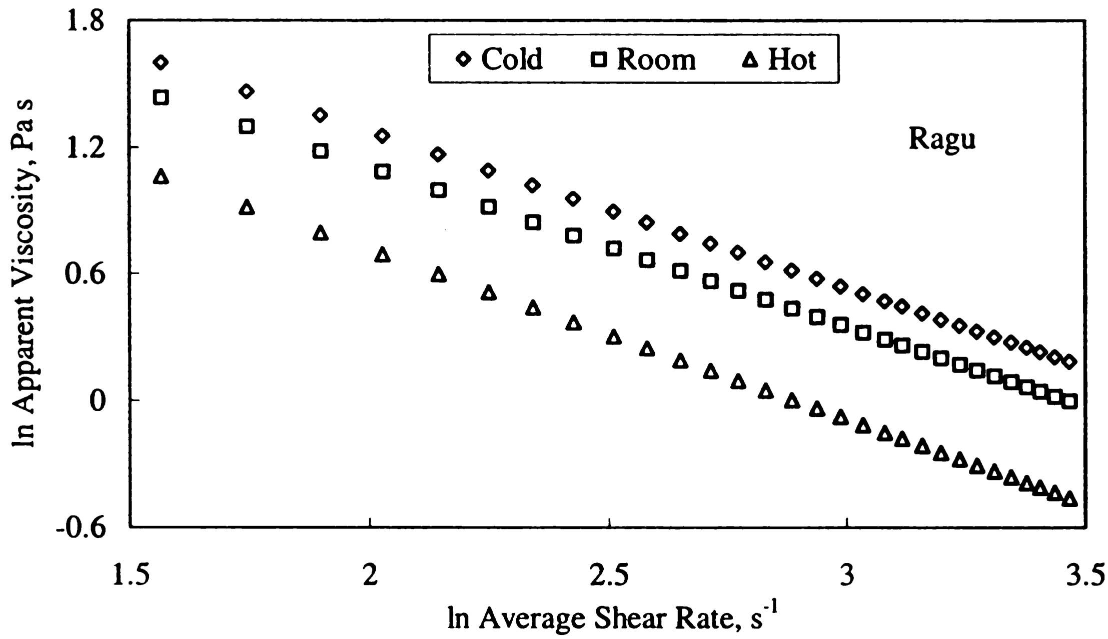

Figure 5.7. ln η versus ln $\dot{\gamma}_a$ for Ragu at cold (7 °C), room (23 °C) and hot (80 °C) temperatures using the interrupted helical screw impeller.

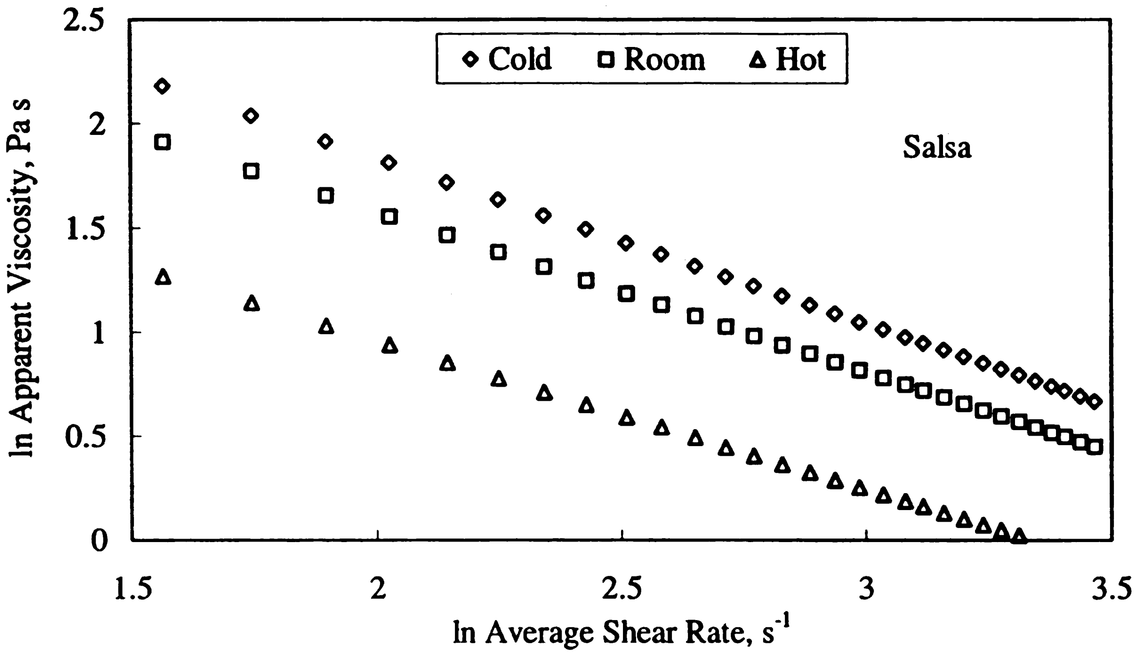

Figure 5.8. ln η versus ln $\dot{\gamma}_a$ for salsa at cold (7 °C), room (23 °C) and hot (80 °C) temperatures using the interrupted helical screw impeller.

