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Design Criteria for an On-line Viscometer
for Baby Food Puree

presented by

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James F. Steffe
Major professor

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DESIGN CRITERIA FOR AN ON-LINE VISCOMETER FOR BABY FOOD PUREE

by

Marc Christian Marcel Vercruysse

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ABSTRACT

DESIGN CRITERIA FOR AN ON-LINE VISCOMETER FOR BABY FOOD PUREE

by

Marc Christian Marcel Vercruysse

Rheological properties of four baby food products (applesauce, carrot puree, vegetable and beef dinner, and turkey and rice dinner) were investigated with a Bostwick Consistometer and a concentric cylinder viscometer from 73 to 92 ^{o}C. A power law fluid behavior was found for all products. The relationship between the two methods of measurement, considered in terms of the Bostwick readings and the apparent viscosity, was very poor. The effect of temperature was product-dependent with applesauce and turkey and rice dinner being the most temperature sensitive.

Rheological properties for turkey and rice dinner were also investigated with a tube viscometer. Different constants were obtained for the consistency coefficient, but the fluid could still be characterized by a power law model.

The design criteria for an on-line viscometer were determined based on a sensitivity analysis and the rheological properties. This analysis showed that the flow behavior index influenced the pressure drop the most. The

influence of the consistency coefficient on the pressure drop depended on the values of the other variables. The flowrate was a much less sensitive variable, which was a positive point, considering wear of the pump with time.

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Very special thanks are given to Bob Dail, who helped in carrying out the experiments with the tube viscometer. I also want to thank Brian, Kim, Larry and Robin, for their practical help.

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LIST OF SYMBOLS

A : constant (Pa s)

BR : Bostwick Consistometer reading (cm/s)

D : diameter (m)

E_a : activation energy (J/mol)

h : height of the bob (m)

K : consistency coefficient (Pa s^n)

L : length of pipe between pressure measurements (m)

L_i : length of pipe between tube viscometer inlet and first pressure measurement (m)

M : external torque (N m)

n : flow behavior index (dimensionless)

ΔP : pressure drop (Pa)

Q : volumetric flowrate (m^3/s)

r : correlation coefficient

r^2: coefficient of determination

R : radius (m)

R_g : universal gas constant (8.314 J/mol K)

SSE : sum of the squares of the errors

T : temperature (^oC or K)

T_1 : temperature of the product at the first pressure transducer (^oC)

T_2 : temperature of the product at the second pressure transducer (^oC)

T_3 : temperature of the steam at the outlet (^oC)

T_4 : temperature of the steam at the inlet (^{o}C)

U_s : effective slip velocity (m/s)

v_w : velocity at the wall (m/s)

β : slip coefficient (m/Pa s)

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

η_a : apparent viscosity (Pa s)

μ : Newtonian viscosity (Pa s)

ρ : density of product (kg/m^3)

σ : shear stress (Pa)

σ_o : yield stress (Pa)

Ψ_1 : primary normal stress difference (Pa)

Ψ_2 : secondary normal stress difference (Pa)

Ω : angular velocity of the bob (rad/s)

subscripts :

b : bob

c : cup

w : wall

CHAPTER 1

INTRODUCTION

1.1. Introduction

Rheology is that field of science which studies the deformation and flow of matter, in response to an applied stress. Rheological properties of food materials have been the subject of several studies. These properties are determined for a number of purposes : quality control, process engineering and design, understanding structure, and correlation with sensory evaluation, are just some examples.

Quality control of a typical pureed baby food product can be assessed at different levels of the process. First, in the process line itself where adjustments can be made before the product goes into the jar. Secondly, on the final product, and finally, on the shelf (e.g. shelf-life stability). The major concern is the consistency of the product, more often referred to as the "thickness". The consistency can be characterized and quantified by rheological parameters.

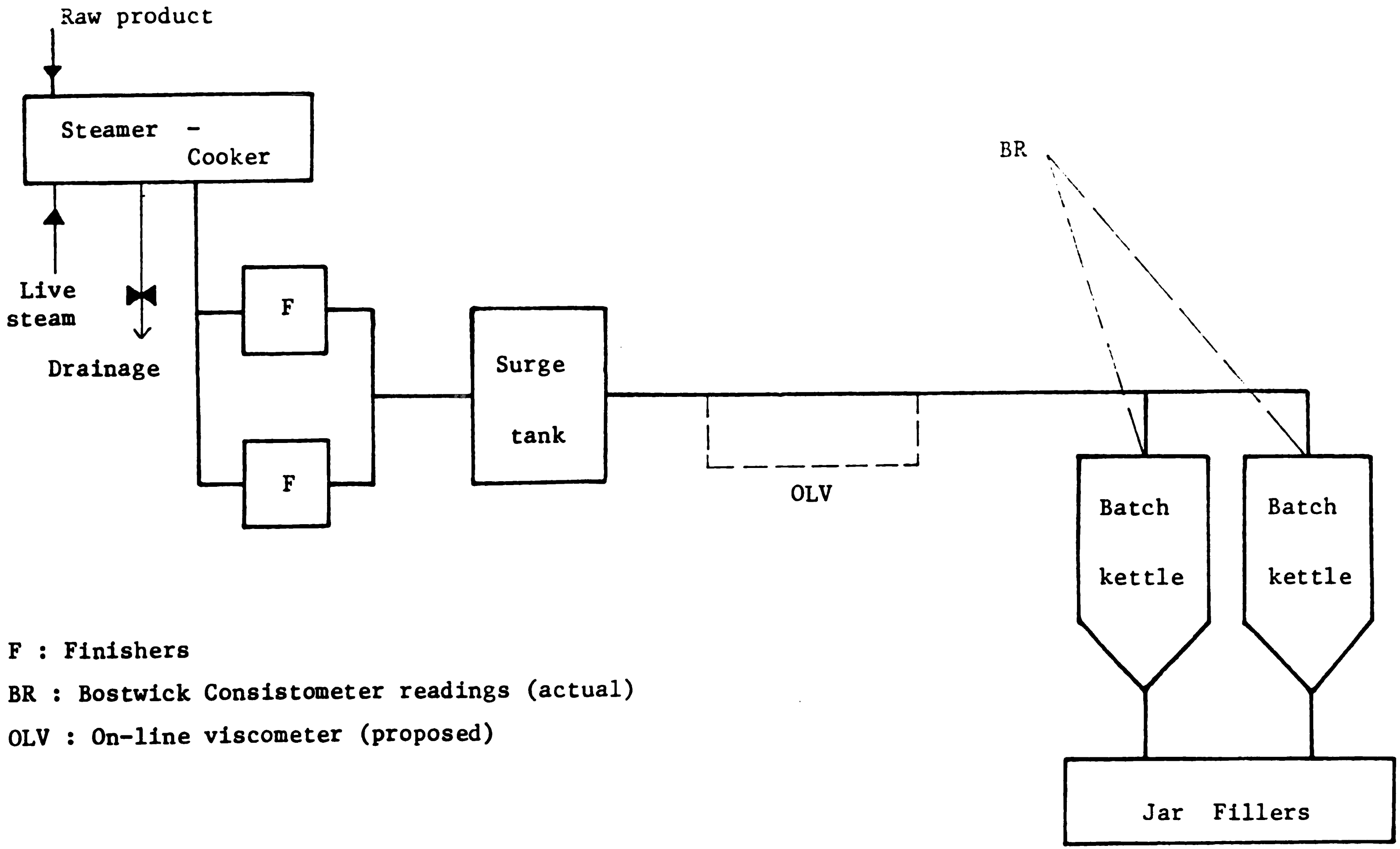
It is a real challenge to investigate these parameters in the process line. Typically, this can be achieved in two ways : either on-line or in-line. An on-line measurement requires sampling from the the main line, performing a measurement and, if desired, returning the sample to the main line. The in-line measurement performs the task without sampling.

The overall focus of this study is to develop design criteria for an on-line viscometer for pureed (not chunky) baby food products to assess the quality of the material. Rheology is used to determine the quality parameters and the design criteria for the on-line viscometer. The on-line viscometer is a tube viscometer, which is compatible with existing industrial pipeline systems.

1.2. An actual process line

An actual process line, for pureed fruit and vegetable products, is schematically represented in Figure 1.1. The raw product is fed into a steamer where it is mashed and cooked. A valve controls draining to allow a desired consistency. Then, the product goes into a series of finishers (screen diameter : 0.7874 mm) and is finally dumped into a surge tank, from where it is pumped to final batch kettles located before the jar fillers.

Usually, a sample is taken out of the batch kettles and a consistency measurement is performed. A frequently used instrument is the Bostwick Consistometer, which is described in section 2.1. The reason why this is so frequently used in the industry is that it is inexpensive, fast and simple. However, the disadvantages are that it is labor intensive,



F : Finishers

BR : Bostwick Consistometer readings (actual)

OLV : On-line viscometer (proposed)

Figure 1.1. Schematic view of a process line.

time consuming and not suitable for on-line consistency measurements. Also, from a rheological point of view, the Bostwick Consistometer provides only one single value, which lumps all the rheological properties together.

It is the objective in the future to substitute the Bostwick Consistometer with an on-line viscometer. The location of this viscometer would be best just after the surge tank and before the batch kettles. The rheological information from the viscometer can then be used to make adjustments at the point of the steamer, by opening and closing the drainage valve, at the point of the batch kettles, water can be added or removed. The on-line viscometer will give more accurate rheological information and it is also fast and simple. In addition, it will lend itself to better control and automation of the process, eventually leading to feedback or feedforward control modes.

1.3. Objectives

The objective of this study was to develop design criteria for an on-line tube viscometer based on the information from the Bostwick Consistometer and the rheological properties measured with a concentric cylinder viscometer and with a tube viscometer.

The specific objectives were :

- to carry out the Bostwick measurements and to obtain the rheological properties of four baby food products (applesauce, carrot puree, vegetable and beef dinner, turkey and rice dinner) at processing temperatures (70-90 ^{o}C), using a concentric cylinder viscometer;

- to investigate a relationship between the Bostwick measurements and the rheological properties of the above products;
- to obtain preliminary, on-line viscometer design information by running one product (turkey and rice dinner) through a tube viscometer;
- to establish design criteria for an on-line tube viscometer for pureed baby food products.

CHAPTER 2

LITERATURE REVIEW

2.1. Bostwick measurements

The Bostwick Consistometer is a simple, cheap and fast way of measuring flow properties of a fluid. The instrument (Figure 2.1) consists of a rectangular trough, 25 cm long, made out of stainless steel, whose floor is graduated in increments of 5 mm. One end has a spring-loaded valve and encloses a compartment with a capacity of 100 cm^3.

At the time of the measurement the sampling container is filled to the top and the valve is released. The fluid starts to flow under its own weight, and movement down the trough reflects the fluid properties. The instrument has a fixed inclination to increase the flowrate and to overcome a small yield stress, if present. Measurements are taken after a fixed time and are reported in units of cm/s or cm/min, thus the appropriate physical quantity would be a velocity. However, since the time is fixed for a particular test, readings are actually distances.

There is no agreement in the literature upon the fixed testing time : Bookwalter et al. (1968) read the Bostwick value after exactly 1 minute, Davis et al. (1954) and Luh et al. (1954) took readings after 30 seconds, Rao and Bourne

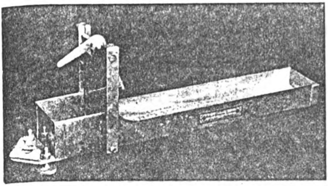


Figure 2.1. The Bostwick Consistometer (Davis et al., 1954).

(1977) obtained their data after 10 seconds. A typical industrial testing time for pureed baby food products is 5 seconds. Clearly, the testing time will be a function of the consistency of the product and of the speed one wants to perform the measurements.

Many variables affect the readings. Some are given below :

- the loading of the product,
- the testing time,
- the nature of the product,
- location of the reading (center or wall),
- inclination of the trough,
- geometry and surface roughness of the trough,
- temperature of the trough.

Again, although measurements are very simple and straightforward, a lot of variables are involved and they all influence the reading. Therefore, Bostwick readings are only meaningful if they are totally described and specified.

Davis et al. (1954) reported that they took an average of the values at the center and both walls. Marsh et al. (1980) used a special consistometer with a trough, 50 cm long, made of plexiglas acrylic plastic.

The effect of temperature on the Bostwick reading has been investigated by Davis et al. (1954). They reported a linear relationship in a range from 21 to 87 ^{o}C for tomato puree.

Data, related to this study, were obtained by Rao and Bourne (1977) :

- applesauce : 6.73 cm/10s at 25 ^{o}C;
- carrot puree : 2.68 cm/10s at 25 ^{o}C.

The Bostwick Consistometer has been and is still used extensively in the industry. It is an empirical method, and as long as one is consistent in taking the readings it can be a meaningful number. However, it lumps all the rheological properties together, since just one value is reported, which is the distance after a fixed testing time. A more modern approach characterizes the fluid with different parameters. Section 2.3 will describe two methods to accomplish this.

2.2. Fluid models

Rheological properties of fluids can be characterized by different fluid models. An extensive review of the official nomenclature for the material functions has been carried out by Dealy (1984). The three major material functions, which are generally accepted are (Rao, 1986) :

- the apparent viscosity : $\eta_a(\dot{\gamma})$
- the primary normal stress difference : $\Psi_1(\dot{\gamma})$
- the secondary normal stress difference : $\Psi_2(\dot{\gamma})$.

In this work only the first material function will be considered; the two other material functions are probably zero and insignificant in this study.

The apparent viscosity can be used to classify the flow behavior of several foods. The simplest model is a Newtonian fluid

$$\eta_a = \frac{\sigma}{\dot{\gamma}} = \mu \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (2.1)$$

More complicated models involve more rheological parameters. The Herschel-Bulkley model (Herschel and Bulkley, 1926) is

$$\eta_a = \frac{\sigma}{\dot{\gamma}} = K\,\dot{\gamma}^{n-1} + \frac{\sigma_o}{\dot{\gamma}} \quad \dots\dots\dots\dots\dots\dots\dots (2.2)$$

Equation 2.2 collapses into Equation 2.1, if $n = 1$ and $\sigma_o = 0$.

Power law fluids are a special case of the Herschel-Bulkley model where the yield stress is equal to zero

$$\eta_a = \frac{\sigma}{\dot{\gamma}} = K\,\dot{\gamma}^{n-1} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2.3)$$

If the flow behavior index is smaller than 1, the fluid is said to be pseudoplastic or shear-thinning. When n is greater than 1, the fluid is called dilatant or shear-thickening. An overview of the different fluid models is given in Figures 2.2,a and 2.2,b. Figure 2.2,a is called a rheogram and plots the shear stress versus the shear rate. In Figure 2.2,b the shear stress is divided by the shear rate, to yield the apparent viscosity. It shows how the apparent viscosity is a function of the shear rate for non-Newtonian fluids.

It must be emphasized that many other models exist and they may even describe the fluid even more accurately, e.g. over greater shear rate ranges (Ofoli et al., 1987). However, the Herschel-Bulkley or power law models are most often used in the food industry, because they are general models, fit most foods and can be integrated to solve many process engineering problems.

So far, only time-independent models have been considered. A plot similar to Figure 2.2,b can be constructed, with time as the independent variable. The apparent viscosity, at a constant shear rate, is now a function of time. Figure 2.3 shows two possible time-dependent effects : thixotropy (curve A) and rheopexy (curve B). The first effect is a decrease of the apparent

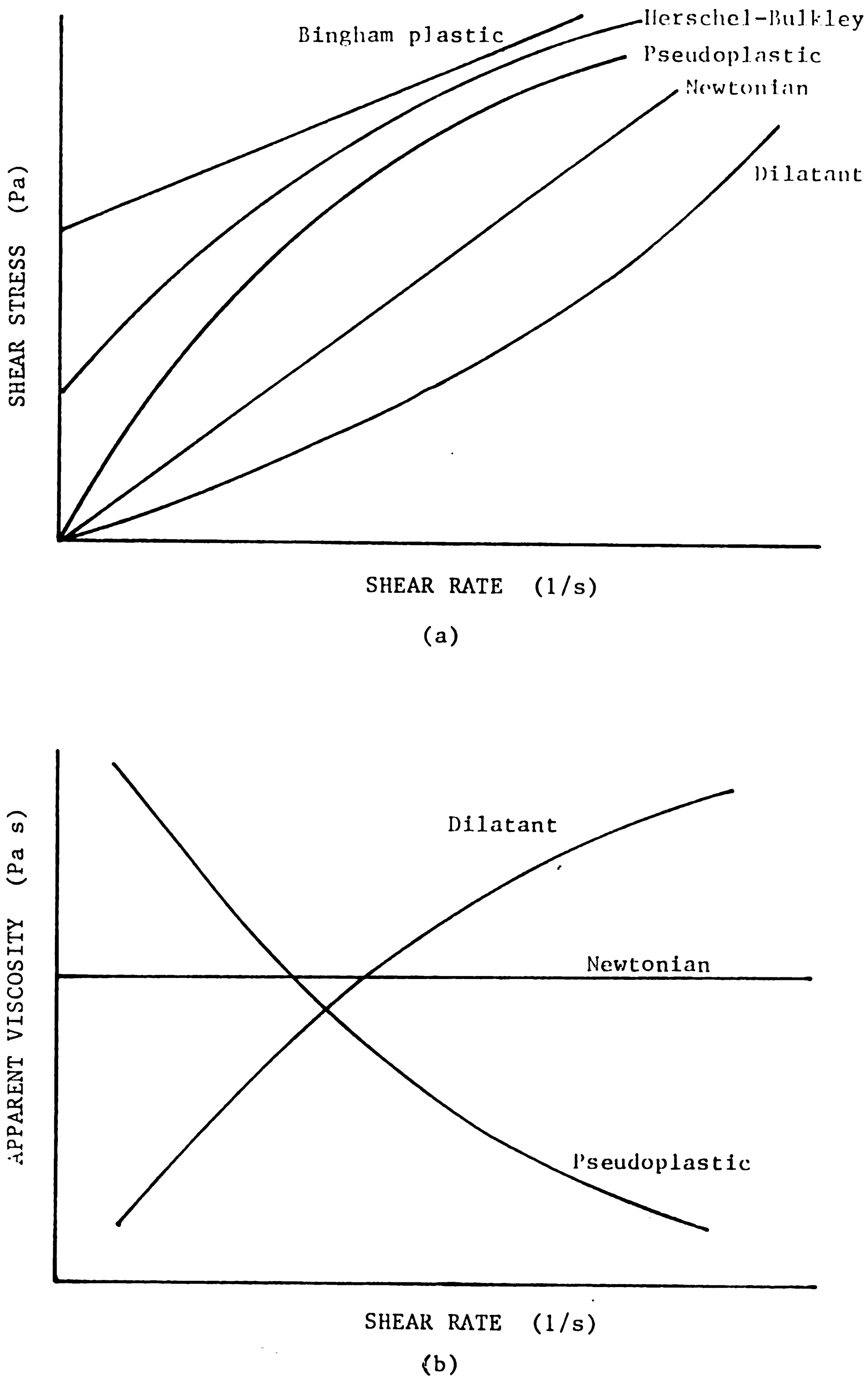


Figure 2.2. Newtonian and time-independent, non-Newtonian fluids.