All products exhibited similar slopes over the temperatures studied, and the lowest temperature trial always produced the highest apparent viscosity readings. Table 5.5 lists the regressed *K* and *n* values at each temperature for all four products. The temperatures listed are average values. The *n* values do not appear to be a strong function of temperature. As the temperature increases, the consistency coefficient decreases for all food products except for cream corn.

Table 5.5. Rheological parameters for foods with particulates at cold, room, and hot temperatures using the interrupted helical screw impeller.

Fluid Food	K (Pa s^n)	n (-)	R^2	Temperature (°C)
Cream Corn				
-Cold	23.8	0.35	0.854	5
-Room	17.9	0.36	0.871	23
-Hot	20.4	0.26	0.979	80
Prego				
-Cold	40.3	0.19	0.978	8
-Room	38.3	0.17	0.959	23
-Hot	21.8	0.18	0.984	80
Ragu				
-Cold	15.9	0.26	0.969	7
-Room	13.7	0.24	0.959	23
-Hot	10.1	0.20	0.988	80
Salsa				
-Cold	30.8	0.20	0.957	7
-Room	22.6	0.23	0.932	23
-Hot	10.9	0.28	0.877	80

Figure 5.9 is a graphical representation of the logarithm of Equation [2.5]. An intermediate average shear rate of 18.88 s^{-1} was chosen to compare apparent viscosities at each temperature. Apparent viscosity is clearly dependent on temperature. The slope (activation energy) and y-intercept (constant A) were determined by regression analysis of these plots and compared in Table 5.6. Looking at the energy activation terms, salsa's apparent viscosity changes the most with temperature.

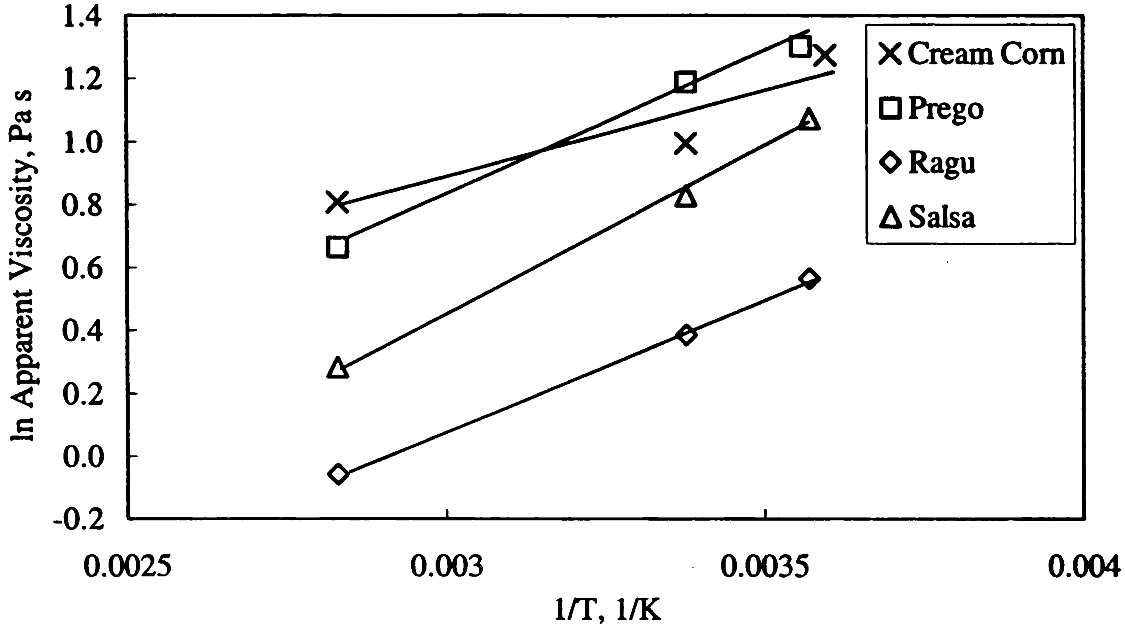

Figure 5.9. ln η versus 1/T at 18.88 s^{-1} for each fluid food with particulates using the interrupted helical screw impeller.

Table 5.6. Activation energy and *A* values for each fluid food with particulates using the interrupted helical screw impeller.

Product	E_a/R	A	R^2
Cream Corn	561	0.45	0.879
Prego	898	0.15	0.995
Ragu	840	0.09	0.999
Salsa	1057	0.07	0.997

Figure 5.10-12 depicts regression lines of each product at cold, room and hot temperatures respectively on a ln η versus ln $\dot{\gamma}_a$ plot for comparison. Ragu pasta sauce was consistently the least viscous. Prego, Ragu, and salsa had similar slopes; while

cream corn intercepted the salsa and Prego lines at cold temperature and only the salsa line at room temperature. At the cold and room temperatures, Prego was the most viscous of the food products. For the hot temperature, the cream corn was more viscous than Prego.

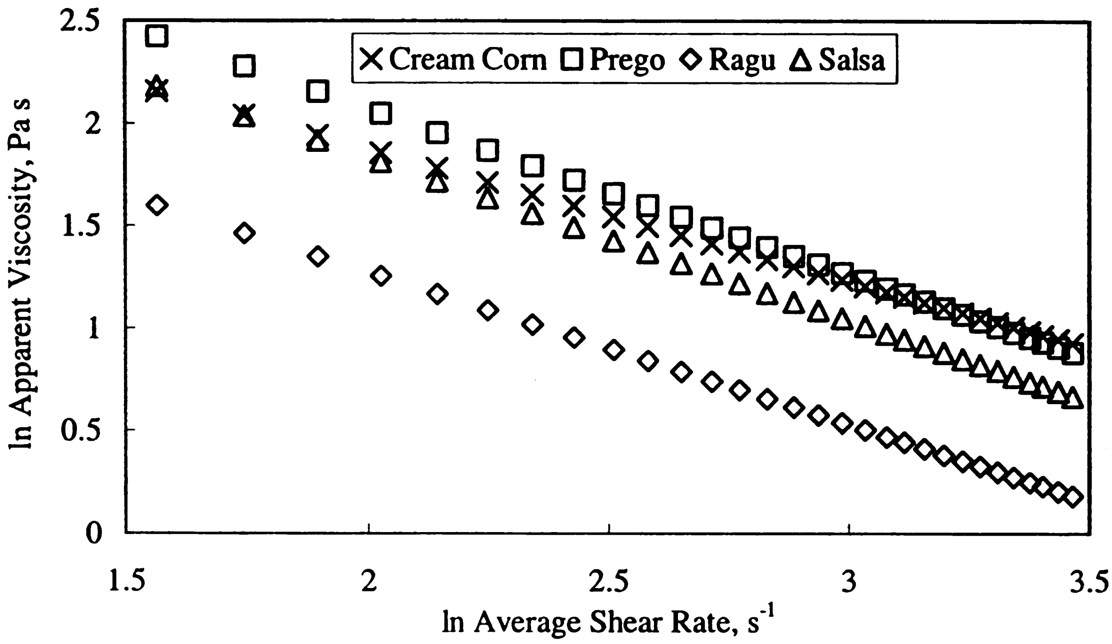

Figure 5.10. ln η versus ln $\dot{\gamma}_a$ of fluid food products with large particulates at cold temperature (5-8 °C) using the interrupted helical screw impeller.

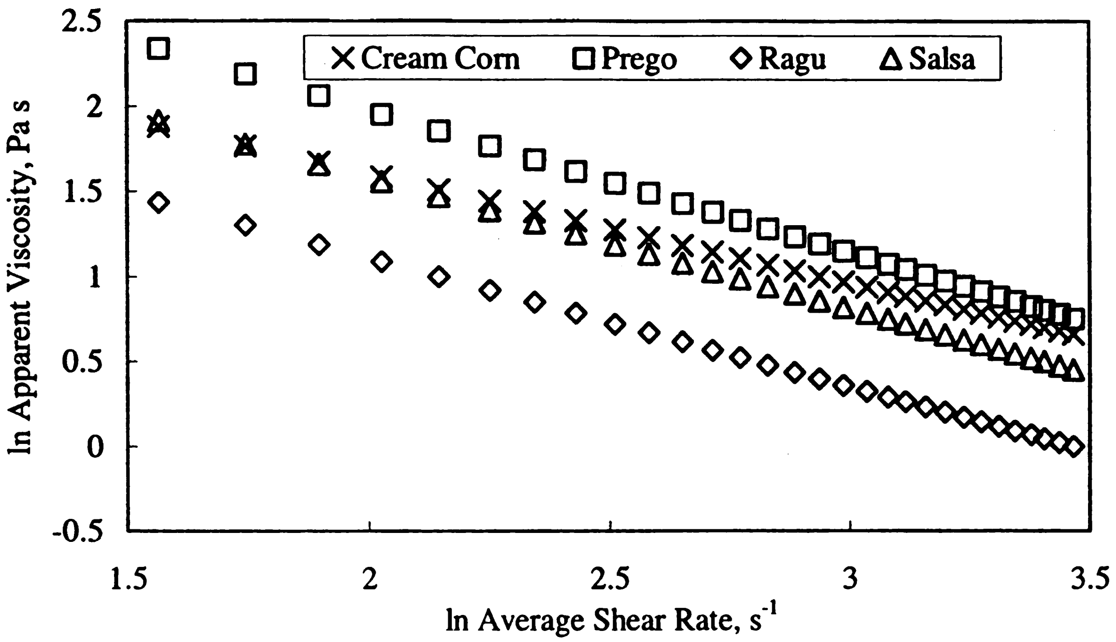

Figure 5.11. ln η versus ln $\dot{\gamma}_a$ of fluid food products with large particulates at room temperature (23 °C) using the interrupted helical screw impeller.