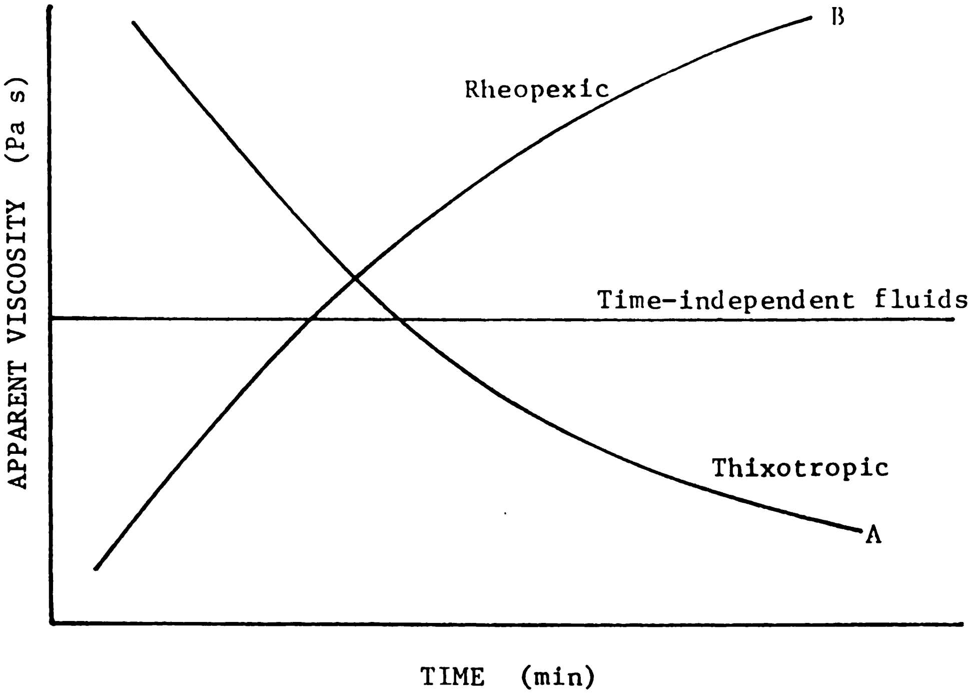


Figure 2.3. Time dependent, non-Newtonian fluids : thixotropy (A) and rheopexy (B).

viscosity with time, while the latter is an increase. The time-independent fluids are represented with a horizontal line.

The rheological model for thixotropic fluids can be based on one of the previous models, multiplied by a structural parameter. Tiu and Boger (1974) employed the Herschel-Bulkley model and assumed the structural parameter to obey a second order rate equation. Other approaches have been taken by Higgs and Norrington (1971) and Tung et al. (1970).

In general, after a certain amount of time the structural decay stops and an equilibrium is reached; no further breakdown or building up will take place. Then, the time effect is said to be removed.

Finally, as mentioned earlier, fluids can show viscoelastic behavior; those fluids have both viscous and elastic properties. They will not be considered in this study.

2.3. Rheological measurements

There is a wide variety of instruments to measure rheological properties of foods. It is beyond the scope of this work to describe all the instruments. More interested readers are referred to Van Wazer et al. (1963) and Whorlow (1980). Here, the concentric cylinder viscometer and the tube viscometer will be discussed because they were used in this study.

2.3.1. Concentric cylinder viscometer

The determination of the shear rate in a non-Newtonian fluid, sheared between rotating coaxial cylinders, has been mathematically solved by Krieger (1968). He showed that the shear rate at the bob for an unknown fluid can be expressed as

$$\dot{\gamma}_b = \frac{2\ \Omega}{s} \left[\frac{(R_c)^{2/s}}{(R_c)^{2/s}-(R_b)^{2/s}}\right]\{1 + s^2\ s'\ f(t)\} \qquad \text{....(2.4)}$$

where $$s = \frac{d(\ln\sigma_b)}{d(\ln\sigma)}$$

$$s' = \frac{d(1/s)}{d(\ln\sigma_b)}$$

$$t = \frac{2}{s}\ \ln(\frac{R_c}{R_b})$$

$$f(x) = \frac{x[e^x(x-2) + x + 2]}{2(e^x-1)^2}$$

while the shear stress at the bob is expressed as

$$\sigma_b = \frac{M}{2\ \pi\ h\ R_b 2} \qquad \text{..............................(2.5)}$$

The assumptions for this solution were :

- the flow is steady; the system is at steady state,
- the fluid is incompressible,
- the flow is laminar,
- no heat generation : isothermal flow,
- the fluid is time-independent,
- the fluid is homogeneous and isotropic,
- gravitational effects are negligible,
- no viscoelastic behavior,
- no slip,
- no end effects.

Keeping the above assumptions in mind, a rheogram (σ_b versus $\dot{\gamma}_b$) can be constructed and a model can be fitted through the experimental values.

2.3.2. Tube viscometer

It is also possible to evaluate the rheological parameters from a consideration of the pressure drop and the volumetric flowrate in a tube. Rabinowitch (1929) and Mooney (1931) developed the following expression

$$\dot{\gamma}_w = \frac{3\ Q}{\pi\ R^3} + \sigma_w \frac{d(Q/\pi R^3)}{d\sigma_w} \quad ....(2.6)$$

and

$$\sigma_w = \frac{\Delta P\ R}{2\ L} \quad ....(2.7)$$

The assumptions that were made to obtain Equations 2.6 and 2.7 were the same as those mentioned to obtain Equations 2.4 and 2.5.

2.4. Rheological properties of the products under study

Many workers have conducted studies to determine the rheological properties of several foodstuffs, but surprisingly enough, no real agreement has been found among the results for one particular product. Holdsworth (1969, 1968), Rao (1977), Steffe et al. (1983) and Dervisoglu and Kokini (1986) reviewed published values for non-Newtonian fluid foods. Differences among results for similar products can be attributed to the instrument of determination, the shear rate range, the soluble solids content, the variety and the composition (particle size), and the rheological model fitted. An overview of applesauce, obtained by several researchers, is given in Table 2.1. It was not the intention to summarize all the existing data for applesauce, but to give an idea of the variability of the reported parameters.

Rao et al. (1986) investigated the effect of cultivar, firmness and processing parameters. The n values ranged from 0.29 to 0.39 and the K values ranged from 7.38 to 19.95 Pa s^n.

To eliminate some of this variability, a collaborative study has been carried out by Prentice and Huber (1983). The only variable was the technique to determine the flow curve. The same products, including applesauce, were shipped to the different labs. Table 2.2 summarizes applesauce results (at 25 ^oC). One can see that the rheological parameters were indeed closer together.

Data for carrot puree were reported by Rao et al. (1977). The flow behavior index was 0.228 and the consistency coefficient was 24.16 Pa s^n. No yield stress was reported for both products. Only Charm (1962) and

Table 2.1. Rheological parameters for applesauce.

Product	Temperature (^oC)	Soluble solids (%)	Shear rate (1/s)	Technique	Model	K (Pa s^n)	n (-)	Yield stress (Pa)	Reference
Applesauce	22	-	50-1500	Merrill viscometer	Power law	.43	.645	-	Charm and Merrill (1959)
	32	-	50-1500		Power law	.38	.645	-	
	40	-	50-1500		Power law	.34	.640	-	
	50	-	50-1500		Power law	.25	.650	-	
Applesauce	27.2	-	-	Brookfield viscometer LV	Power law	10.85	.382	-	Charm (1962)
	50.6	-	-	Brookfield viscometer LV	Power law	7.7	.301	-	
brand A	23.8	-	-	Merrill viscometer	Power law	.5	.645	-	
brand B	23.8	-	-	Tube viscometer	Power law	.66	.408	-	
Applesauce	-	-	8.42-1370	Haake viscometer	Herschel-Bulkley	5.63	.470	58.6	Charm (1963)
Applesauce	30	11	5-50	Brookfield viscometer RVT	Power law	11.6	.340	-	Saravacos and Moyer (1967)
	82	11	5-50		Power law	9.0	.340	-	
Applesauce screen size 3.175 mm	27	11.6	160-1200	Tube viscometer	Power law	12.7	.280	-	Saravacos (1968)
1.016 mm	27	11.6	160-1200		Power law	4.93	.350	-	
0.508 mm	27	11.6	160-1200		Power law	2.6	.500	-	
Applesauce + 25% water	20	-	3.3-530	Concentric cylinder	Power law	16.68	.302	-	Haugen and Tung (1976)
	25	-	0.1-1.1		Power law	2.39	.438	-	
Applesauce	25	-	-	Plastometer of Eolkin	Power law	10.41	.253	-	Rao and Bourne (1977)

Table 2.1. (cont'd).

Product	Temperature (^{o}C)	Soluble solids (%)	Shear rate (1/s)	Technique	Model	K (Pa s^n)	n (-)	Yield stress (Pa)	Reference
Applesauce brand A	25	18.2	1-300	Concentric cylinder	Herschel-Bulkley	6.8	.420	34	Barbosa and Peleg (1983)
brand B	25	18.1	1-300		Herschel-Bulkley	6.4	.430	30	
Applesauce	26	10.5	.78-1260	Tube viscometer	Power law	7.32	.450	-	Steffe (1984)
	26	9.6	.78-1260		Power law	5.63	.450	-	
	26	8.5	.78-1260		Power law	4.18	.450	-	
Applesauce	23	-	1-1600	Tube viscometer	Power law	18.4	.271	-	Dervisoglu and Kokini (1986)
	23	-	1-1600		Herschel-Bulkley	11.51	.330	9	

Barbosa and Peleg (1983) found a yield stress for applesauce (see Table 2.1).

No data were found in the literature for vegetable and beef dinner, and turkey and rice dinner.

2.5. Effect of temperature on the rheological properties

Fluid foods are subjected to different temperatures during processing and for this reason it is often useful to know the effect of temperature on the rheological properties. Arrhenius, in 1912, and De Gusman, in 1913, (Holdsworth, 1971) independently suggested the following relationship

$$\eta_a = A \exp(\frac{E_a}{R_g T}) \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2.8)$$

The magnitude of the activation energy, E_a, and the constant A can be determined by analysis of experimental data. Holdsworth (1971) also suggested that, in general, the higher the activation energy the greater the effect of temperature on the viscosity. The constant A can be interpreted in terms of the molecular weight and molecular volume of the liquid.

From a collaborative study on applesauce (Prentice and Huber, 1983), the activation energy for viscous flow at a shear rate of 10 s^{-1} was calculated within a temperature

Table 2.2. Viscometric constants for applesauce at 25 ^{o}C (Prentice and Huber, 1983).

Laboratory	K ($Pa\ s^n$)	n (-)	σ_o (Pa)
A	21.0	0.35	-
B	28.4	0.27	-
C	16.8	0.35	-
D	32.6	0.29	-
E	30.0	0.33	8
F	30.1	0.25	-
G	36.1	0.28	5.5

Table 2.3. Activation energy for viscous flow of applesauce (Prentice and Huber, 1983).

Laboratory	ln A (Pa s)	E (kJ/mol)
C	-2.75	10.2
D	-0.21	4.2
E	-3.51	13.3
G	-2.90	11.8

range of 10-45 ^{o}C. These results are presented in Table 2.3.

Charm and Merrill (1959) reported an activation energy of 5.44 kJ/mol for applesauce. Saravacos (1970) reported a value of 5.02 kJ/mol for applesauce with a 11^{o} Brix value at a constant shear rate of 100 s^{-1}.

It is interesting to note that, in all the above cases, a logarithmic transformation of Equation 2.8 was performed to determine the constants,

$$\log \eta_a = \log A + \frac{E_a}{R_g\ T} \qquad \text{..................(2.9)}$$

A plot of log η_a versus 1/T yields the necessary parameters, after linear regression. No attempt was made to perform a non-linear regression.

Rao (1977) summarized activation energies for several products; however, no data were found for carrot puree, vegetable and beef dinner, and turkey and rice dinner.

2.6. Relationship between Bostwick Consistometer readings and apparent viscosity

The investigation of the relationship between the Bostwick readings and the apparent viscosity is one of the objectives of this study. Actually, one is trying to correlate a subjective measurement with an objective measurement.

Rao and Bourne (1977) have correlated Bostwick Consistometer data to measurements on a plastometer of Eolkin. The relationship obtained was valid for all purees investigated and was found to be

$$\log(\eta_B-\eta_A) = 0.075 - 0.065\ BR \qquad \text{............(2.10)}$$

where η_A : apparent viscosity at 400 s^{-1}
η_B : apparent viscosity at 50 s^{-1}
BR : Bostwick reading after 10 s (cm/10s)

It is important to note that this correlation was only valid for shear-thinning purees. Also, they concluded that the structure of the food played an important role during the measurement of the consistency with the Bostwick Consistometer. This method was not suitable for pseudoplastic non-pureed foods; it was believed that adhesion of the non-pureed foods to the gate of the Bostwick Consistometer was the reason.

CHAPTER 3

BOSTWICK CONSISTOMETER AND APPARENT VISCOSITY MEASUREMENTS

The objective of this chapter is to investigate a correlation between the Bostwick Consistometer readings and the apparent viscosity, determined with a concentric cylinder. The main difference between the two techniques is that the Bostwick measurement is an empirical method, while the determination of the apparent viscosity is more a theoretical or fundamental method. However, both are a means of characterizing the fluid.

3.1. Bostwick analysis

3.1.1. Experimental procedure

In this study four baby food products, applesauce, carrot puree, vegetable and beef dinner, and turkey and rice dinner (Gerber Products Company, Fremont, Michigan) were examined at four temperatures : 73, 80, 86 and 92 ^{o}C. All materials were received in jars as finished products, except turkey and rice dinner, which came directly from the process line and was subsequently stored in a cold room.

Since it was the objective to simulate the product in a process line, it can be assumed that in an actual process line, the product is fully broken down. Therefore, the product was stirred in its jar for 12 min until the thixotropy was removed. This was accomplished with a mixer, turning at approximately 400 rpm. A three-blade marine-type mixing propeller was used. The mixing occurred while the jar remained in a temperature controlled waterbath. A lid of a jar was attached to the rod of the mixer to minimize evaporation of the product. This whole procedure was checked for complete breakdown and for temperature with a concentric cylinder (Haake RV-12, see section 3.2.1) and a thermocouple attached to the bob. A thixotropy test was performed by recording the torque over time, while the product was sheared at a constant speed (50 rpm). A raw curve is shown in Figure 3.1. The increase in torque in the beginning was due to the decrease in temperature, which was caused by contact of the colder bob with the product. The slight decrease of the torque further on, was due to the temperature increase of the product again. Almost the same torque was obtained as when started (at time = 0). It can be seen that the thixotropy was completely removed. The temperature was controlled with a waterbath within ± 1 ^{o}C.

The fully broken down and heated sample was poured into the compartment of the Bostwick Consistometer and the gate was opened. Readings were visually recorded after 5, 15, 30 and 60 s. The time was measured with a regular watch.

As pointed out in section 2.1, the method to determine

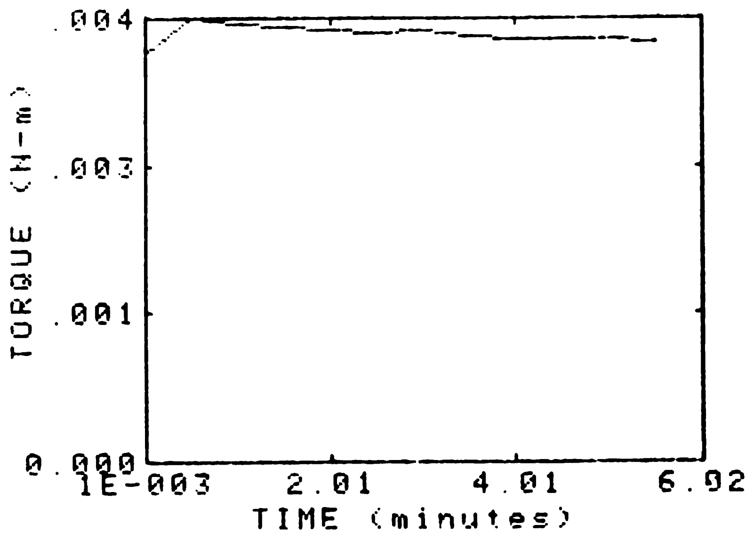


Figure 3.1. Thixotropy test for applesauce at 87 °C.

the consistency of a product with a Bostwick Consistometer is very empirical and subjective. All the experiments were carried out with the same trough and were operated by one person; in that way, the accuracy on the readings was always judged in the same manner. This eliminated the human and instrument variability. The trough was always dry and clean before each run and was washed with water at the same temperature after each run.

3.1.2. Results

The results are presented in Table 3.1. Four replicates were taken for each product at each temperature. The average values are shown and raw data are given in Appendix A.

Table 3.1. Bostwick Consistometer readings for different products.

Product	Temperature (°C)	BR 5s (cm/5s)	liquid	BR 15s (cm/10s)	liquid	BR 30s (cm/30s)	liquid	BR 60s (cm/60s)	liquid
Applesauce	73	8.3		9.0		9.5		10.0	
	80	9.0		9.7		10.3		10.8	
	86	9.9		10.4		10.8		11.0	
	92	10.3		10.8		11.1		11.3	
Carrot puree	73	6.7	7.9	6.7	8.6	6.8	9.2	6.8	10.5
	80	6.9	8.0	6.9	8.5	6.9	9.3	6.9	10.9
	86	7.5	-	7.5	9.5	7.5	10.3	7.5	11.3
	92	7.8	8.6	7.8	8.9	7.8	9.9	7.8	11.3
Vegetable and beef	73	11.1		12.9		14.0		14.9	
	80	11.3		13.0		14.2		14.9	
	86	12.0		13.5		14.2		14.8	
	92	12.1		13.9		14.6		15.1	
Turkey and rice	73	9.2		10.8		11.2		11.6	
	80	9.6		10.9		11.4		11.7	
	86	10.7		11.9		12.3		12.5	
	92	10.9		12.2		12.7		13.0	

3.1.3. Discussion

After some time, the flow pattern of the products was curved with the highest velocity at the center (Figure 3.2). Measurements were taken in the center.

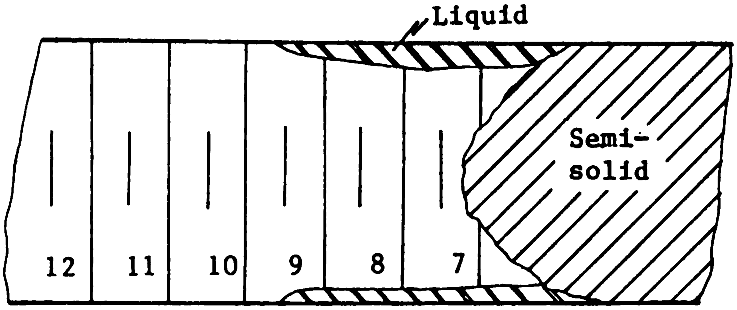


Figure 3.2. Typical flow pattern in a Bostwick Consistometer with a product showing liquid-solid separation.

Carrot puree was the only product which showed a separation of the liquid and the semi-solid portion, and has therefore two values in Table 3.1. The value for the liquid is the average of the values at the left and the right wall. It was observed that the semi-solid part hardly moved and, actually, only the liquid was flowing. This would suggest a high yield stress for the semi-solid portion of carrot puree.

It can be seen from the raw data (Appendix A) that the data were very close together for each replicate. It has no meaning, however, to do a statistical analysis on four data points. The small variances observed can be attributed to the variable amount of product for each run, since it was not accurately measured (just poured into the compartment to the top), and the force needed to release the gate, which produced a different shockwave with each test. This shockwave has not been described in the literature. It was observed that this seemed to be a very important fact. So far, it has received little attention. Different results can be obtained if the shockwave is reduced by holding one's hand on the instrument. Here, the gate was released without holding the instrument.

As expected, the Bostwick readings increased with temperature and obviously with time. Although the liquid part from the carrot puree - the semi-solid part was stationary - seemed to follow the same pattern, the increase in distance with temperature was not always evident. It was believed that the thermal history of the product was responsible for this.

It is known that β-hemicellulose holds water very strongly; however, β-hemicellulose breaks down with a heat treatment and its water-holding capacity decreases significantly (Uebersax, 1986). If a sample is held at a certain temperature for a longer time than another sample, more separation will take place in the first sample. Consequently, the temperature will not be the only factor determining the Bostwick reading for similar products. The reason why this phenomenon did not occur with applesauce was that it was known that applesauce was very susceptible to discoloration (pink color) due to a heat treatment

(Uebersax, 1986), and the samples were never preheated longer than needed.

The other two products were meat products and were flowing regularly in the trough.