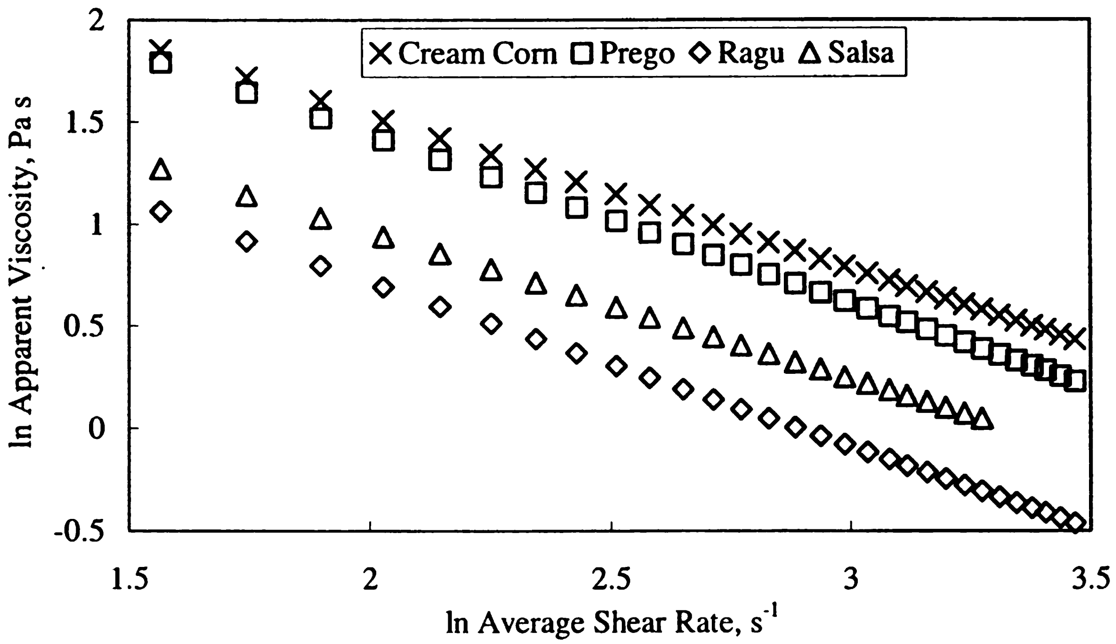

Figure 5.12. ln η versus ln $\dot{\gamma}_a$ of fluid food products with large particulates at hot temperature (80 °C) using the interrupted helical screw impeller.

Table 5.7 contrasts the power law parameters for the whole fluid food and the fluid phase analyzed by the helical ribbon at room temperature (23 °C). Similar shear rates were selected for each instrument (4 s^{-1} to 27 s^{-1}) for a fair comparison. Relatively speaking, there is a large increase in the consistency coefficient that corresponds with the loading of particulates for all products except Ragu. The similarity of the results reflects the small amount of particulates in the fluid initially, and therefore, small effect in the fluid. Based on the flow behavior indices, the fluid phase appears to be less shear-thinning than the complete product with the particulates included. These findings are in agreement with past investigations (Bhamadipati and Singh, 1990).

Table 5.7. Comparison of the rheological parameters of whole fluid food products with large particulates at room temperature (23 °C) using the interrupted helical screw impeller to the fluid phase at room temperature (23 °C) using a helical ribbon.

Fluid Food	K (Pa s^n)	n (-)	R^2
Cream Corn	18.5	0.34	0.854
Cream Corn Fluid	2.8	0.47	0.955
Prego	38.9	0.16	0.952
Prego Fluid	22.3	0.19	0.993
Ragu	14.2	0.22	0.953
Ragu Fluid	17.7	0.21	0.980
Salsa	23.8	0.21	0.936
Salsa Fluid	3.09	0.33	0.965

Preliminary trials of Bush's Baked Beans and Dinty Moore Beef Stew were unsuccessful. The baked beans exhibited high particle-to-particle interaction and appeared to move as a whole entity rather than moving as discrete particles, which indicates excessive slip. Another issue of concern with the beans was the observation of particle degradation during testing. Also, the beef stew particulates (the largest tested in this investigation) became jammed between the impeller and side of the beaker.

5.4. Regression Control Charts

ln η were plotted against ln $\dot{\gamma}_a$ for each food product with large particulates at each temperature. Figure 5.13, a plot for Prego pasta sauce at cold temperature, is an example of typical results. All ten repetitions are represented in the figure. Linear regression produced an average control line and the upper and lower control limits for each figure. Due to the wide spread of the data, the control limits are based on three times the standard error rather than two. This allows for a lower risk of false alarms. Table 5.8 compares the standard errors for each food product at each temperature. The lower average standard error values correspond to the food products with lower percentages of solids by weight. Temperature did not affect the standard errors in a consistent manner.

One trial from cream corn and Ragu at room temperature appear separated from the rest of the data pool. When reviewing the circumstances of the tests, no extraordinary conditions were recorded; therefore, these outlying test trials were included in the analysis.