The values in Table 3.1 can be viewed as "apparent velocities" and can be expressed in cm/s. This is not a real velocity because the product first accelerates and then decelerates. However, the transition point from acceleration to deceleration, for the products investigated, was believed to be less than 5s. The apparent velocities are presented in Table 3.2. Since carrot puree did not flow, it was omitted. Apparent velocities decreased with time and increased with temperature.

Now, the average rate of deceleration between two observations can be calculated ; those values are also tabulated in Table 3.2. For the same product the deceleration was always slightly higher at higher temperatures. It is interesting to note that the deceleration is almost independent of the product. This means that, once a value at a specified time interval is known, values at other time intervals can be estimated. This can be very helpful in comparing data from the literature. Unfortunately, not many, if any, data at the investigated temperatures and for different testing times, are published to verify this hypothesis.

As mentioned earlier, Davis et al.(1954) found a linear

Table 3.2. Apparent velocities and decelerations in the Bostwick Consistometer for different products.

Product	Temperature (^oC)	Apparent velocity at 5s (cm/s)	Deceleration (cm/s^2)	Apparent velocity at 15s (cm/s)	Deceleration (cm/s^2)	Apparent velocity at 30s (cm/s)	Deceleration (cm/s^2)	Apparent velocity at 60s (cm/s)
Applesauce	73	1.7	0.11	0.6	0.02	0.3	0.003	0.2
	80	1.8	0.12	0.6	0.02	0.3	0.003	0.2
	86	2.0	0.13	0.7	0.02	0.4	0.006	0.2
	92	2.1	0.14	0.7	0.02	0.4	0.006	0.2
Vegetable and beef	73	2.2	0.13	0.9	0.03	0.5	0.01	0.2
	80	2.3	0.14	0.9	0.03	0.5	0.01	0.2
	86	2.4	0.15	0.9	0.03	0.5	0.01	0.2
	92	2.4	0.15	0.9	0.03	0.5	0.006	0.3
Turkey and rice	73	1.8	0.11	0.7	0.02	0.4	0.006	0.2
	80	1.9	0.12	0.7	0.02	0.4	0.006	0.2
	86	2.1	0.13	0.8	0.03	0.4	0.006	0.2
	92	2.2	0.14	0.8	0.03	0.4	0.006	0.2

relationship between the Bostwick measurements and the temperature in a range from 20-90 ^{o}C for tomato puree. Relying on this linearity, the following equations were obtained for the different products at 5 s, including all the raw data (see Appendix A),

applesauce : $BR = .1062\ T + 0.5957$; $r = .93$ ......(3.1,a)

vegetable and beef : $BR = .056\ T + 6.9814$; $r = .80$ ......(3.1,b)

turkey and rice : $BR = .1019\ T + 1.6526$; $r = .87$ ......(3.1,c)

carrot puree (solid) : $BR = .06\ T + 2.18$; $r = .88$ ......(3.1,d)

where T : temperature (^{o}C)
BR : Bostwick Consistometer reading at 5 s (cm/5s)

These regression lines are presented in Figure 3.3 and Figure 3.4. No effort has been made to fit other models, such as non-linear models, since only four points were available. This regression is given to have a better idea of the effect of temperature within the range of 70-92 ^{o}C on the Bostwick Consistometer readings. Turkey and rice dinner and applesauce were the most temperature sensitive, while the other products were only half as sensitive.

The Bostwick reading for applesauce, reported by Rao and Bourne (1977), 6.7 cm/10s at 25 ^{o}C, is, considering the

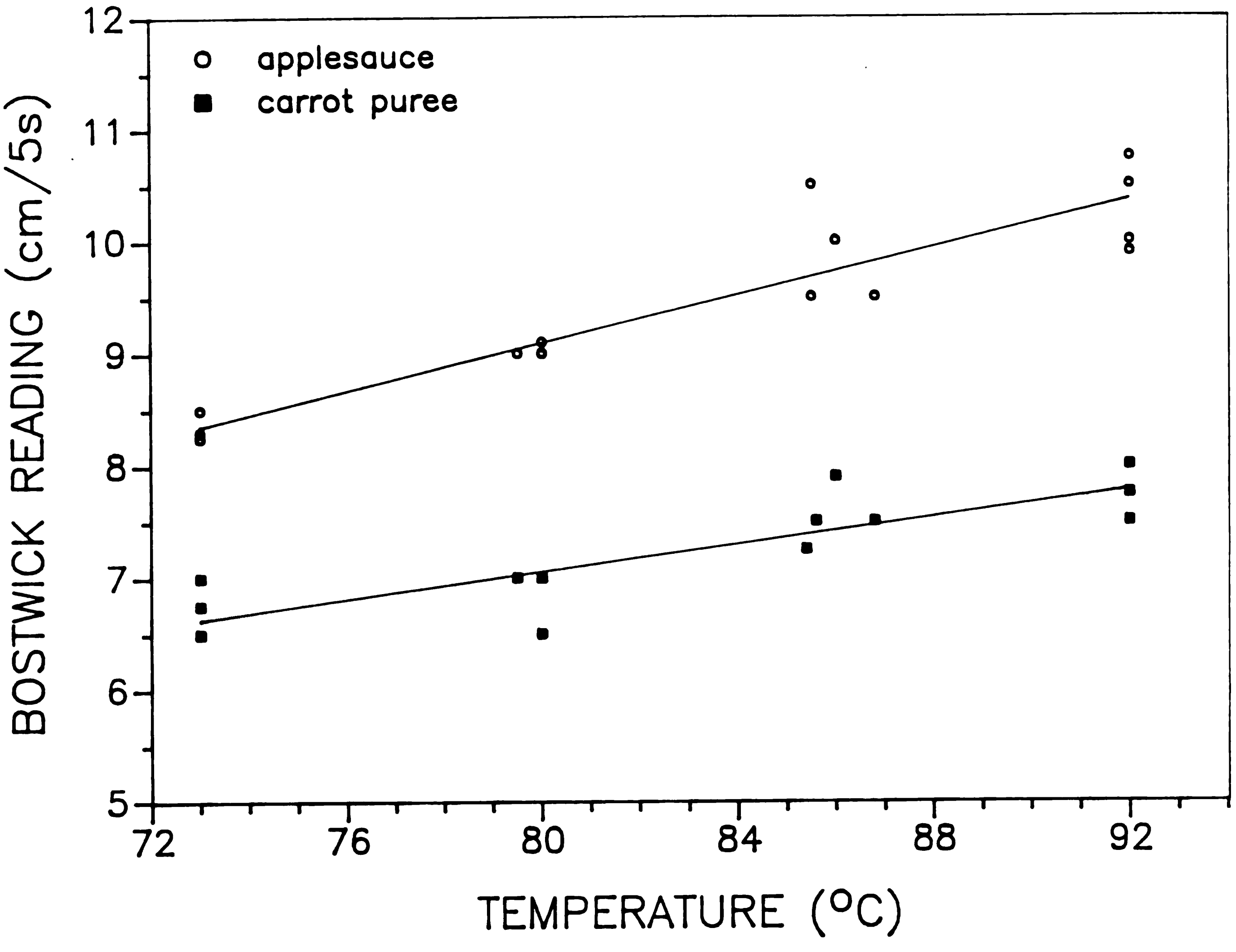


Figure 3.3. Effect of temperature within the range of 73 °C to 92 °C on Bostwick Consistometer readings (applesauce and carrot puree).

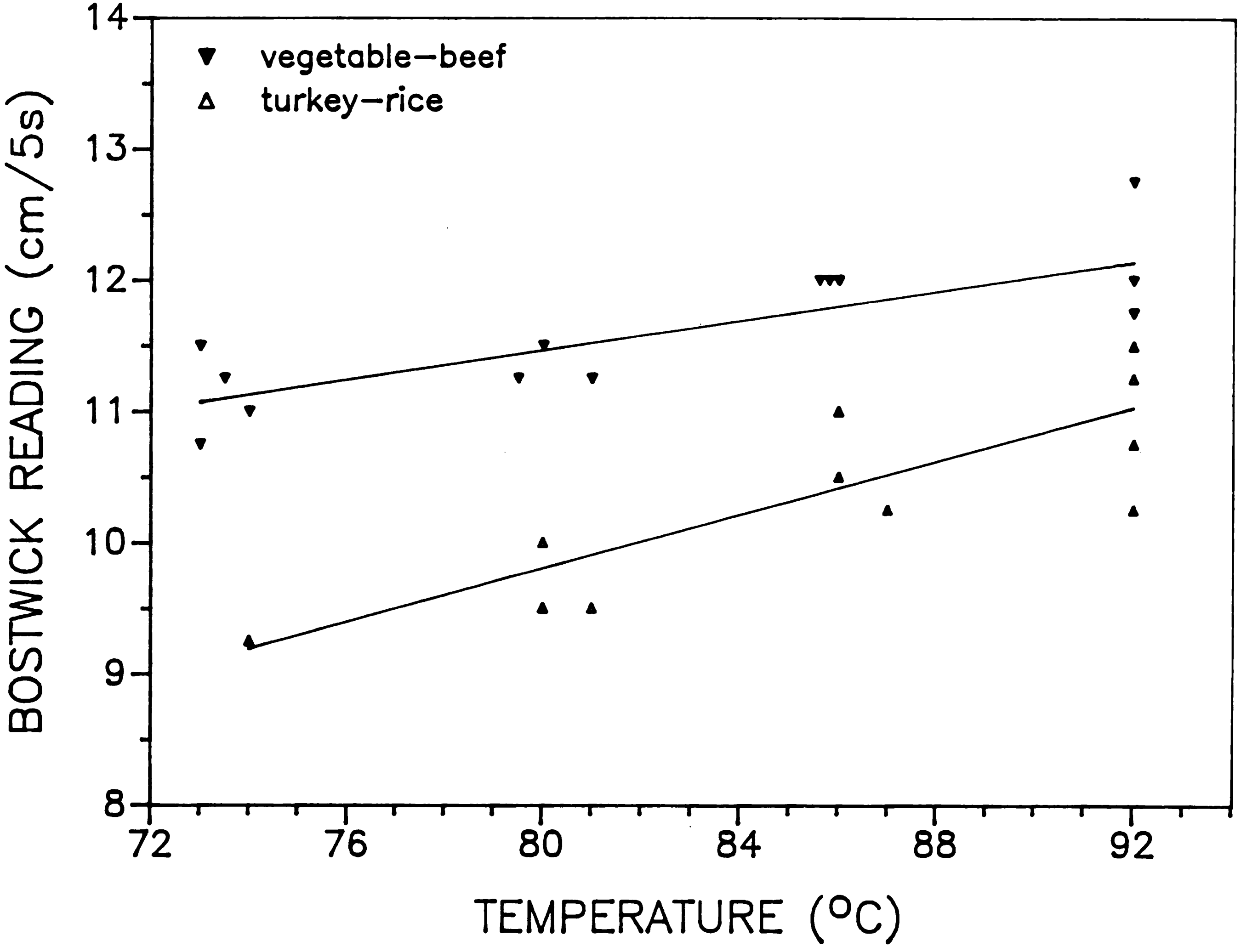


Figure 3.4. Effect of temperature within the range of 73 ^{o}C to 92 ^{o}C on Bostwick Consistometer readings (vegetable-beef and turkey-rice).

regression, not in good agreement. Possible reasons are that the applesauce used in their study was unstrained as opposed to strained (used in this study), the extrapolation to room temperature is not acceptable or the confidence in the regression model is too small. The value for carrot puree was 2.68 cm/10s at 25 ^{o}C; no separation was mentioned, which supports the thought that β-hemicellulose was responsible for this phenomenon.

3.2. Rheological parameters obtained with a concentric cylinder viscometer

3.2.1. Materials and methods

A Haake RV-12 concentric cylinder viscometer was used to collect data for the same baby food products considered in the Bostwick Consistometer. The inner cylinder, the bob (MVI), was rotating, while the outer cylinder, the cup, was stationary. The height of the bob was 60.32 mm, the radius was 20.04 mm. The radius of the cup was 21.00 mm. The torque was measured and transformed into a proportional electrical signal by the measuring drive unit (M150) .

A Haake PG-142 was connected to the measuring drive unit to manually control the speed of the bob. The whole system was connected to a HP-3497A (HP meaning Hewlett-Packard) data acquisition system, which was connected to a HP-85 via a 82937A HP-IB interface. This was developed in the food rheology lab at Michigan State University. The whole system was calibrated over the full scale of the load cell. Known weights were used to generate a known torque. The voltage was displayed on the data acquisition system and the calibration factor was found to be .00290 N m/V (the previous factor was .00291). Then calibration fluids were run with a Newtonian viscosity of 0.0505 Pa s and 0.985 Pa s in a shear rate range of, respectively, 5-350 s^{-1} and 5-100 s^{-1}. No further adjustments had to be made; the values were accurate to ± 0.75%.

Samples were treated in exactly the same way as they were treated for the Bostwick measurements. They were heated in a waterbath and stirred until thixotropy was removed (12 min), while the product remained in the jar. Then, the product was poured in the preheated cup and an additional check for thixotropy was performed for each test. The torque was recorded at a speed of 50 rpm and a pattern similar to Figure 3.1 was observed. The rheological measurements were only taken when equilibrium was reached. Four replicates were performed for each test. The content of each jar provided two samples.

Once the product was in the cup, the temperature control was established with a temperature vessel (Haake FC-3) built around the cup. The vessel had three functions : it connected the sensor system to the measuring drive unit, centered the bob and the cup and controlled the temperature of the tested material. The vessel had two hose fittings, which were connected to the waterbath. The temperature could be controlled within ± 1 °C. A small protective lid (Haake) covered the samples and prevented evaporation. Tests were performed at four temperatures : 73, 80, 86 and 92 °C. The speed ranged from 2-150 rpm, resulting in a shear rate range of approximately 10-400 s^{-1}, depending on the product and temperature. Twenty five data points were taken in this range for each test. Soluble solids content was measured with an Abbe-3L Refractometer (Bausch and Lomb). Values for applesauce and carrot were 9.0% and 6.8%, respectively. The total solids content was determined with a drying oven at 103 °C for 24 hours. Values for applesauce, carrot puree, vegetable and beef, and turkey and rice dinner were 20.7%, 18.1%, 25.3% and 20.1%, respectively.

3.2.2. Results

A computer program on the HP-85 provided the raw data for each test : the speed (rad/s) and the corresponding torque (N m). They were, together with the geometric data, substituted into Equations 2.4 and 2.5 to yield data for the shear stress, σ_b, and the shear rate, $\dot{\gamma}_b$. A power law model was then fitted to obtain a rheogram. Following this, the shear stress was divided by the shear rate to yield the apparent viscosity. Then, the apparent viscosity was plotted against the shear rate.

Figures 3.5 through 3.8 plot the regression lines for the different products at the different temperatures. The

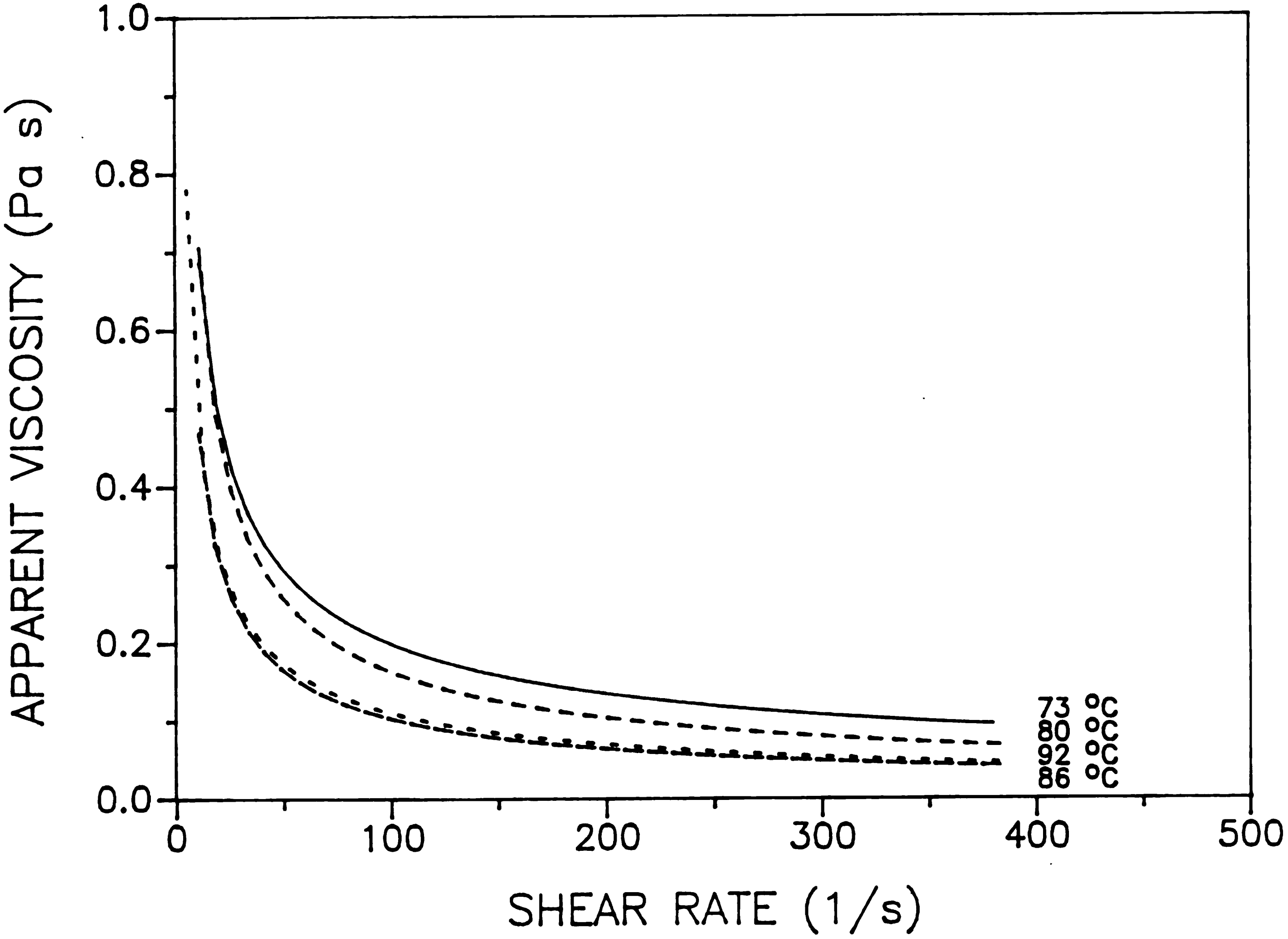


Figure 3.5. The apparent viscosity as a function of the shear rate at different temperatures for applesauce.

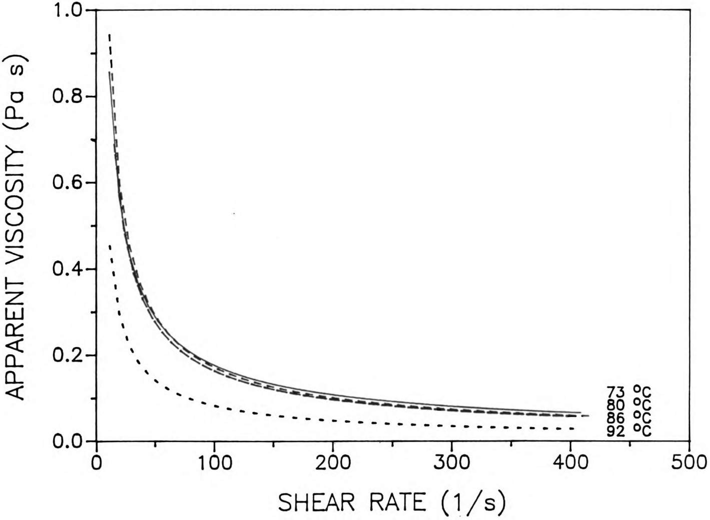


Figure 3.6. The apparent viscosity as a function of the shear rate at different temperatures for carrot puree.

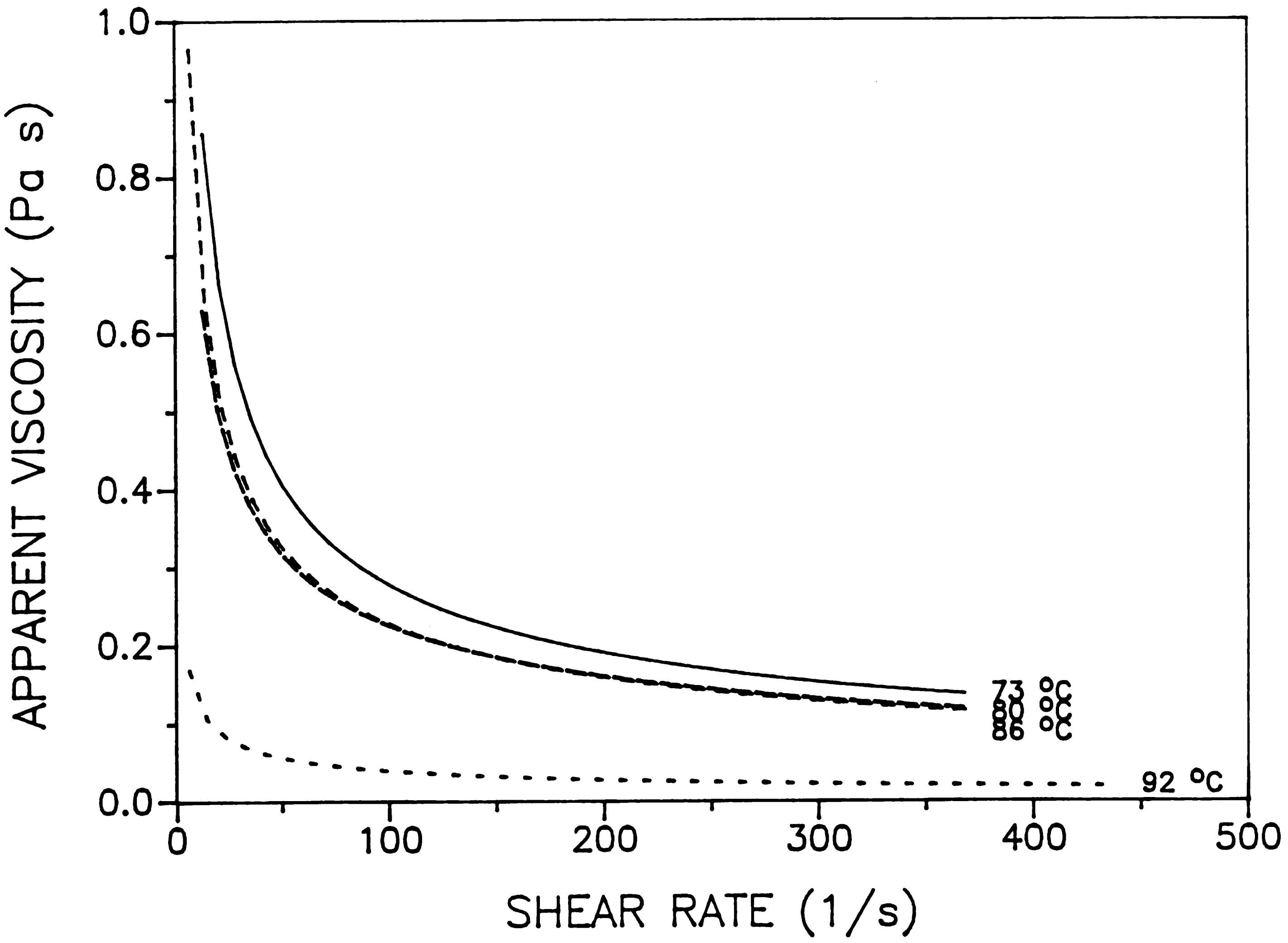


Figure 3.7. The apparent viscosity as a function of the shear rate at different temperatures for vegetable and beef dinner.

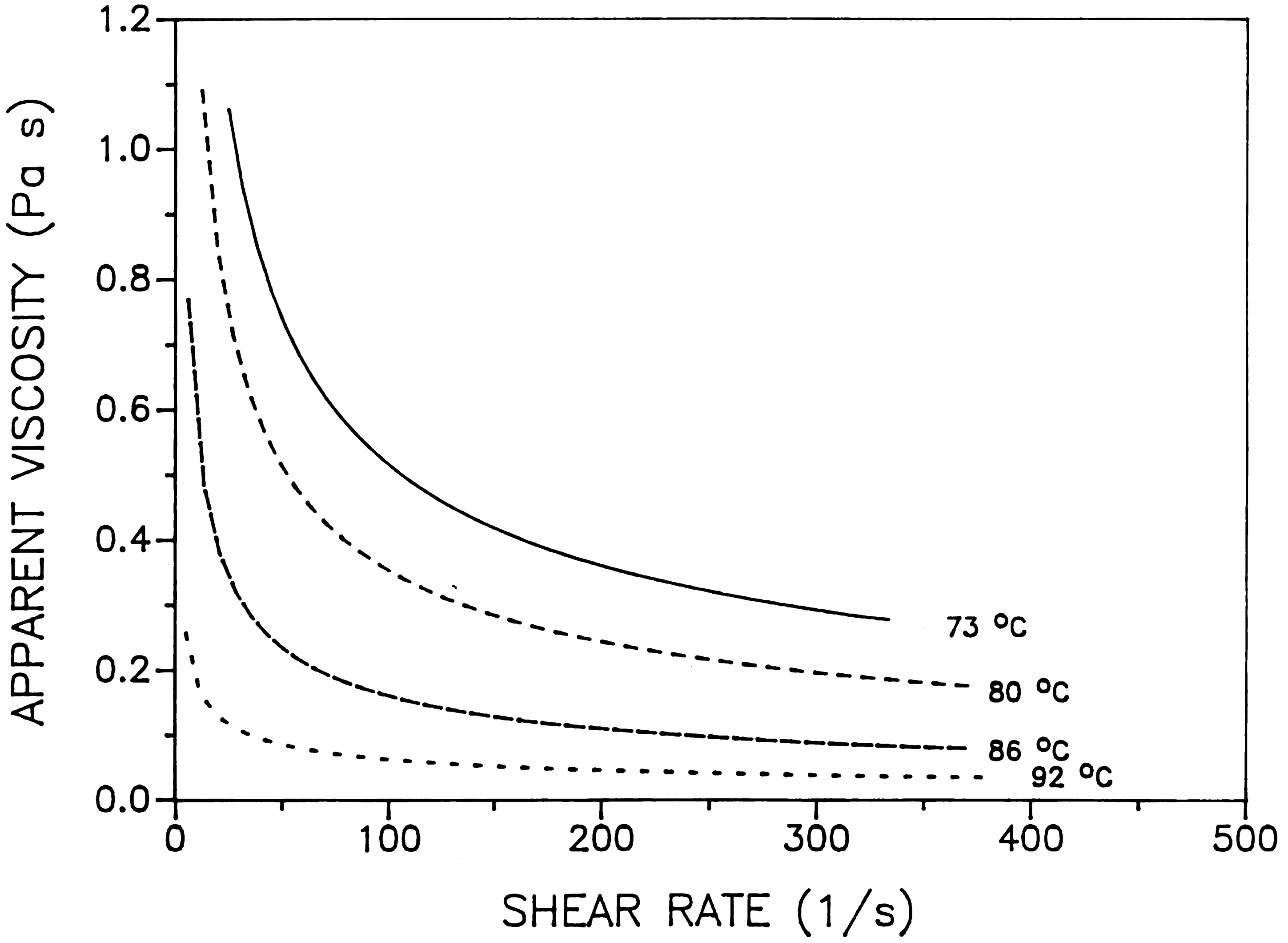


Figure 3.8. The apparent viscosity as a function of the shear rate at different temperatures for turkey and rice dinner.

rheological parameters and their limits, evaluated at 95%, are given in Table 3.3 and Table 3.4, respectively. Each regression line represents approximately 100 data points. The rheological parameters for the individual runs are given in Appendix B and the raw data in Appendix C.

3.2.3. Discussion

All the assumptions made in section 2.3.1 were considered. The only assumption which could not be checked was laminar flow. A criterion to predict the transition point in a concentric cylinder has been proposed for Newtonian fluids by Dealy (1982). When rotating the inner cylinder, secondary flow will occur if

$$\frac{\Omega R_b \rho h}{\mu} \left[\frac{h}{R_b}\right]^{1/2} > 41 \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.2)$$

This can be checked for the available data. With $h = 60.32$ mm, $R_b = 20.04$ mm, $\rho = 1055\ \mathrm{kg/m^3}$ (turkey-rice), Equation 3.2 becomes

$$\frac{\Omega}{\mu} > 18.5 \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.3)$$

The difficulty is now to substitute for the Newtonian viscosity. One can use the apparent viscosity, but it is known that this is usually not a good approach. If this is

Table 3.3. Viscometric constants for different products in concentric cylinder viscometer.

		POWER LAW				HERSCHEL-BULKLEY				
Product	Temperature (^oC)	K ($Pa\ s^n$)	n (-)	r^2	SSE	K ($Pa\ s^n$)	n (-)	σ_o (Pa)	r^2	SSE
Applesauce	73	2.59	0.442	0.986	0.017	2.09	0.566	0.079	0.990	0.012
	80	3.24	0.350	0.947	0.100	3.37	0.330	0.007	0.947	0.099
	86	2.30	0.324	0.995	0.003	2.36	0.312	0.003	0.995	0.003
	92	2.19	0.349	0.975	0.030	2.21	0.347	0.001	0.975	0.030
Carrot puree	73	4.55	0.293	0.904	1.091	4.25	0.375	-0.066	0.908	1.036
	80	5.80	0.234	0.850	2.671	5.52	0.298	0.051	0.852	2.627
	86	5.25	0.245	0.967	0.133	5.28	0.241	0.002	0.967	0.133
	92	2.98	0.220	0.985	0.032	3.08	0.189	0.009	0.985	0.031
Vegetable and beef	73	3.42	0.454	0.849	0.597	5.82	0.156	0.147	0.877	0.480
	80	2.47	0.481	0.948	0.112	2.75	0.416	0.037	0.950	0.108
	86	2.15	0.509	0.998	0.002	2.33	0.466	0.023	0.998	0.002
	92	0.42	0.486	0.706	0.028	0.53	0.338	0.013	0.711	0.028
Turkey and rice	73	5.54	0.484	0.937	0.390	5.43	0.493	-0.012	0.937	0.390
	80	4.12	0.466	0.921	0.340	4.28	0.446	0.017	0.921	0.340
	86	1.96	0.456	0.977	0.043	2.04	0.430	0.012	0.977	0.042
	92	0.49	0.554	0.784	0.053	0.45	0.673	-0.036	0.789	0.051

Table 3.4. Confidence limits at 95% for the power law constants for different products.

Product	Temperature (°C)	K_{low} (Pa s^n)	n_{low} (-)	K_{high} (Pa s^n)	n_{high} (-)
Applesauce	73	2.44	0.427	2.74	0.457
	80	2.91	0.321	3.57	0.379
	86	2.23	0.315	2.37	0.333
	92	2.07	0.331	2.33	0.367
Carrot puree	73	4.09	0.249	5.00	0.337
	80	5.06	0.168	6.54	0.300
	86	4.83	0.219	5.66	0.271
	92	2.83	0.198	3.12	0.242
Vegetable and beef	73	2.95	0.416	3.90	0.492
	80	2.28	0.460	2.67	0.503
	86	2.11	0.504	2.20	0.514
	92	0.33	0.430	0.51	0.541
Turkey and rice	73	5.00	0.461	6.07	0.507
	80	3.66	0.437	4.58	0.495
	86	1.86	0.441	2.06	0.471
	92	0.42	0.513	0.56	0.594

done, transition points ranging from 4-7 rad/s (38-67 rpm) are predicted, depending on the product and temperature. However, it was thought that the flow was still laminar. The problem is very complex and not well understood for non-Newtonian materials.

Applying Equation 2.4 required a polynomial to calculate the derivative ,s , from a plot of $\ln\Omega$ versus $\ln\sigma$. A third order polynomial was fitted (the third degree coefficient was always zero). The resulting correlation coefficient was always higher than 0.99. Equation 2.4 was further simplified by neglecting the correction term s^2 s' f(t). As pointed out by Krieger (1968) :

> "Since f(t) has a maximum value of about 0.1, it is evident that even the first correction ... will always be small and frequently negligible."

Here, typical values for s were 0.25 and for s' a value of 0.8. This makes the correction term even smaller giving it a magnitude of approximately 0.02.

Instead of calculating the rheological parameters for each run separately - those results are given in Appendix B - and then averaging, a non-linear regression analysis has been carried out on the combined data from the four replicates (100 data points). The same technique was used by Barbosa and Peleg (1983). Both the power law model and the Herschel-Bulkley model were fitted. The sum of the squares of the errors (SSE) for the Herschel-Bulkley model was always less than or equal to the one for the power law model, indicating a better fit with the Herschel-Bulkley model (Table 3.3).

In three cases, the yield stress was calculated to be negative, which is physically not possible. In the other cases, the calculated yield stress was so small, that it can be said to be zero. In practice, it is not even possible to measure such small yield stresses. Therefore, from a rheological standpoint, the power law model obtained by a non-linear regression model was thought to be the best model.

From the Bostwick Consistometer observations it was expected that carrot puree would have a yield stress, since the semi-solid part stayed stationary. The data obtained here did not show a yield stress. In the concentric cylinder, the product was homogeneous and no separation could take place; in the Bostwick Consistometer, on the other hand, separation could readily occur and, essentially, a different product was evaluated. This is an example of how a Bostwick Consistometer can provide totally different information, because it reports just one value.

A higher temperature, generally, results in a lower apparent viscosity, which can be observed in Figures 3.9 and 3.10. However, it seems that this is a function of the product under consideration.

As opposed to the usual linear fit after a logarithmic transformation, a non-linear regression was carried out on the Arrhenius equation (Equation 2.8). The apparent viscosity was evaluated at 200 s^{-1}. Figures 3.9 and 3.10 represent the regression lines through the apparent viscosities of the four replicates at each temperature for the different products. The parameters obtained by this method are presented in Table 3.5.

Results show that the average flow behavior index is proportional to the activation energy. The higher the value of n (less pseudoplastic fluid), the higher the activation energy and, following Equation 2.8, the greater the effect of temperature on the apparent viscosity. This is in agreement with earlier observed data on fruit purees and juices obtained by Holdsworth (1971).

The fit was worst for carrot puree, indicating that there was almost no temperature dependency in this range. Applesauce and vegetable and beef dinner showed a small temperature effect, while turkey and rice dinner was the most sensitive product. The same trend was observed with the Bostwick Consistometer, although applesauce was a little more sensitive in those low shear rate ranges (Figures 3.3 and 3.4).

Table 3.3 indicated that the flow behavior index was not a function of temperature, but the consistency coefficient seemed to be affected significantly by temperature variations. This effect is the same as that reflected in the apparent viscosity, because the latter was evaluated at a constant value and n was not a function of

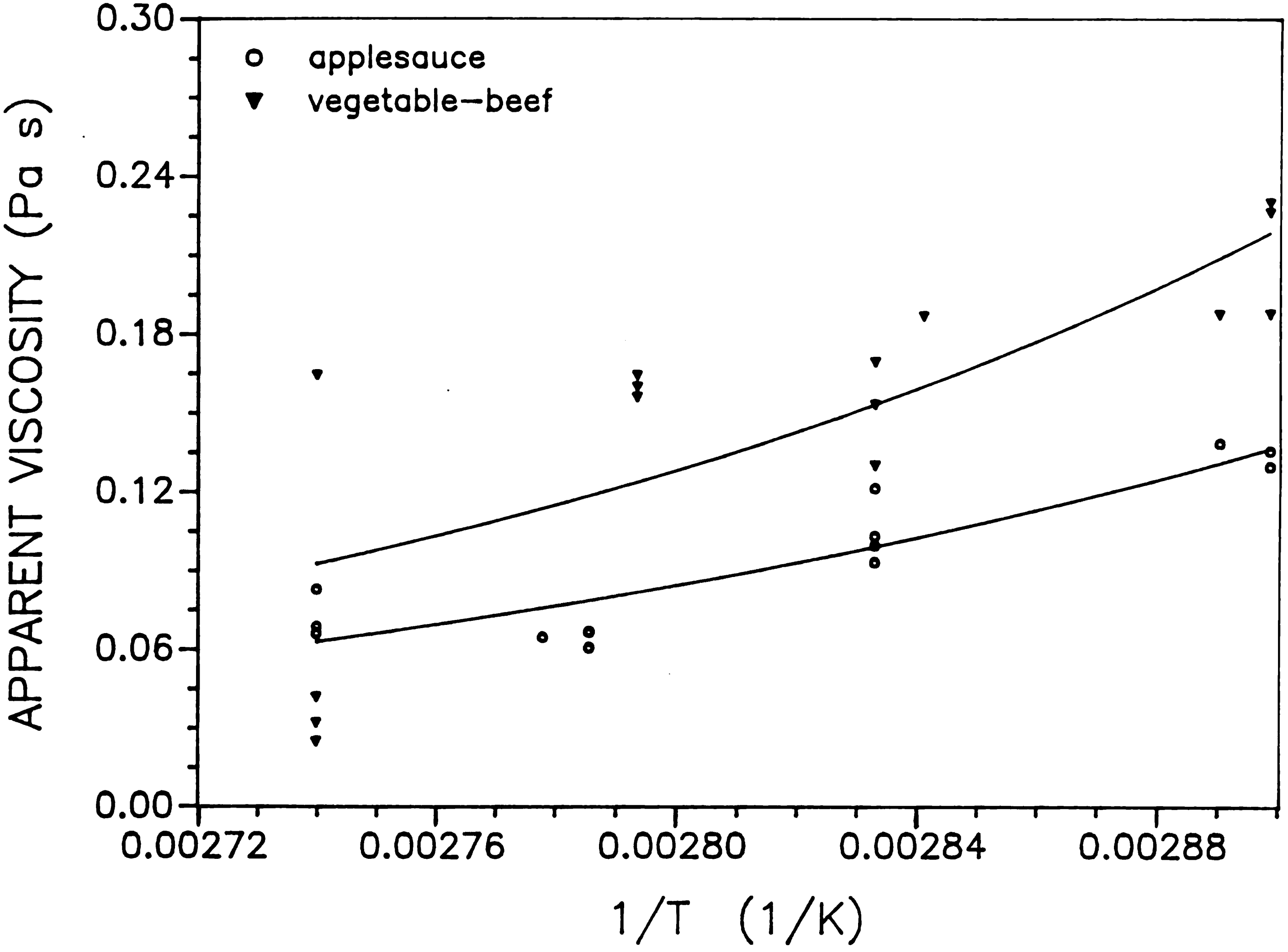


Figure 3.9. Effect of temperature within a range of 73 °C to 92 °C on the apparent viscosity (applesauce and vegetable-beef).