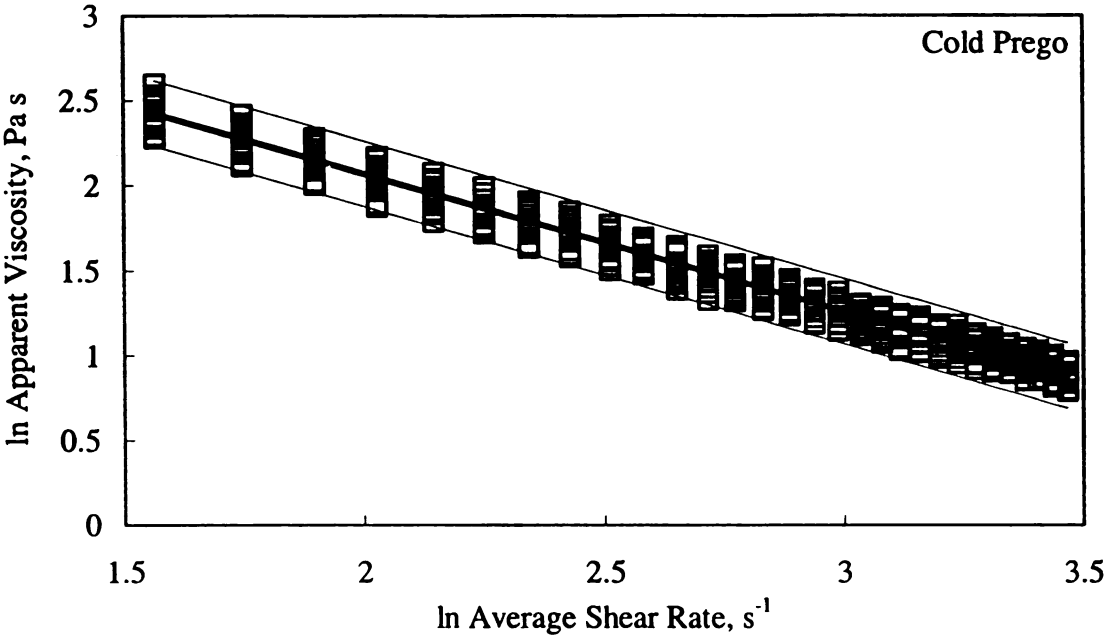

Figure 5.13. ln η versus ln $\dot{\gamma}_a$ for Prego sauce at cold temperature (5 °C) using the interrupted helical screw impeller.

Table 5.8. Comparison of standard errors for each fluid food with large particulates at each temperature.

Fluid Food	Standard Error of ln η Data
Cream Corn	
-Cold	0.142
-Room	0.131
-Hot	0.057
Average	0.110
Prego Hot	
-Cold	0.064
-Room	0.091
-Hot	0.056
Average	0.070
Ragu	
-Cold	0.071
-Room	0.083
-Hot	0.048
Average	0.067
Salsa	
-Cold	0.090
-Room	0.110
-Hot	0.130
Average	0.110

5.5. Statistical Quality Control Protocol

Using the interrupted helical screw impeller, a quality control program can be established for fluid food products with large particulates. Based on steady-state shear ramp tests similar to this study, regression control charts can be produced. The number of trials on acceptable product samples to establish the control line and control limits is a management decision based on the variance of the product. Recommended values differ between authors (Bafna, 1995; Hubbard, 1990).

Personnel can run a test on the product and compare results to the established control chart. The management would decide the frequency of the testing. The most thorough assessment would be to run the same steady state ramp up-and-down test and compare the regressed curve to the control chart. Occasional outlying points, caused by random particulates colliding with the impeller blade may be eliminated from the data pool using residual analysis. If the result lies within the limits, then the product is in accordance with accepted values. A test result that intersects a control line indicates a problem with the flow behavior index; whereas, a test line that runs parallel to the control line but outside the control limits, indicates an unacceptable value of K. The protocol for actions to be taken when a product is found to be out of specification is a management decision, that may involve reformulation or disposal.

Another quality control test option using the regression control chart is to determine the apparent viscosity at two different shear rates and see if the points are located within the control limits. This test would only give a general indication of how the product behaves because it is based on only two points. Adding more apparent viscosity point tests would make the quality control procedure more laborious, but may be necessary with some products. Single point testing is generally unacceptable with shear-thinning products.

This type of test and regression control chart for quality control purposes is aimed at batch processes rather than continuous. This type of chart is not as suitable to follow the progress of a process with time because the chart represents only one test result.

Separate tests could be run at different points in the processing of the product. Another use for regression control charts is in product development of fluid foods with large particulates. The results can be compared with acceptable rheological parameters of competing products.

CHAPTER 6

6. Summary and Conclusions

A mixer viscometer impeller modeled after an impeller used to evaluate the rheological properties of fresh concrete was successfully designed and constructed. Using Newtonian fluids, it was characterized by a mixer coefficient constant (k'') value of 3047.4 rad m^{-3}. The mixer viscometer constant (k') was determined with non-Newtonian fluids to be 1.6 rad^{-1} over the angular velocity range of 3 – 30 rad s^{-1}.

The interrupted helical screw impeller was effectively used to evaluate the rheological behavior of fluid foods with large particulates. Apparent viscosity measurements were obtained and power law parameters were found using regression analysis for cream corn, salsa, a smooth pasta sauce and a chunky pasta sauce at typical application temperatures: cold (6 °C), room (23 °C), and hot (80 °C). The largest particulates in each food ranged from approximately 1 cm to 2 cm in the longest direction.