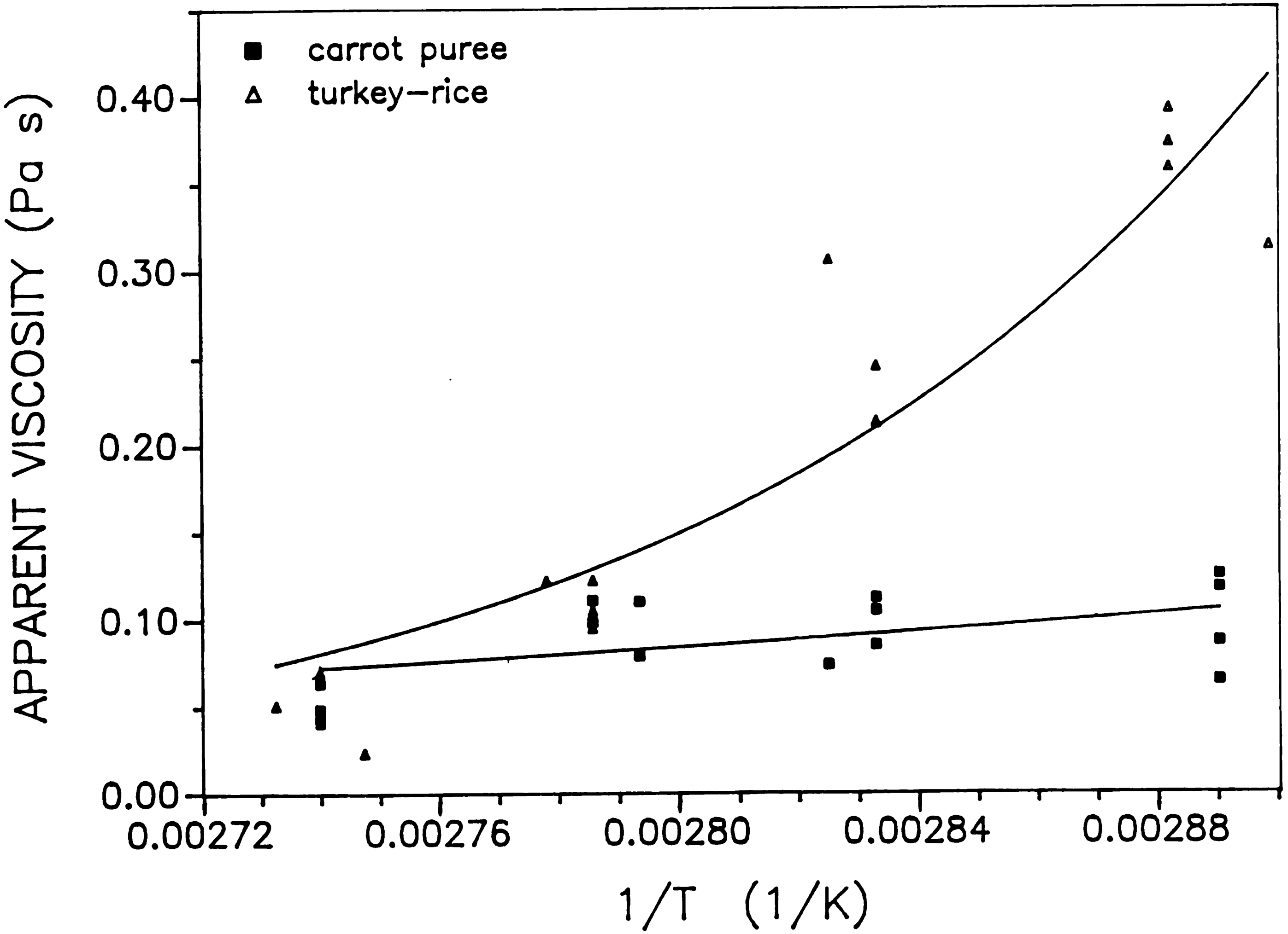


Figure 3.10. Effect of temperature within a range of 73 °C to 92 °C on the apparent viscosity (carrot puree and turkey-rice).

Table 3.5. Activation energy and constant for different products.

Product	A (Pa s)	E_a (kJ/mol)	r
Applesauce	$9.2\ 10^{-6}$	40.758	0.92
Carrot puree	$7.4\ 10^{-3}$	20.869	0.50
Vegetable and beef	$3.2\ 10^{-6}$	45.157	0.78
Turkey and rice	$4.6\ 10^{-12}$	85.539	0.93

temperature. Consequently, it is sufficient to relate the temperature to the apparent viscosity only.

3.3. Relationship between Bostwick Consistometer measurements and rheological parameters

In this section the data from the two previous sections are brought together. It is known that the Bostwick Consistometer yields data at very low shear rates, while the data from the concentric cylinder viscometer are evaluated at much higher shear rates. The two instruments are in a sense not compatible. For the Bostwick Consistometer a distance is reported and for the concentric cylinder viscometer two or more parameters are investigated, eventually leading to the apparent viscosity. However, the apparent viscosity was evaluated at a constant shear rate of 200 s^{-1} (see section 5.3) to investigate a relationship.

First, each product was considered separately. Previously, all relationships were developed with the raw data; here, the Bostwick readings and the rheological parameters were measured using different samples and consequently, an average value had to be used. This brings the number of data points down to four for each product. Those four points represent the four different temperatures. Figure 3.11 illustrates the pattern of the relationship, for each product (the temperature is only indicated for one product). Data points between the different temperatures are only connected for the purpose of illustration.

As expected, the apparent viscosity tended to be inversely proportional to the Bostwick readings. Applesauce and turkey and rice dinner showed the best relationship and suggested a straight line. The activation energy of turkey and rice was very high, and the slope of both products in the Equations 3.1 was higher than the other products. Both are indications of their sensitivity to temperature. The other products were much less sensitive and only a trend was visible : a decrease in the apparent viscosity with increasing temperature.

Next, all products can be considered at one particular temperature. This has been investigated by Rao and Bourne (1977) for 28 different products at room temperature. They found a single relationship for all non-pureed foods (Equation 2.10).

It has already been shown (Figure 3.11) that no such

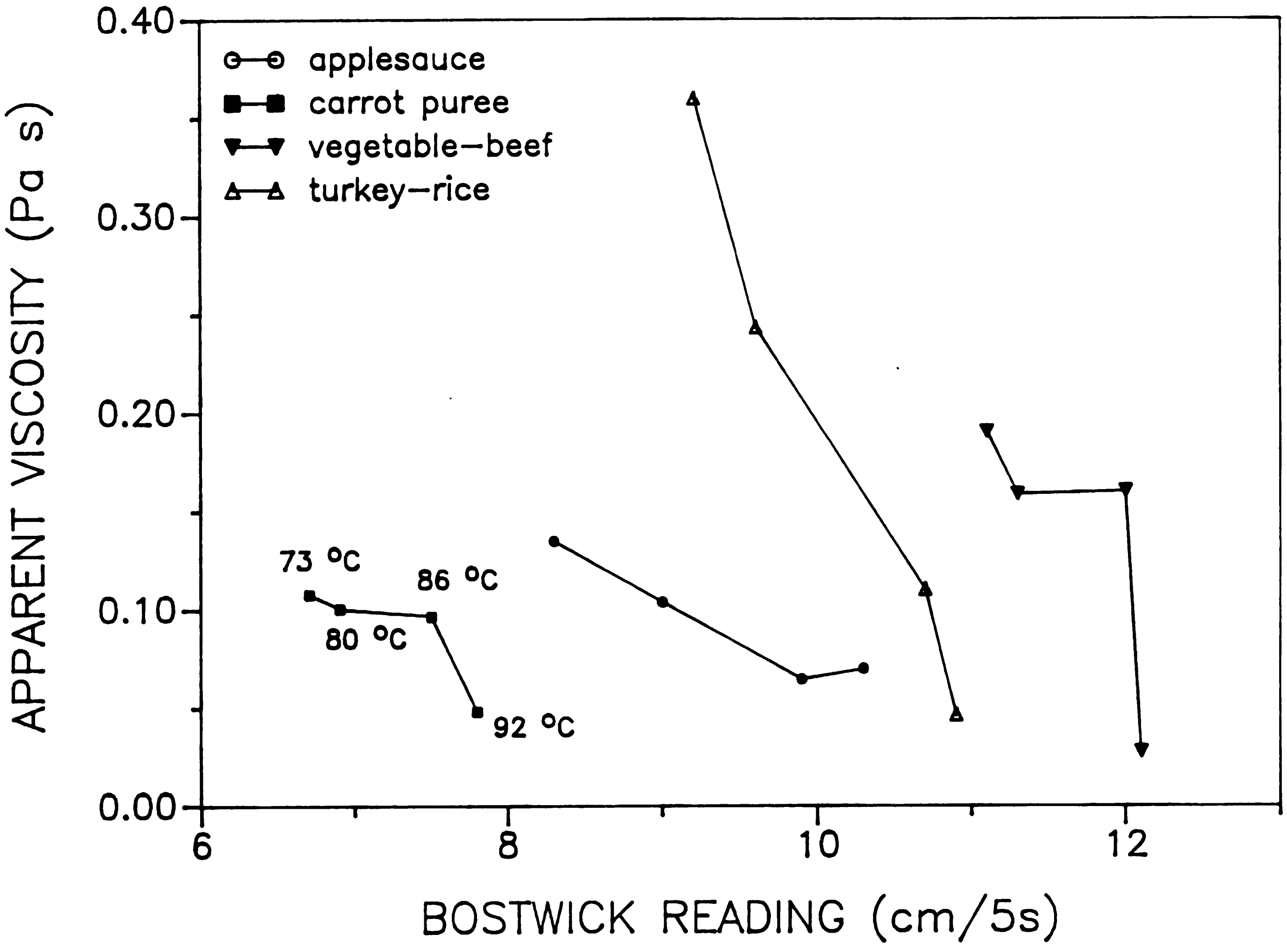


Figure 3.11. Bostwick Consistometer readings versus apparent viscosity, evaluated at 200 s^{-1}.

relationship existed between the Bostwick readings and the apparent viscosity. Connecting each first point of every product shows the pattern at 73 °C; connecting each second point at 80 °C, etc... One would expect a lower apparent viscosity for a higher Bostwick reading and vice versa. Here, the points were scattered. To illustrate this, the results of this study, for the lowest temperature and at a testing time of 5 s, were plotted versus the results from Rao and Bourne (1977) (Figure 3.12). As seen, their results were not reproducible in this study.

Finally, the slope of the regression lines (equations 3.1) can be plotted versus the activation energies. Again a scatter was obtained.

Summarizing, it can be said that the more the product was temperature sensitive, the better the correlation with the Bostwick reading. A single relationship for all products was not found.

3.4. Conclusions

In this chapter the rheological properties of four baby food products have been determined in two ways : empirical and theoretical. No real agreement has been found between the two methods, except for the turkey and rice dinner and applesauce.

The combination of the temperature insensitivity of the products, the small number of different products, and the

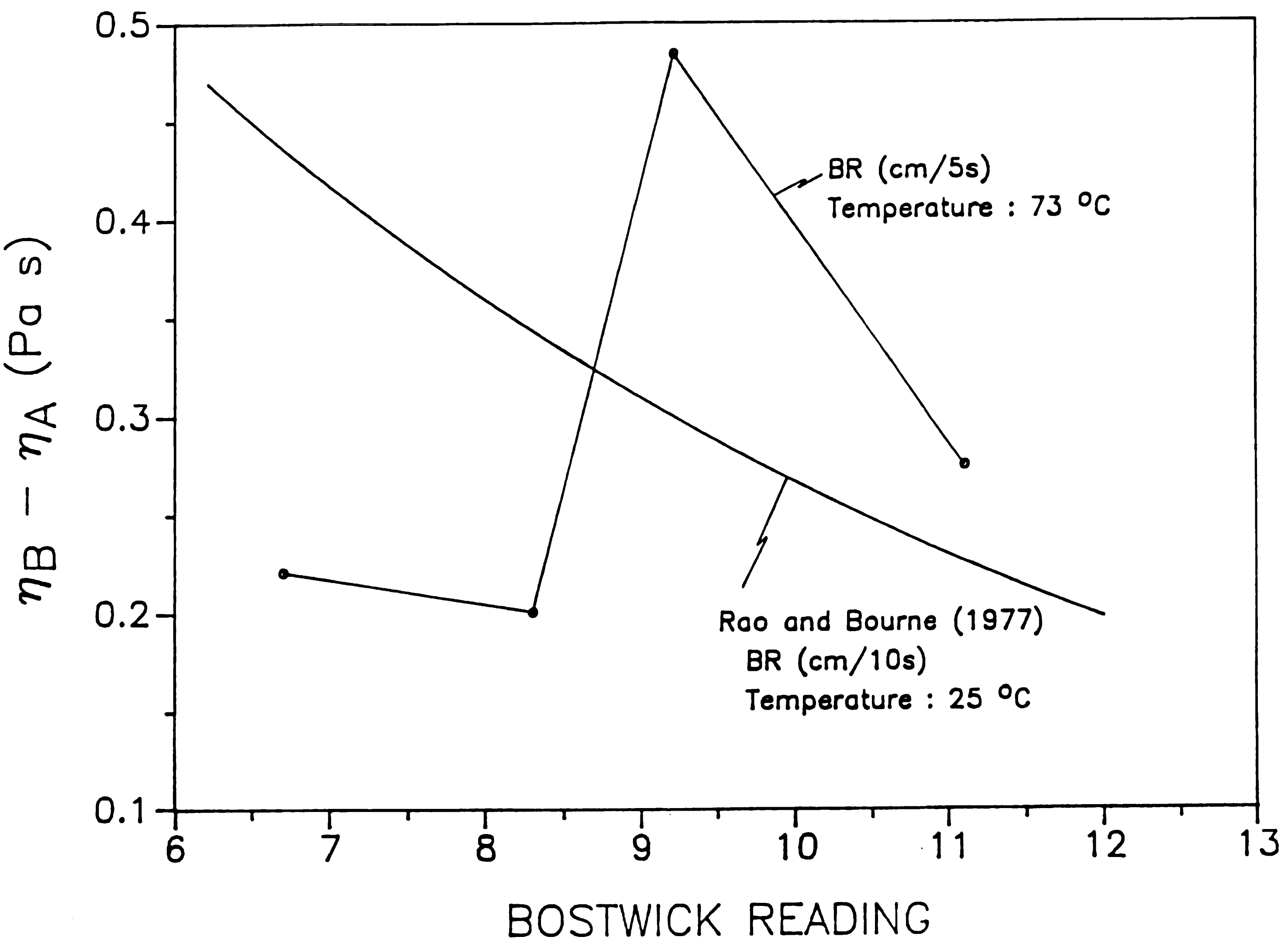


Figure 3.12. Comparison of data in this study with data obtained by Rao and Bourne (1977).

small temperature range investigated, made it extremely difficult to build a true relationship. The results at a constant temperature, obtained by Rao and Bourne (1977) could not be reproduced.

Although no relationship has been found, the target change from Bostwick readings to apparent viscosities can still be made. Quality control can now be based on the apparent viscosity, however, this will be product specific. How this can be done in an on-line viscometer will be outlined in the next chapter.

CHAPTER 4

TUBE VISCOMETER

4.1. Introduction

Rheological properties of materials can be evaluated from the pressure drop and the volumetric flowrate in a pipe. This technique is very useful in the industry, because it provides on-line information and thus on-line quality control.

There is no need to work with delicate laboratory instruments, which are often expensive, complicated and time-consuming. No extra cleaning is required as opposed to commercially available on-line rheometers. Cheng et al. (1985) reviewed and evaluated the current applications of some commercial process control viscometers. In their discussion they point out that :

> "Commercial instruments may exist to do a good job; but the cost has a high profile. ... Homemade instruments have been successfully developed ... "

This study is a first step toward a self-made on-line viscometer. In this chapter tests were performed with different sizes of tube viscometers. In the next chapter a sensitivity analysis will be presented along with some criteria.

4.2. Materials and methods

A schematic view of the total system is given in Figure 4.1. Two tanks were available : one tank (D = 0.7 m; h = 0.7 m) held water for cleaning purposes, while the other tank (D = 0.8 m; h = 0.7 m) contained the product. A mixer stirred the product continuously at a low speed (40-50 rpm) and the whole system was made out of stainless steel.

Prior to testing, the product was stored in a cold room. A volume of 230 liters of turkey and rice dinner was divided into three equal parts, to run three different tests. Three tube viscometers were available with an inside diameter of 0.0127 m, 0.00635 m and 0.003175 m.

A positive displacement rotary pump, variable speed, size 60 (Waukesha, Abex Corp., Wisconsin), was installed in the system. The displacement of this pump was 0.568 l/min with a maximum allowable pressure to insure seal integrity of 1379 kPa.

A bypass was constructed just after the pump to allow for a lower flowrate. An air-to-close valve was used to control the flowrate. An additional air-to-close valve was mounted at the end of the tube viscometer, to pressurize the system and hence control the flowrate. When air was applied, the orifice at the end was physically more closed, putting more fluid through the bypass.

Flexible hoses were attached to the end of the bypass

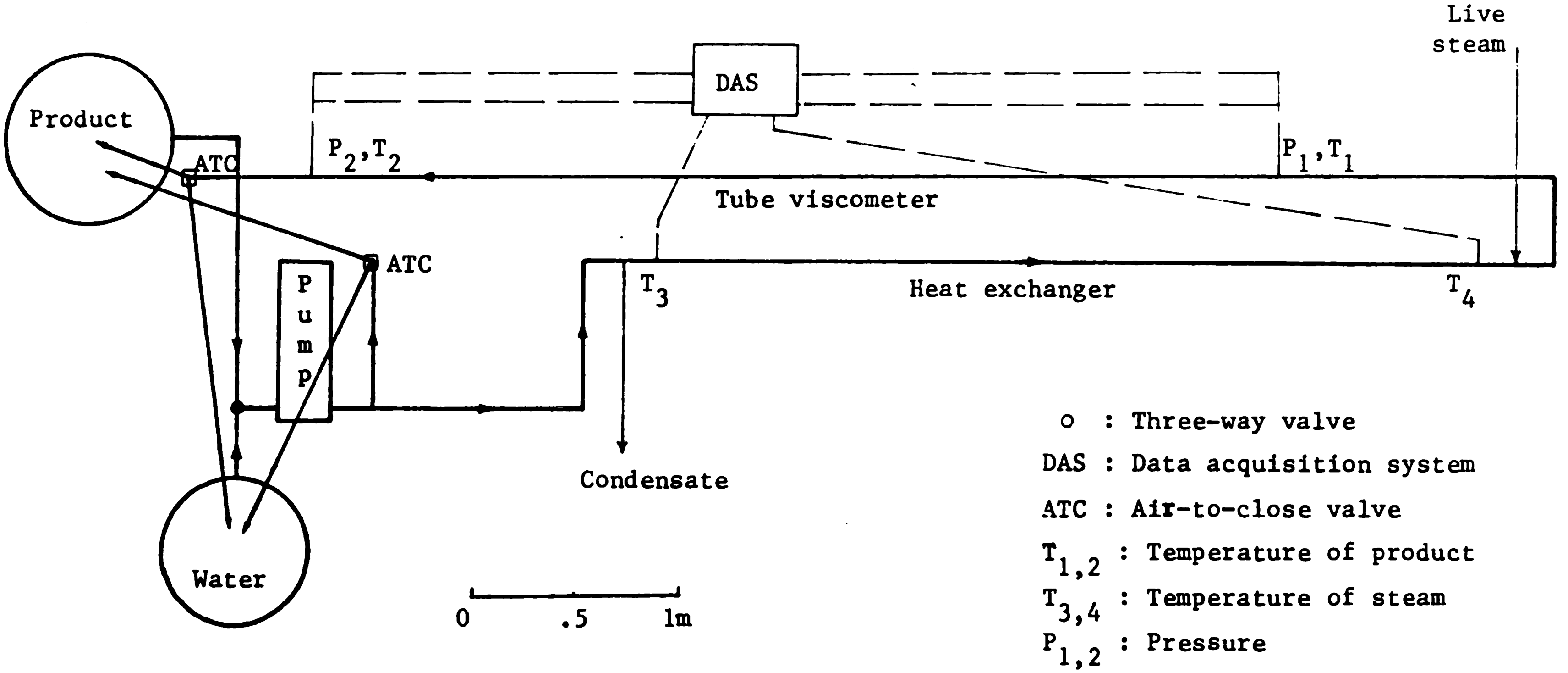


Figure 4.1. Schematic diagram of the tube viscometer set-up.

and the tube viscometer which made it easy to switch from vat to vat. These hoses, just like the leading pipes in the whole system, had an inside diameter of 0.0381 m.

Tests were performed at two different temperatures : 73 °C and 80 °C. The product was heated in a double tube heat exchanger with steam flowing countercurrently in the outside annulus. The inside diameter of this inner pipe was 0.022 m. Two thermocouples were inserted in the steam jacket to monitor (then manually control) the temperature. The steam pressure controlled the temperature.

The tube viscometer was connected directly after the heat exchanger. Two pressure transducers and two thermocouples were installed. The tubes were insulated to reduce the heat losses and to keep a constant temperature at the wall. The distance between the two transducers was 4.594 m for the tubes with a diameter of 0.0127 m and 0.00635 m; the length was 5.193 m for the tube with a diameter of 0.003175 m. The distance from the entrance of the tube viscometer to the first pressure transducer was 1.33 m, 1.33 m and 0.73 m respectively; the distance from the second pressure transducer to the end was always 0.73 m.

The volumetric flowrate was measured by collecting and weighing samples after a fixed period of time. Due to the failure of the available flowmeter, no continuous recording was possible. Product was always collected for exactly one minute.

Density measurements were taken at the time of the test by weighing a sample and measuring its volume.

The four thermocouples and the two pressure transducers were connected to a data acquisition system. A 21X micrologger (Campbell Scientific Inc., Logan, Utah) was used to collect the data every second and average them over 1 minute. It was carefully noted down at which minute the flow rate was taken, to completely agree with the average values, over the same minute, of the micrologger. An inside clock reported the time and was set exactly at the same time as a wrist watch. The execution time which was needed to average and store the data from the six transducers, and to store the real time was, according to the manual, 0.5142 s. This was perfectly in the safe range. Data were downloaded on a tape recorder and from there to a floppy disk, using the C20 Cassette Interface (Campbell).

All the thermocouples were checked in ice water and boiling water and were within 0.5 ^{o}C of the expected values. The pressure transducers, model 808 (Sensotec, Columbus, Ohio) were a flush diaphragm type and were temperature compensated up to 160 ^{o}C. The transducers were bonded strain gage type; they were wired into four active arms of a Wheatstone Bridge and bonded to the sensing element of the transducer. The excitation voltage was 5 VDC. The range covered was from 0-1379 kPa.

The pressure transducers were calibrated with a dead weight tester, type #1300 (Ashcroft, Manning Maxwell and

Moore, Bridgeport, Conn.). Known weights produced a known pressure. Calibration was performed before and after the experiments with differences less than 0.1% found. The multipliers as an input in the data acquisition system were calculated to be 67.235 and 67.032; the off-sets were -8.6573 and 7.9845 for the serial numbers 161287 and 161290, respectively.

4.3. Results

The rheograms obtained by the tube viscometers are given in Figures 4.2 (at 73 ^{o}C) and 4.3 (at 80 ^{o}C) for two and three different diameters, respectively. The power law coefficients, and their limits at 95%, are given in Table 4.1. A Herschel-Bulkley fit always gave a negative yield stress, which was physically not acceptable. The average temperature for the whole run is also indicated. The raw data for each run are given in Appendix D.

4.4. Discussion

Using the Rabinowitch-Mooney equation (Equation 2.6), required fulfillment of the assumptions made in section 2.3.2. The most important criterion was that of laminar flow. The prediction of the transition point for non-Newtonian fluids in pipes is well established (Hanks and Ricks, 1974). Their equations were programmed by Garcia and Steffe (1987).

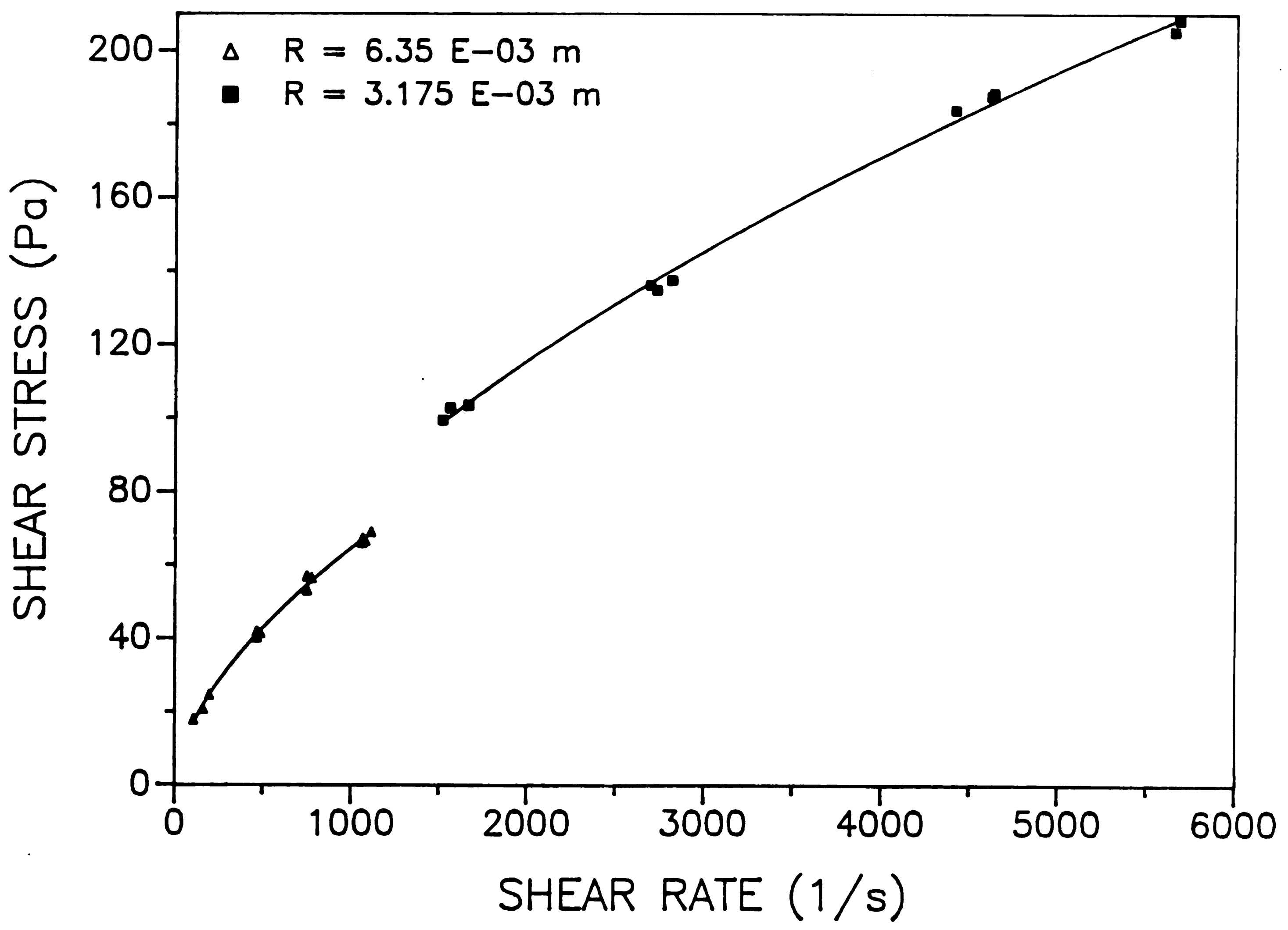


Figure 4.2. Rheogram for two different tube viscometers at 73 °C (turkey and rice).

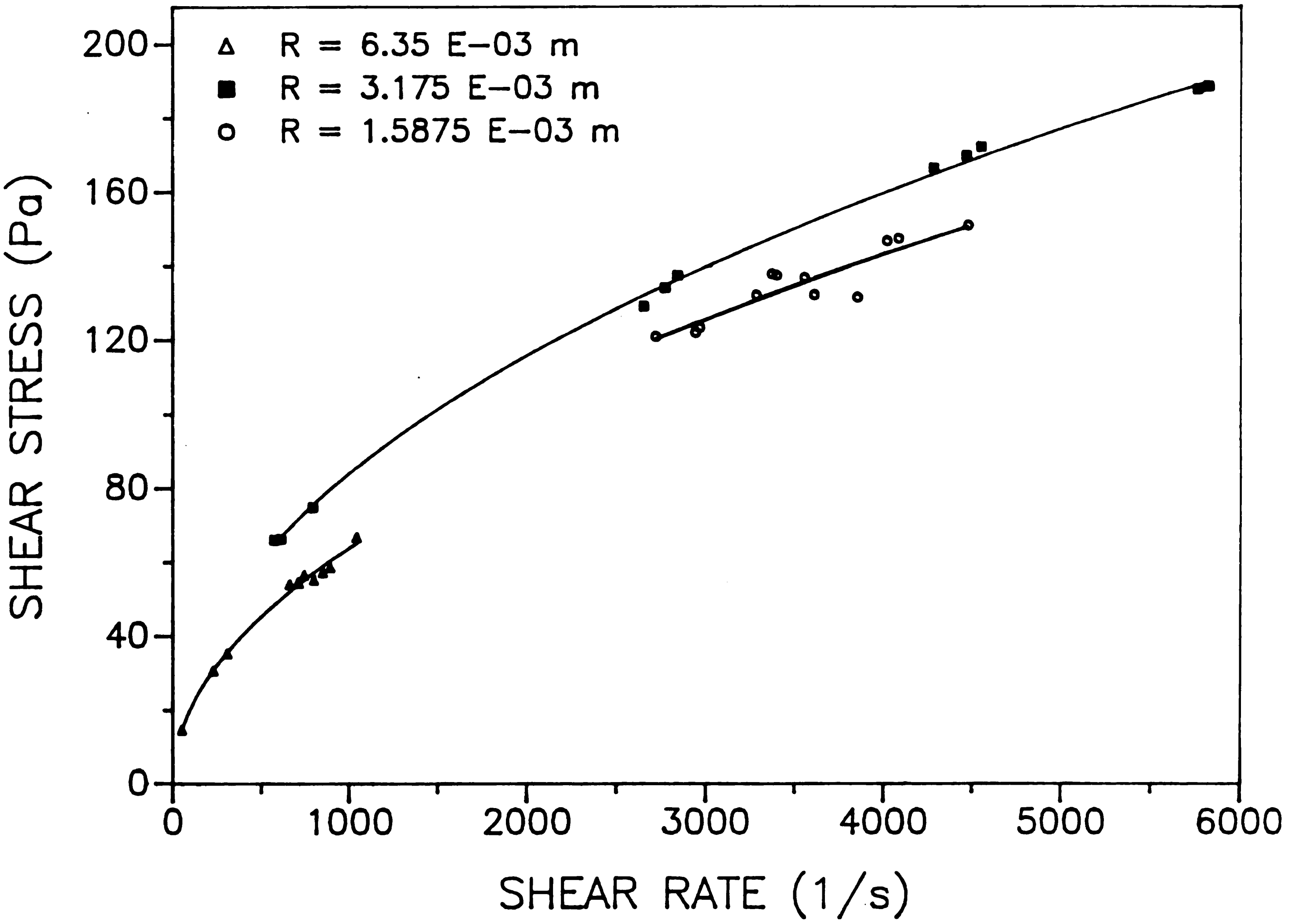


Figure 4.3. Rheogram for three different tube viscometers at 80 ^oC (turkey and rice).

Table 4.1. Viscometric constants for turkey and rice in different tube viscometers.

Inside Diameter (m)	Average temperature (^oC)	K_{low}	K (Pa s^n)	K_{high}	n_{low}	n (-)	n_{high}	r^2
0.0127	72.7	0.86	1.06	1.26	0.567	0.595	0.624	0.996
	78.9	1.53	2.13	2.74	0.448	0.491	0.534	0.992
0.00635	71.5	1.30	1.55	1.81	0.547	0.567	0.587	0.998
	83.6	3.05	3.42	3.79	0.450	0.463	0.476	0.999
0.003175	78.6	1.02	3.30	10.71	0.310	0.454	0.599	0.831

The transition point (critical Reynolds number) and the generalized Reynolds number were calculated for the worst case (highest flowrate) for each tube viscometer at each temperature. The rheological parameters from Table 4.1. were used to perform the calculations. As seen in Table 4.2, all tests were performed in the laminar region, far from the transition point.

The next assumption considered end effects, which can cause turbulence. As a rule of thumb, end effects are usually negligible if $L_i/D > 100$ (Cho and Hartnett, 1982). This tells that either a long length or a small diameter causes less problems, because in those cases a higher total pressure drop is obtained, making the end pressure error relatively small. The smallest ratio in this study was 105. End effects were therefore negligible.

Equation 2.6 assumed no slip at the wall. A slip coefficient β can be calculated for each σ_w, using various

Table 4.2. Critical and generalized Reynolds number for the different products.

	$R = 6.35\ 10^{-3}$ m		$R = 3.175\ 10^{-3}$ m		$R = 1.5875\ 10^{-3}$ m
	T=73 °C	T=80 °C	T=73 °C	T=80°C	T=73 °C
Generalized Reynolds Number	275	223	588	575	122
Critical Reynolds Number	2340	2385	2354	2392	2394

tubes with different radii. Then, an additional term shows up in the generalized form of the Rabinowitch-Mooney equation, as follows

$$Q = \frac{\pi R^3}{\sigma_w 3} \int_0^{\sigma_w} \sigma_w{}^2 f(\sigma_w) d\sigma_w + \pi R^2 U_s \qquad \text{..........(4.1)}$$

where $U_s = \beta\sigma_w$: effective slip velocity (m/s)

$f(\sigma_w) = \dot{\gamma}_w$: appropiate rheological model

Equation 4.1 can be rewritten as

$$\frac{Q}{\pi R^3 \sigma_w} = \frac{\beta}{R} + \frac{1}{\sigma_w 4} \int_0^{\sigma_w} \sigma_w{}^2\ f(\sigma_w) d\sigma_w \qquad \text{.....(4.2)}$$

From equation 4.2 it can be observed that β is obtained as the slope of a plot of $Q/\pi R^3 \sigma_w$ versus $1/R$. However, a slip coefficient was desired for each particular value of σ_w, thus a curve for each σ_w was needed. To do this, first a plot of $Q/\pi R^3\sigma_w$ versus σ_w was made. Figures 4.4 and 4.5 illustrate this for the two different temperatures. The curves obtained in those figures were determined by linear regression. The regression equations were :

for 73 °C :

radius 6.35 E-03 m : $Q/\pi R^3\sigma_w = 0.0403\ \sigma_w + 0.73$; $r^2=.972$
radius 3.18 E-03 m : $Q/\pi R^3\sigma_w = 0.0231\ \sigma_w + 0.91$; $r^2=.983$

for 80 °C :

radius 6.35 E-03 m : $Q/\pi R^3\sigma_w = 0.0534\ \sigma_w - 0.21$; $r^2=.963$
radius 3.18 E-03 m : $Q/\pi R^3\sigma_w = 0.0313\ \sigma_w - 0.97$; $r^2=.991$
radius 1.59 E-03 m : $Q/\pi R^3\sigma_w = 0.0323\ \sigma_w + 1.07$; $r^2=.513$

Disregarding the results for the smallest tube viscometer, because of the bad correlation, one can see that the slopes were different for the different radii.

Next, the plot of $Q/\pi R^3\sigma_w$ versus 1/R should be constructed for constants values of σ_w, using the above regression lines. However, no effort has been made to do this, because negative slip coefficients would have been obtained, for the slope of the above regression lines was higher for larger values of the radius (smaller 1/R).

The velocity profile for a power law fluid in a pipe is presented in Figures 4.6,a and 4.6,b. In the first case there is no slip at the wall. In the latter, a positive slip is illustrated; the flow rate is higher and this was accounted for by an additional term in Equation 4.1. Considering this, a negative slip coefficient would give

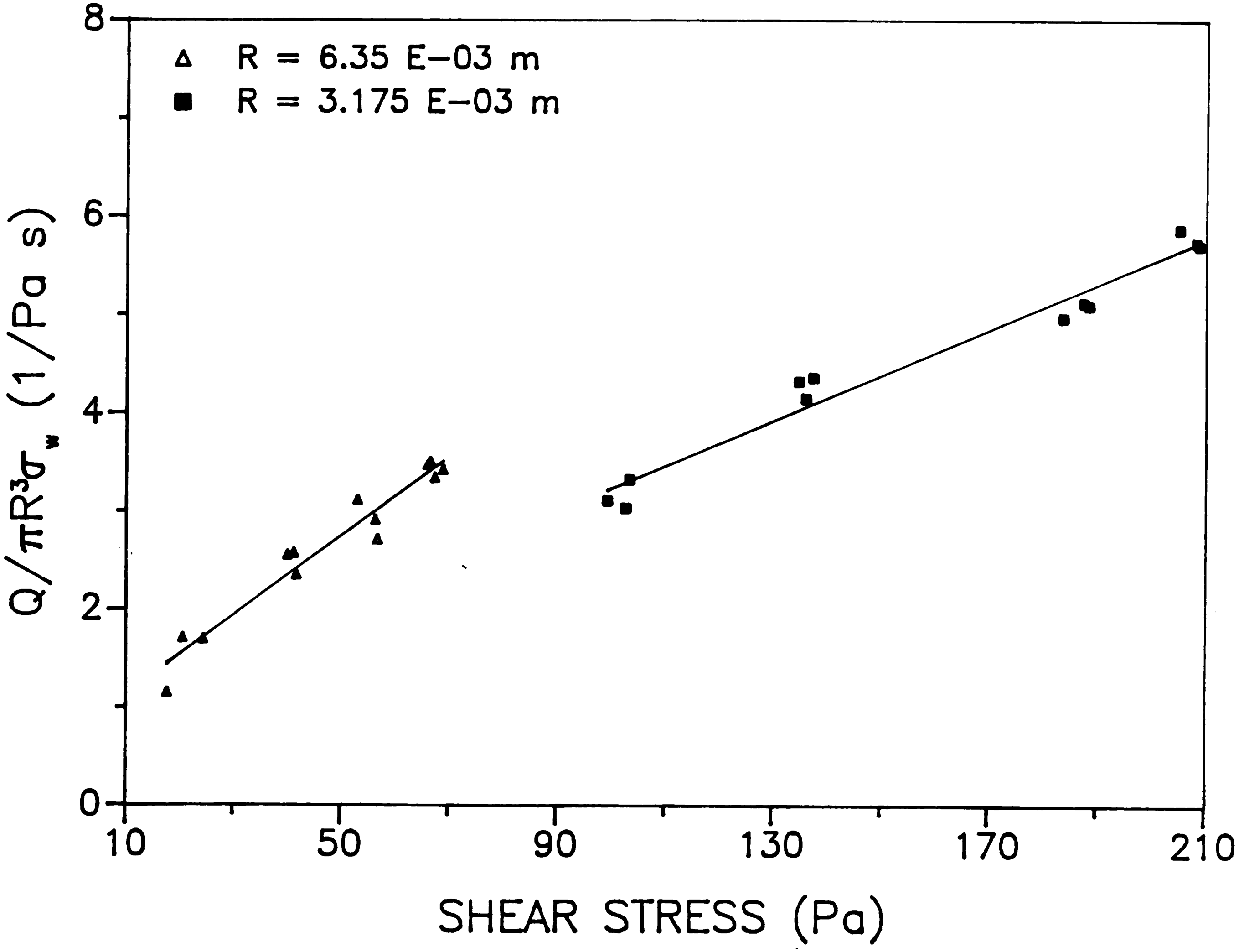


Figure 4.4. Evaluation of slip coefficient at 73 °C (turkey and rice dinner).