There was variation within a single test and between tests due to the positioning and quantity of particulates in the samples. However, a definite trend could be determined: higher particulate loading resulted in higher standard error values. Apparent viscosity was found to decrease with increasing temperature. For cream corn, Prego, and salsa, K was larger for the whole product versus only the fluid phase. The chunky pasta sauce was the most viscous, followed by cream corn, salsa, and then the smooth pasta sauce at room temperature.

Regression control charts of ln η versus ln $\dot{\gamma}_a$ were made for all the food products investigated at each temperature. The control line and control limits represent the acceptable range of flow behavior for each product. Such charts can be established in food manufacturing facilities for quality control purposes. Fluid foods with large particulates can be tested using the interrupted helical screw impeller and compared to a regression control chart. This is a valuable discovery to the food industry because currently no standardized test exists to assess objective parameters of such foods. The ability to quantitatively test rheological properties of fluid foods containing large particulates is also important for process design calculations involving pipeline design, mixing and pumping.

CHAPTER 7

7. Future Research

The following topics are recommended for future study:

1. Expanding the pool of large particulate fluid foods analyzed to include items such as fruit preserves and chunky soups.

2. One specific brand was chosen to represent each type of food considered in the current study. Evaluating different brands, of similar large particulate products for comparison of rheological parameters is suggested.

3. In this study, the amount of solids in the fluid foods affected the rheological parameters. Future study correlating particulate loading (size, shape and volume) with changes in flow behavior is recommended.

4. Determining the range of sizes and loading of particulates appropriate for the interrupted helical screw impeller in this study.

5. Studying the effect of different gap sizes.

6. Constructing a permanent temperature control device for the testing container.

7. Beef stew contained particulates that were of a size inappropriate for this study. A scaling investigation is suggested to address extraordinarily sized particulates. First, a basis for scaling must be determined. The author suggests scaling on a geometrical basis. Next, a relationship must be developed between the particulates in question and the impeller system for scaling. Important factors must be established, such as blade size and gap size, so if distortion is necessary, those design factors will not be sacrificed. Torque capacity of the instrument may become an important issue with large impellers.

8. The quality control plan for this study was aimed at batch processes, and therefore did not lend itself to monitoring historical trends in results. A method is needed to measure the progress with time of the rheological parameters of fluid foods using statistical quality control applications.

9. Multivariate quality control was investigated for monitoring K and n values; however, the process involved complex statistical analysis inappropriate for typical food plant environment. Designing a software program to easily carry out multivariate quality control calculations would greatly simplify the process. This technique may be useful in some applications.

10. Using rheological data found by the interrupted helical screw impeller system to model pipeflow problems found in aseptic processing systems.

APPENDIX:
Typical experimental data for the interrupted helical screw impeller

Table A.1. Interrupted helical screw impeller data to determine k'' using Newtonian fluids at 23 °C.

Fluid	Angular Velocity (rad/s)	Torque x 10^{-6} (Nm)	Viscosity (Pa s)
Corn Syrup	1.04	722	2.3
	2.07	1454	
	3.10	2188	
	4.14	2930	
	5.17	3660	
	6.21	4400	
	7.24	5146	
	8.26	5860	
	9.30	6568	
	10.40	7310	
	11.40	8030	
	12.40	8802	
	13.40	9510	
	14.50	10260	
	15.50	11000	
	16.60	11760	
	17.60	12510	
	18.60	13270	
	19.70	14060	
	20.70	14840	
	21.70	15640	
	22.80	16390	
	23.80	17220	
	24.80	18000	
	25.90	18870	
	26.90	19660	
	27.90	20490	
	29.00	21250	
	30.00	22040	

Table A.1. (cont'd)

Fluid	Angular Velocity (rad/s)	Torque x 10^{-6} (Nm)	Viscosity (Pa s)
Honey	0.42	1068	7.5
	0.83	2082	
	1.25	3180	
	1.65	4236	
	2.07	5300	
	2.48	6314	
	2.90	7390	
	3.31	8410	
	3.73	9466	
	4.14	10480	
	4.55	11510	
	4.96	12560	
	5.38	13600	
	5.79	14580	
	6.21	15650	
	6.62	16640	
	7.04	17650	
	7.43	18620	
	7.86	19660	
	8.26	20630	
	8.70	21720	
	9.09	22650	
	9.51	23670	
	9.94	24680	
	10.40	25680	
	10.80	26690	
	11.20	27580	
	11.60	28660	
	12.00	29520	

Table A.2. Interrupted helical screw impeller data to determine k' using non-Newtonian fluids at 23 °C.