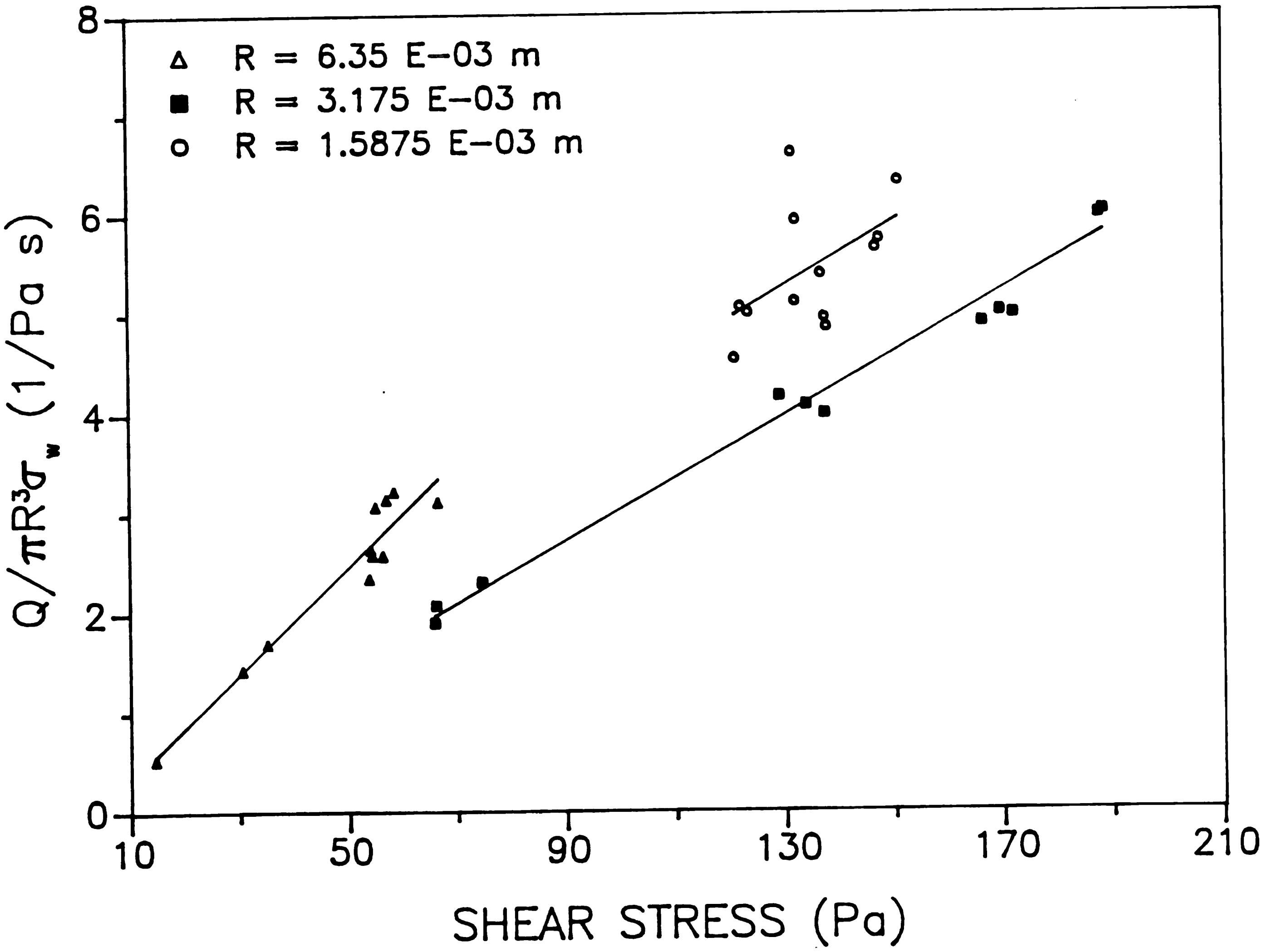


Figure 4.5. Evaluation of slip coefficient at 80 ^{o}C (turkey and rice dinner).

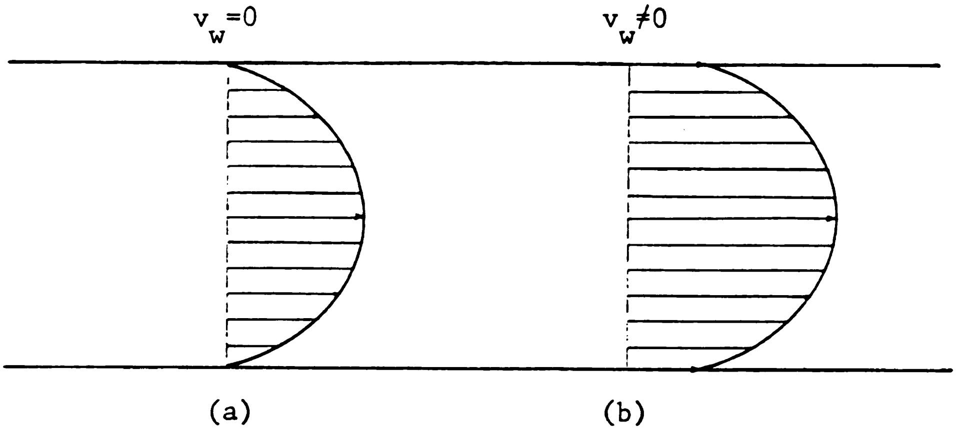


Figure 4.6. Velocity profile of a power law fluid in a pipe : without slip (a) - with slip (b).

a lower flowrate. Physically, this has no meaning. As a consequence, the flowrate was not corrected for slip.

With the data of the flowrate and the pressure drop in a tube viscometer, one has now sufficient information to construct a rheogram, according to Equations 2.6 and 2.7. The shear stress at the wall was easy to calculate. The shear rate at the wall involved the determination of the derivative $d(Q/\pi R^3)/d\sigma_w$, which was accomplished by fitting a polynomial. A software package, developed at Michigan State University, calculated the Rabinowitch-Mooney equation and fitted a Herschel-Bulkley or power law model through the data. The Rabinowitch-Mooney equation and the regression were both checked with other packages to verify the program in the range of this study; practically no differences were observed. The Michigan State University program was used to solve Equations 2.6 and 2.7, but the same non-linear regression model as in the previous chapter was used to fit the model. Only for the smallest tube viscometer the non-linear regression failed (bad correlation) and therefore a linear regression was performed on the logarithmic transformed data. This result was also close to the fit given by the Michigan State University program (least square curve fit).

The confidence limits for the results of the tube viscometer are of the same order of magnitude as in the previous chapter, except for the smallest tube viscometer; this is probably due to the bad fit and the logarithmic transformation.

Temperature control was very hard to achieve in the system. The steam had to be continuously turned on and off, based on the temperature of the product and the steam as displayed on the micrologger. The product would eventually heat up to 100 °C or more, if this had not been done. Secondly, the pipe inside diameter from the heat exchanger was rather small, so the product heated up too fast. Finally, in order to obtain low shear rates at the wall, a low flowrate was required, which increased the rate of heating even more. Technical problems prevented heating of the vat. This is a much larger volume to heat up and the temperature control would have been improved. Most problems were encountered with the smallest tube viscometer because of the low flowrates; as seen in Figure 4.3, data do not correlate as well as they do for the other sizes.

According to the temperature sensitivity of turkey and rice dinner, an effort was made to stay in the neighborhood of the target values of 73 and 80 ^{o}C. Higher temperatures were too difficult to control. The average temperatures over the whole run were 72.7 and 71.5 ^{o}C, and 78.9, 83.6 and 78.6 ^{o}C, which allowed comparison with the data obtained from the concentric cylinder viscometer at 73 and 80 ^{o}C, respectively.

Lack of a better control over the temperature prevented experimentation at low flowrates. Consequently, shear rates covered with the tube viscometer were higher than in the previous chapter.

The results from the tube viscometer showed that the consistency coefficient increased with temperature and that the flow behavior index decreased. Both effects are very unusual. The most probable reason was evaporation, which caused the fluid to thicken and to change properties. The time between the two experiments at 73 and 80 ^{o}C was around 30 minutes. During that time the product was constantly hot and could evaporate (only half the tank was covered due to returning hoses).

The data at the same temperature for the different tube viscometers were reasonably close. How close the results were, is outlined in the next section.

Comparing the data with the previous chapter revealed that the fluid had a lower consistency coefficient and was less pseudoplastic at 73°C in the tube viscometer. At 80 °C the same flow behavior index was obtained, but again a lower consistency was observed. It was not believed that the different shear rate range played an important role in the discrepancy of the results. Comparing data that did fall in the same range (40-400 s^{-1}) were not compatible. Figure 4.7 illustrates the rheograms obtained with the concentric cylinder viscometer and the largest tube viscometer at two different temperatures.

4.5. Accuracy of the results - Sensitivity analysis

The rheological parameters were obtained with the Rabinowitch-Mooney equation. This involved a polynomial fit and a curve fit to obtain a rheogram. To assess the accuracy on the rheological parameters, the program developed at Michigan State University was perturbed by giving small variances to the variables and observing the changes in the rheological parameters.

The accuracy can be determined by combining the errors as follows in the root-sum square formula (Scarborough, 1955)

on the flow behavior index :

$$\Delta n = \sqrt{\left(\frac{\partial n}{\partial(\Delta P)}\,\Delta(\Delta P)\right)^2 + \left(\frac{\partial n}{\partial D}\,\Delta D\right)^2 + \left(\frac{\partial n}{\partial L}\,\Delta L\right)^2 + \left(\frac{\partial n}{\partial Q}\,\Delta Q\right)^2}$$

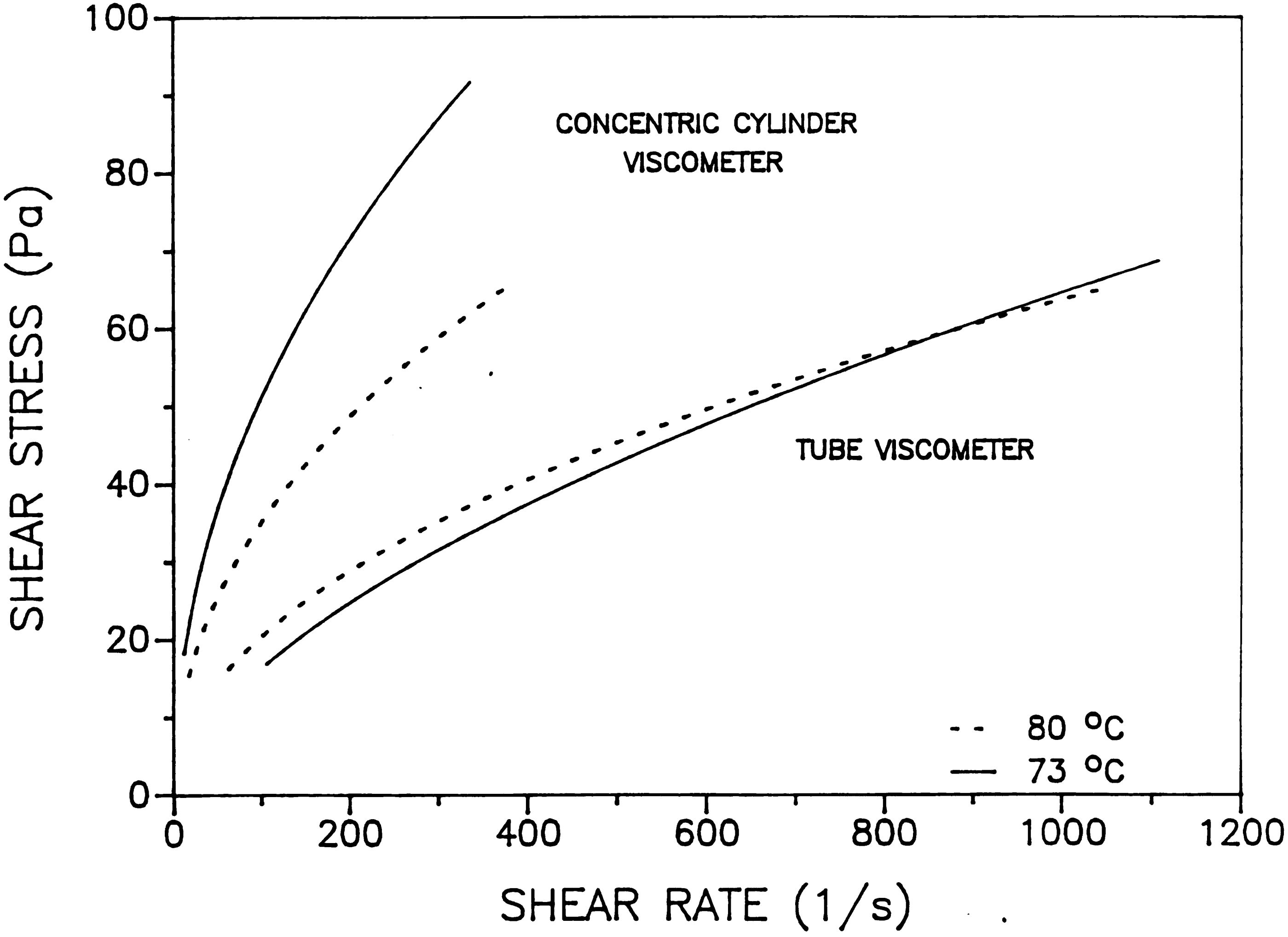


Figure 4.7. Rheograms of turkey and rice dinner obtained with a concentric cylinder viscometer and tube viscometer at 73 °C and 80 °C.

on the consistency coefficient :

$$\Delta K = \sqrt{\left(\frac{\partial K}{\partial(\Delta P)}\,\Delta(\Delta P)\right)^2 + \left(\frac{\partial K}{\partial D}\,\Delta D\right)^2 + \left(\frac{\partial K}{\partial L}\,\Delta L\right)^2 + \left(\frac{\partial K}{\partial Q}\,\Delta Q\right)^2}$$

The partial derivatives were obtained by perturbing the program. . Their magnitude is not so important, however, multiplied by the accuracy of the variable, it reflects the importance of the contribution to the overall error.

First, the accuracy on each variable was determined. The accuracy on the pressure drop was obtained as follows. Since ΔP is a difference of two pressures, the accuracy on each pressure transducer must be multiplied by $\sqrt{2}$. Using the calibration accuracy, the error on ΔP was calculated to be ± 300 Pa. The accuracy on the diameter of the pipe was based on the accuracy of the measurements at both ends and its uniformity, which was estimated; ΔD was then set to be ± 0.0004 m. The length between the two pressure transducers was measured three times and the difference between the average and the highest measurement was thought to be the accuracy; ΔL was then found to be ± 0.002 m for all three tube viscometers. The accuracy on the flowrate consisted of a chain of equations, and was based on density measurements - which were volume and weight measurements - time measurements and weight measurements. The worst case was calculated and found to be $\pm\ 9.36\ 10^{-6}$ m^3/s, which was approximately 5%.

Next, the program was perturbed with the data from the largest tube viscometer at 73 °C. The partial derivatives are given in Table 4.3. After multiplying and squaring, the following numbers were obtained

$$\Delta n = \sqrt{1.41\ 10^{-5} + 0 + 0 + 40.5\ 10^{-4}} = \pm\ 0.064$$

$$\Delta K = \sqrt{6.54\ 10^{-4} + 9.92\ 10^{-3} + 1.9\ 10^{-7} + 147\ 10^{-3}}$$
$$= \pm\ 0.4\ \text{Pa s}^{n}$$

The derivative of n with respect to L and D was zero. In other words, changing the geometry did not influence the value of n. This means that the velocity profile stays identical, regardless of the geometry.

Since the above calculations were obtained by perturbing, it was only valid in the neighborhood of the chosen values. Identical calculations for the middle size tube viscometer yielded a value of Δn of ± 0.056 and for ΔK a value of ± 0.62 Pa s^n.

As can be seen from the above equations, the flowrate contributed most in the error and was thus the most sensitive parameter in this study. This was expected, because its accuracy was lowest.

Considering these accuracies, the results for identical temperatures, presented in Table 4.1, come closer together and are more acceptable. However, the increase of K and decrease of n with temperature can still not be explained.

Table 4.3. Error terms and partial derivatives of n and K with respect to the variables for the largest tube viscometer at 73 °C.

			Actual error		Error at 1%	
Variable	$\frac{\partial n}{\partial x}$	$\frac{\partial K}{\partial x}$	$\frac{\partial n}{\partial x}\Delta x$	$\frac{\partial K}{\partial x}\Delta x$	$\frac{\partial n}{\partial x}\Delta x$	$\frac{\partial K}{\partial x}\Delta x$
ΔP	$1.25\ 10^{-5}$	$8.5\ 10^{-5}$	$3.75\ 10^{-3}$	0.026	0.0122	0.083
D	0	249	0	0.100	0	0.032
L	0	0.22	0	$4\ 10^{-4}$	0	0.010
Q	6800	41000	0.636	0.384	0.0123	0.074

The discrepancies of the tube viscometer results with the results from the concentric cylinder viscometer are still too high. A similar error analysis on Equations 2.5 and 2.6 revealed an error on K of ± 0.25 Pa s^n and ± 0.0005 on n. This higher accuracy could be expected, because they were carried out on a laboratory scale. As pointed out earlier, the confidence limits were similar.

A possible reason for the discrepancy in Figure 4.7 is that there was a two week delay between the measurements with the concentric cylinder viscometer and the tube viscometer. Enzymatic, chemical or microbial activity could have influenced the properties, however, no visible changes were detected during this period. Another reason could have been the extended heat treatment or the fact that the product was more broken down in the tube viscometer. However, it was more than likely that the rheological parameters were instrument-dependent. Work from other researchers (Tables 2.1 and 2.2) demonstrated this already for applesauce. Different instruments shear the product differently. Saravacos (1968) pointed out that the shear rates in rotational viscometers can cause separation of the suspended solids in a puree, resulting in an erroneous measured consistency (usually lower). Charm (1963) believed that aggregates are broken and that fluid is released in the area of the rotating cylinder surface. Less torque is exerted on the cylinder wall, resulting in a lower consistency. In a tube viscometer, the whole fluid is subjected to high shear rates and the measured value is more representative of the true consistency. On the other hand, particle migration can take place in a tube viscometer, also predicting a lower consistency. In any case, rheological parameters obtained by a concentric cylinder viscometer, could not, within the limits of this study, be used to predict the pressure drop in a tube viscometer.

Finally, a sensitivity analysis can be performed by attributing the same accuracy (1%) to all the variables in Equation 4.3. A similar analysis has been carried out by Mohamed and Steffe (1985) to predict the flowrate for a Herschel-Bulkley fluid.
Calculations (Table 4.3) showed that the pressure drop and the flowrate were equally sensitive with respect to n. As mentioned earlier, the geometry had no effect on n. For the consistency coefficients, it was shown that the pressure drop was the most sensitive parameter, closely followed by the flowrate. Errors in the diameter and the length contributed much less to the total error.

In summary, one can state that the determination of the rheological parameters in a tube viscometer is equally sensitive to errors in pressure drop and flow rate. The accuracy on the geometry can be considered negligible. If one wants to establish the target values for the rheological parameters with a tube viscometer, this should be kept in mind.

4.6. Conclusions

In this chapter the rheological properties of turkey and rice were measured by means of a tube viscometer. Two important conclusions can be drawn.

The results from the tube viscometer seemed not to agree with what was obtained with the concentric cylinder viscometer. The flow behavior indices were in one case higher than, and in the other case, equal to the earlier observed values. The product seemed to have a lower consistency in the tube viscometer. Calculations of the accuracies on the parameters did not bring the results from the two different instruments together. Consequently, target values should also be investigated with a tube viscometer, despite a higher obtainable accuracy with a concentric cylinder viscometer.

Secondly, a sensitivity analysis showed that for the calculations of the rheological parameters, the flowrate and the pressure drop were equally sensitive variables, while the geometry was negligible. This is exactly what is preferred, namely the pressure drop will now be the new target to predict a change in the rheological parameters. The next chapter will investigate the sensitivity of the pressure drop, as a criterion for quality control.

CHAPTER 5

SENSITIVITY ANALYSIS AND DESIGN CRITERIA

5.1. Introduction

In this chapter the design criteria for an on-line viscometer are determined. This will mainly be based on the experiments of the two previous chapters. In addition to this, a sensitivity analysis will be carried out to investigate the sensitivity of the pressure drop, as a variable to assess changes in the rheological parameters. This analysis is different from the one in section 4.5, because now, the variables which affect the pressure drop will be of interest. It is not the intention to estimate the rheological parameters, for this is not possible with the measurements of one flowrate and one pressure drop.