Fluid	Angular Velocity (rad/s)	Torque x 10^{-6} (N m)
1% Guar Gum	0.03	74
	1.28	1300
	2.53	1900
	3.78	2310
	5.03	2630
	6.27	2880
	7.53	3090
	8.77	3290
	10.00	3470
	11.30	3650
	12.50	3820
	13.80	4010
	15.00	4180
	16.30	4370
	17.50	4550
	18.80	4740
	20.00	4930
	21.20	5120
	22.50	5320
	23.80	5530
	25.00	5750
	26.30	5960
	27.50	6190
	28.70	6430
	30.00	6670

Table A.2. (cont'd)

Fluid	Angular Velocity (rad/s)	Torque x 10^{-6} (N m)
2.0% Methylcellulose	0.03	24
	1.28	1370
	2.53	2470
	3.78	3440
	5.03	4340
	6.27	5160
	7.53	5920
	8.77	6640
	10.00	7320
	11.30	7970
	12.50	8590
	13.80	9200
	15.00	9770
	16.30	10300
	17.50	10900
	18.80	11500
	20.00	12000
	21.20	12500
	22.50	13100
	23.80	13600
	25.00	14100
	26.30	14600
	27.50	15100
	28.70	15600
	30.00	16100

Table A.2. (cont'd)

Fluid	Angular Velocity (rad/s)	Torque x 10^{-6} (N m)
2.5% Methycellulose	0.03	90
	0.87	2480
	1.70	4320
	2.53	5990
	3.36	7450
	4.19	8800
	5.03	10100
	5.85	11200
	6.69	12300
	7.53	13400
	8.35	14400
	9.19	15300
	10.00	16200
	10.80	17100
	11.70	17900
	12.50	18800
	13.30	19500
	14.20	20300
	15.00	21000
	15.80	21700
	16.70	22400
	17.50	23000
	18.30	23700
	19.20	24300
	20.00	24900

Table A.3. Interrupted helical screw impeller data for cream corn.

Angular Velocity (rad/s)	Torque x 10^{-6} (Nm)		
	5 °C	23 °C	80 °C
3.0	8530	6860	6580
3.6	9430	6860	6730
4.2	10400	7050	6320
4.8	10700	7120	6600
5.3	11200	7660	6890
5.9	11500	8520	7170
6.5	11600	8120	6830
7.1	12700	8430	7740
7.7	12300	8850	7980
8.3	12600	8920	7950
8.9	13200	9150	7750
9.4	13300	9260	8200
10.0	13500	9100	8280
10.6	14200	9990	8040
11.2	13900	9590	8370
11.8	13900	9760	8500
12.4	14300	9660	8780
13.0	13700	10300	8950
13.6	14500	10800	9140
14.1	14800	11100	8810
14.7	14900	10300	9140
15.3	15400	10300	9140
15.9	15500	11400	9210
16.5	16000	11400	8820
17.1	15700	11600	9010
17.7	16300	11700	9310
18.3	16100	11900	9060
18.8	16600	12300	9600
19.4	16100	11800	9630
20.0	16500	12500	10200

Table A.3. (cont'd)

Angular Velocity (rad/s)	Torque x 10^{-6} (Nm)		
	5 °C	23 °C	80 °C
20.0	16100	12000	10200
19.4	15600	12200	10500
18.8	15900	11300	10000
18.3	15600	11800	9660
17.7	15100	11500	10200
17.1	15100	11100	9140
16.5	15000	10600	9130
15.9	14700	10900	9460
15.3	14600	9860	8660
14.7	14500	9820	8600
14.1	13700	9830	8960
13.6	13200	9630	8390
13.0	13300	10500	8400
12.4	12900	8870	7580
11.8	13000	9140	7950
11.2	12900	8570	8620
10.6	13000	8970	8800
10.0	12200	8680	8060
9.4	12100	8570	7970
8.9	11900	7870	7310
8.3	11100	8010	7170
7.7	10500	7830	7170
7.1	10600	7780	7380
6.5	9880	7250	7250
5.9	9620	6800	7200
5.3	9470	6860	6710
4.8	8890	6680	6770
4.2	8860	6410	6470
3.6	8420	6620	6420
3.0	7990	6110	6010

Table A.4. Interrupted helical screw impeller data for Prego.

Angular Velocity (rad/s)	Torque x 10^{-6} (Nm)		
	8 °C	23 °C	80 °C
3.0	10900	11200	5420
3.6	11500	10900	5620
4.2	11400	11600	5870
4.8	11700	11600	6020
5.3	12000	11800	6180
5.9	12200	12200	6290
6.5	12500	12100	6290
7.1	12400	12500	6620
7.7	12900	12500	6920
8.3	13100	12600	7170
8.9	13500	12500	7290
9.4	13700	13000	7400
10.0	13500	13100	7590
10.6	13500	13100	7520
11.2	13700	13300	7610
11.8	13800	13600	8080
12.4	14300	13200	7720
13.0	13900	13400	7900
13.6	14200	13700	7890
14.1	14500	13800	8040
14.7	14900	14200	8030
15.3	15200	14200	8160
15.9	15500	14100	8170
16.5	15500	14100	8290
17.1	15600	14300	8350
17.7	15500	14200	8550
18.3	16000	14600	8440
18.8	15900	14400	8580
19.4	16300	14500	8790
20.0	16000	14600	8940

Table A.4. (cont'd)

Angular Velocity (rad/s)	Torque x 10^{-6} (Nm)		
	8 °C	23 °C	80 °C
20.0	16100	14700	8850
19.4	16000	14800	8180
18.8	15700	14600	8550
18.3	15900	14300	8450
17.7	15500	14200	8320
17.1	15800	14200	8220
16.5	15200	14000	8050
15.9	15000	14000	7980
15.3	14700	13900	8010
14.7	14900	13700	7890
14.1	14300	13600	8050
13.6	14200	13800	7890
13.0	14200	13500	8110
12.4	14600	13200	8110
11.8	13800	13400	7830
11.2	14300	12900	7570
10.6	13600	13000	7680
10.0	13600	12900	7660
9.4	13600	12900	7480
8.9	13500	12600	7420
8.3	13400	12600	7360
7.7	13400	12500	7360
7.1	13400	12300	7430
6.5	12900	12300	7180
5.9	12600	12000	7020
5.3	12600	12100	6860
4.8	11800	11600	6910
4.2	11900	11600	6720
3.6	12000	11000	6630
3.0	11400	11400	6320

Table A.5. Interrupted helical screw impeller data for Ragu.

Angular Velocity (rad/s)	Torque x 10^{-6} (Nm)		
	7 °C	23 °C	80 °C
3.0	5490	4110	3080
3.6	5610	4220	3120
4.2	5790	4380	3170
4.8	5900	4510	3170
5.3	6040	4550	3240
5.9	6160	4640	3270
6.5	6270	4750	3320
7.1	6450	4810	3410
7.7	6610	4860	3460
8.3	6630	4950	3510
8.9	6800	5020	3620
9.4	6820	5110	3620
10.0	6980	5170	3720
10.6	7110	5180	3800
11.2	7210	5330	3830
11.8	7330	5450	3800
12.4	7380	5500	3860
13.0	7510	5600	3930
13.6	7570	5690	4010
14.1	7750	5710	4050
14.7	7830	5800	4060
15.3	7890	6030	4170
15.9	8030	6050	4220
16.5	8040	6030	4260
17.1	8160	6250	4230
17.7	8310	6410	4320
18.3	8400	6550	4360
18.8	8460	6720	4430
19.4	8530	6660	4430
20.0	8590	6620	4520

Table A.5. (cont'd)

Angular Velocity (rad/s)	Torque x 10^{-6} (Nm)		
	7 °C	23 °C	80 °C
20.0	8660	6540	4530
19.4	8520	6580	4460
18.8	8490	6440	4380
18.3	8450	6320	4320
17.7	8290	6370	4320
17.1	8260	6310	4250
16.5	8210	6350	4160
15.9	8140	6200	4180
15.3	8060	6110	4090
14.7	7890	5950	4080
14.1	7820	6220	4000
13.6	7700	5980	3980
13.0	7700	5750	3920
12.4	7510	5630	3890
11.8	7450	5550	3920
11.2	7330	5500	3850
10.6	7260	5500	3780
10.0	7190	5400	3760
9.4	7010	5370	3710
8.9	6970	5300	3730
8.3	6920	5230	3640
7.7	6840	5140	3590
7.1	6680	5090	3590
6.5	6480	5080	3470
5.9	6380	4960	3450
5.3	6270	4900	3470
4.8	6140	4660	3360
4.2	5960	4670	3340
3.6	5730	4470	3220
3.0	5610	4270	3170

Table A.6. Interrupted helical screw impeller data for salsa.

Angular Velocity (rad/s)	Torque x 10^{-6} (Nm)		
	8 °C	23 °C	80 °C
3.0	8540	7920	3380
3.6	8050	7910	3860
4.2	8370	7090	4290
4.8	8510	8000	4670
5.3	8910	8340	3940
5.9	8580	7960	4130
6.5	9380	8380	4130
7.1	9620	8680	4200
7.7	8840	8590	4550
8.3	8530	8880	4460
8.9	9480	8580	4560
9.4	10000	9340	4580
10.0	9590	9100	4520
10.6	10100	9940	4430
11.2	9860	9020	4710
11.8	10200	9320	5570
12.4	10700	9170	5100
13.0	10500	9850	5350
13.6	10300	9620	5020
14.1	10800	11200	5040
14.7	11200	10100	5710
15.3	10500	9860	5740
15.9	10800	10100	5280
16.5	10800	11300	5980
17.1	11100	10400	5750
17.7	12000	10800	6210
18.3	11600	11600	6420
18.8	11000	12100	6640
19.4	11200	11900	7220
20.0	11200	11700	7520

Table A.6. (cont'd)

Angular Velocity (rad/s)	Torque x 10^{-6} (Nm)		
	8 °C	23 °C	80 °C
20.0	11600	11700	7490
19.4	11000	11700	6960
18.8	11200	11000	7040
18.3	11100	11400	6770
17.7	10500	10300	6590
17.1	10400	10500	6360
16.5	10200	10800	6080
15.9	10500	9990	5990
15.3	9930	9850	5650
14.7	10100	10200	5590
14.1	10100	10300	5390
13.6	10100	9730	5590
13.0	10100	9980	5300
12.4	10300	9490	5330
11.8	10100	9130	5150
11.2	9490	9690	5290
10.6	9530	9030	4870
10.0	8900	8790	4860
9.4	9010	8860	4530
8.9	8850	9390	4380
8.3	8530	8800	4280
7.7	8440	8720	4390
7.1	9120	8300	4110
6.5	8260	8210	4020
5.9	8170	8170	4020
5.3	7880	8440	3930
4.8	7490	7620	4290
4.2	7470	7730	4000
3.6	7500	7750	3380
3.0	6950	7610	3690

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