5.2. Sensitivity analysis

The Rabinowitch-Mooney equation can be transformed to a much simpler equation, which involves no polynomial fitting, since the model of the fluid materials was shown to be a power law. Rearranging Equation 2.6 for a power law yields

$$\Delta P = \frac{2LK}{R} \left(\frac{Q}{\pi R^3}\right)^n \left(\frac{3n+1}{n}\right)^n \qquad \ldots\ldots\ldots\ldots\ldots(5.1)$$

The accuracy on ΔP can then be expressed as

$$\Delta(\Delta P) = \sqrt{\left(\frac{\partial(\Delta P)}{\partial L}\Delta L\right)^2 + \left(\frac{\partial(\Delta P)}{\partial K}\Delta K\right)^2 + \left(\frac{\partial(\Delta P)}{\partial R}\Delta R\right)^2 + \left(\frac{\partial(\Delta P)}{\partial Q}\Delta Q\right)^2 + \left(\frac{\partial(\Delta P)}{\partial n}\Delta n\right)^2} \qquad \ldots\ldots\ldots(5.2)$$

Since just one equation is used, the derivatives can be calculated mathematically, without the need for perturbing. The partial derivatives are given below

$$\frac{\partial(\Delta P)}{\partial L} = \frac{2K}{R} \left(\frac{Q}{\pi R^3}\right)^n \left(\frac{3n+1}{n}\right)^n$$

$$\frac{\partial(\Delta P)}{\partial K} = \frac{2L}{R} \left(\frac{Q}{\pi R^3}\right)^n \left(\frac{3n+1}{n}\right)^n$$

$$\frac{\partial(\Delta P)}{\partial R} = 2LK \left(\frac{Q}{\pi R^3}\right)^n \left(\frac{3n+1}{n}\right)^n \left(\frac{-1-3n}{R^2}\right)$$

$$\frac{\partial(\Delta P)}{\partial Q} = \frac{2LK}{R} \left(\frac{1}{\pi R^3}\right)^n \left(\frac{3n+1}{n}\right)^n n\, Q^{n-1}$$

$$\frac{\partial(\Delta P)}{\partial n} = \frac{2LK}{R}\left(\frac{Q}{\pi R^3}\right)^n\left(\frac{3n+1}{n}\right)^n\left[\ln\left(\frac{Q(3n+1)}{n\pi R^3}\right) - \left(\frac{1}{3n+1}\right)\right]$$

The derivatives were checked with a numerical solution and were found to be in good agreement. The above derivatives were then incorporated in Equation 5.2.

To investigate the sensitivity of the pressure drop as a function of the variables L, K, R, Q and n, the following representative values were used :

$L = 3$ m

$K = 5.54$ Pa s^n

$n = 0.48$

$R = 0.0127$ m

$Q = 2.53\ 10^{-4}\ m^3/s$

The pressure drop is then 33 kPa.

The precision level was chosen to be 1% to represent reasonable numbers. Equation 5.2 then becomes

$$\Delta(\Delta)P = \sqrt{\underset{L}{110842} + \underset{K}{110842} + \underset{R}{659913} + \underset{Q}{25539} + \underset{n}{610294}}$$

It can be seen that the flowrate term (25539) represents the least sensitive variable, while the radius and the flow behavior index are the most sensitive variables. An error in the consistency coefficient and the length is less important.

The fact that the flowrate is not sensitive turns out to be very practical. A less accurate flowrate, produced by the pump, will not influence the pressure drop too much. This allows more wear on the pump. The lower sensitivity of K, on the other hand, is not so favorable.

If a fixed system is used, there will be no changes in R and L; then, the pressure drop is only a function of n, K and Q. A change in n will be easier to detect. Fortunately, it has been shown that n is not very temperature sensitive; however, further research must be carried out to find out how n changes with the consistency of the product. If this is not significant, then the pressure drop reflects only the changes in K.

Changing the neighborhood of the calculations to n = 0.2 (e.g. carrot puree), yields the following numbers for Equation 5.2

$$\Delta(\Delta)P = \sqrt{\underset{L}{6838} + \underset{K}{6838} + \underset{R}{17504} + 273 + \underset{n}{7189}}$$

This gives essentially the same results, except for the sensitivity of n, which has become approximately equal to the sensitivity of K.

5.3. Design criteria for an on-line viscometer

Figure 1.1 gave a schematic view of a process line and indicated the position of the on-line viscometer. The inside diameter of the main pipe is 0.0635 m and the flowrate ranges from 3.7 10^{-3} to 4.3 10^{-3} m^3/s. The purpose is to connect a smaller pipe to the main line, having its own pump, to produce a more stable flowrate, one temperature sensor and one or two pressure transducers. To reduce the costs, the product must not necessarily be returned to the main line, but it can be pumped directly into a surge tank. This would require only one pressure measurement, because the other is at atmospheric pressure. However, this is not advised, because of uncontrollable end effects.

The smallest commercially available diameter is 0.0254 m. Keeping the rule of thumb in mind to reduce the end effects ($L_i/D > 100$), an entrance length of 2.5 m is advised.

It is best to keep the shear rate in the same range as in the main pipeline to maintain the same texture. The shear rate at the wall can be calculated with the Rabinowitch-Mooney equation, valid for a power law, as follows

$$\dot{\gamma}_w = \frac{Q}{\pi R^3} \frac{3n+1}{n} \qquad \text{.........................(5.3)}$$

The flow behavior index is assumed to be 0.5. Accordingly, the shear rate range in the main pipe becomes 184-215 s^{-1}. The flowrate in the on-line viscometer can be back calculated using Equation 5.3. This yields a flowrate in the range of 2.36 10^{-4} to 2.76 10^{-4} m^3/s. Variation of n will not affect the shear rate range significantly.

The critical Reynolds number is in both cases 2382. The generalized Reynolds number is 27 for the tube viscometer and 174 for the main line. The flow is well within the laminar region.

The assumption of no slip at the wall is acceptable, because the error on the flowrate can be much greater than the error in K, before the same effect is observed on the change in pressure drop.

The pump that suits the requirements is a positive displacement, variable speed pump, size 15 (Waukesha). The displacement of this pump is 4.92 10^{-5} m^3/revolution (Waukesha, 1980). To displace the volume calculated above, the pump will have to turn at 287-336 rpm. A reducer from the port size 0.0381 m to 0.0254 m will be required.

The pressure at the discharge should be calculated to be certain that the upper pressure limitations (1379 kPa) are not exceeded. The pressure was calculated by means of a mechanical energy balance and found to be 37 kPa, which is well within the pump design limitations.

The pressure at the inlet side should be sufficient to fill pump cavity. For the above pump this net inlet pressure required is only 20.7 kPa, at a speed of 300 rpm. No sufficient information was available to calculate the net inlet pressure available, but it is believed that this pressure will be easily attainable.

Pulsations will be very small due to the small discharge volume. Measuring over a long enough period of time and frequently enough will average this out.

The distance between the two pressure transducers can be chosen freely, since the pressure drop varies linearly with distance. A longer length will increase the magnitude of the pressure drop. A length of 3 m is advised, to have a reasonable pressure differential.

Equation 5.2 dictates that the accuracy of the pressure transducers will be a function of the accuracy on the flowrate measurements and the determination of the rheological properties. In the worst case, the flow rate can be measured by recording the speed of the pump, assuming slip of the pump is negligible. This is true for viscous materials (> 0.1 Pa s^n) (Waukesha, Abex Corp., 1980); baby food can be considered viscous enough.

The final design criteria for the proposed on-line viscometer are presented in Figure 5.1.

5.4. Conclusions

Some preliminary design criteria have been developed, according to a sensitivity analysis of Equation 5.1. It was found that, in a fixed system, the flow behavior index was the most sensitive parameter. The consistency was, depending on the values of the other parameters, less sensitive. Both characterize the fluid and can therefore be used as quality control parameters. The flowrate was much

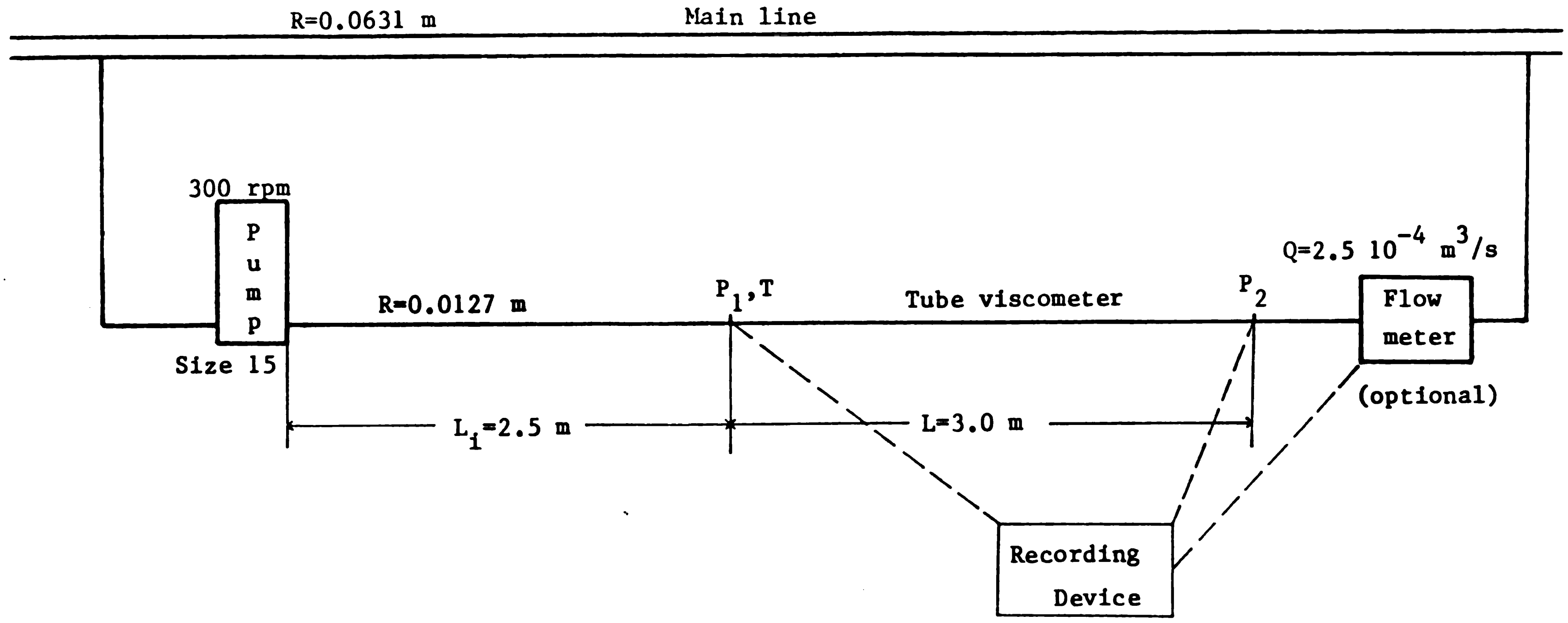


Figure 5.1. Final design criteria for the proposed on-line viscometer.

less sensitive than the rheological parameters, which was a positive point, considering possible wear of the pump with time.

The final design parameters for a start up on-line viscometer for baby food puree were found to be : $L = 3$ m, $Q = 2.5\ 10^{-4}\ m^3/s$, $D = 0.0254$ m, a variable speed pump, size 15, turning at a speed of 300 rpm, two pressure transducers, one temperature sensor and a flowmeter, the latter being optional.

CHAPTER 6

CONCLUSIONS

Rheological parameters for four baby food products were obtained by using a Bostwick Consistometer and a concentric cylinder. Unfortunately, the results could not be related to each other. Rao and Bourne (1977) were able to correlate their Bostwick Consistometer readings with a plastometer. In this study, an analogous relationship could not be reproduced.

This important fact showed that the Bostwick readings could not be translated into rheological parameters. As a consequence, target values for a desired quality are recommended to be determined in terms of the rheological parameters, for each specific product.

Rheological experiments with a tube viscometer, simulating an on-line viscometer, revealed that the rheological properties are significantly different from those obtained with a concentric cylinder viscometer. This means that the determination of the target values are recommended to be carried out in a tube viscometer.

Finally, design criteria were set up for a start up on-line viscometer for baby food puree that would best simulate the actual on-line viscometer. This was based on a sensitivity analysis and on the measured rheological data. The entrance length was 2.5 m, the length between the two pressure transducers was 3 m, the flowrate was 2.5 10^{-4} m^3/s and the diameter was 0.0254 m. Other dimensions can be obtained, if a similar procedure, as outlined in chapter 5, is followed.

CHAPTER 7

SUGGESTIONS FOR FURTHER STUDY

1. To build the proposed on-line viscometer.

2. To investigate the effect of total solids on the Bostwick Consistometer readings and tube viscometer data.

3. To determine the target values of the rheological parameters for a desired consistency, with the above on-line viscometer.

4. To determine the range of the pressure drop as a quality control point.

APPENDICES

APPENDIX A

BOSTWICK CONSISTOMETER READINGS FOR DIFFERENT PRODUCTS

Table A.1. Bostwick Consistometer readings for different products.

Product	Sample	Temperature (°C)	BR 5s (cm/5s)	liquid	BR 15s (cm/15s)	liquid	BR 30s (cm/30s)	liquid	BR 60s (cm/60s)
Applesauce	1	73.0	8.50		9.30		9.75		10.25
	2	73.0	8.30		9.00		9.50		10.00
	3	73.0	8.25		8.90		9.40		9.90
	4	73.0	8.25		8.90		9.40		9.75
Carrot puree	1	73.0	7.00	7.00- 9.00	7.00	7.50- 9.50	7.00	8.00-10.00	7.00
	2	73.0	6.75		6.75		6.75		6.75
	3	73.0	6.50	7.00- 9.00	6.50	7.50-10.00	6.75	8.50-10.50	6.75
	4	73.0	6.50	7.00- 8.50	6.50	7.50- 9.50	6.75	8.00-10.00	6.75
Vegetable and beef	1	74.0	11.00		12.75		13.75		14.75
	2	73.0	11.50		13.25		14.25		15.25
	3	73.0	10.75		12.50		14.00		14.75
	4	73.5	11.25		13.00		14.00		14.90
Turkey and rice	1	74.0	9.25		10.75		11.25		11.50
	2	74.0	9.25		10.75		11.25		11.75
	3	74.0	9.25		10.75		11.25		11.60
Applesauce	1	80.0	9.00		9.60		10.25		10.75
	2	80.0	9.10		9.75		10.25		10.75
	3	79.5	9.00		9.75		10.50		11.00
	4	80.0	9.00		9.60		10.25		10.60
Carrot puree	1	80.0	7.00	7.00- 9.50	7.00	7.75- 9.75	7.00	8.50-10.50	7.00
	2	80.0	6.50	6.50- 8.00	6.50	7.25- 8.50	6.50	8.25- 9.50	6.50
	3	79.5	7.00	7.00- 9.00	7.00	7.50- 9.25	7.00	8.25-10.00	7.00
	4	80.0	7.00	7.00- 9.75	7.00	8.00-10.00	7.00	9.00-10.75	7.25
Vegetable and beef	1	79.5	11.25		12.75		13.90		14.75
	2	81.0	11.25		13.00		14.25		15.00
	3	81.0	11.25		13.00		14.00		14.75
	4	80.0	11.50		13.25		14.50		15.25
Turkey and rice	1	80.0	10.00		11.25		11.75		12.00
	2	81.0	9.50		10.90		11.25		11.60
	3	80.0	9.50		10.75		11.25		11.50
	4	80.0	9.50		10.75		11.50		11.75

Table A.1. (cont'd).

Product	Sample	Temperature (°C)	BR 5s (cm/5s)	liquid	BR 15s (cm/15s)	liquid	BR 30s (cm/30s)	liquid	BR 60s (cm/60s)
Applesauce	1	86.8	9.50		10.25		10.75		11.00
	2	85.5	9.50		10.00		10.50		10.75
	3	85.5	10.50		10.75		11.00		11.25
	4	86.0	10.00		10.50		10.75		11.00
Carrot puree	1	86.8	7.50		7.50		7.50		7.50
	2	85.4	7.25		7.25		7.25		7.25
	3	85.6	7.50		7.50	8.50-10.00	7.50	9.00-10.50	7.50
	4	86.0	7.90		7.90	8.75-10.75	7.90	9.75-11.75	7.90
Vegetable and beef	1	86.0	12.00		13.50		14.25		14.75
	2	85.6	12.00		13.50		14.25		14.75
	3	86.0	12.00		13.50		14.25		14.75
	4	85.8	12.00		13.50		14.25		14.75
Turkey and rice	1	86.0	11.00		12.25		12.75		12.90
	2	86.0	11.00		12.25		12.75		12.90
	3	87.0	10.25		11.40		11.75		12.00
	4	86.0	10.50		11.75		12.00		12.25
Applesauce	1	92.0	10.00		10.50		10.75		10.90
	2	92.0	9.90		10.50		10.75		11.00
	3	92.0	10.75		11.25		11.60		12.00
	4	92.0	10.50		11.00		11.25		11.25
Carrot puree	1	92.0	8.00	8.50- 9.00	8.00	7.50- 9.00	8.25	10.0-10.50	8.25
	2	92.0	7.75	8.00- 9.00	7.75	8.50- 9.50	7.75	9.00-10.00	7.75
	3	92.0	7.50	7.75- 9.75	7.50	8.50-10.00	7.50	9.75-10.50	7.50
	4	92.0	7.75	7.75- 9.25	7.75	8.25- 9.75	7.75	8.75-10.50	7.75
Vegetable and beef	1	92.0	11.75		13.50		14.25		14.75
	2	92.0	12.00		14.00		14.75		15.25
	3	92.0	11.75		13.50		14.00		14.50
	4	92.0	12.75		14.50		15.25		15.75
Turkey and rice	1	92.0	11.25		12.75		13.25		13.50
	2	92.0	10.25		11.60		12.00		12.25
	3	92.0	11.50		12.75		13.40		13.60
	4	92.0	10.75		11.75		12.25		12.80

APPENDIX B

RHEOLOGICAL CONSTANTS OBTAINED WITH THE CONCENTRIC CYLINDER VISCOMETER FOR DIFFERENT PRODUCTS FOR THE SEPARATE RUNS

Table B.1. Rheological constants obtained with the concentric cylinder viscometer for different products for the separate runs.

Product	Sample	Temperature (^oC)	K (Pa s^n)	n (-)	r^2
Applesauce	1	72	2.81	0.428	0.997
	2	73	2.54	0.451	0.972
	3	72	2.43	0.447	0.995
	1	80	3.37	0.335	0.999
	2	80	4.23	0.330	0.999
	3	80	2.23	0.400	0.999
	4	80	2.99	0.364	1.000
	1	87	2.20	0.333	0.999
	2	86	2.11	0.329	0.999
	3	86	2.36	0.327	1.000
	4	86	2.38	0.324	1.000
	1	92	1.65	0.391	1.000
	2	92	2.64	0.346	1.000
	3	92	1.99	0.357	1.000
	4	92	2.24	0.342	0.999
Carrot Puree	1	73	2.06	0.346	0.985
	2	73	6.46	0.244	1.000
	3	73	3.92	0.280	1.000
	4	73	7.33	0.231	1.000
	1	81	3.82	0.254	0.999
	2	80	4.63	0.245	0.999
	3	80	4.00	0.312	0.998
	4	80	10.20	0.148	1.000
	1	85	3.99	0.259	0.999
	2	85	6.26	0.237	1.000
	3	86	5.37	0.244	0.999
	4	86	4.00	0.323	0.993
	1	92	1.52	0.350	0.996
	2	92	2.79	0.286	1.000
	3	92	3.25	0.183	1.000

Table B.1. (cont'd)

Product	Sample	Temperature (^oC)	K (Pa s^n)	n (-)	r^2
Vegetable and beef	1	73	1.24	0.643	0.999
	2	72	3.28	0.496	1.000
	3	72	4.00	0.461	0.999
	4	72	1.07	0.672	0.995
	1	80	2.52	0.490	0.998
	2	79	2.63	0.500	1.000
	3	80	1.88	0.495	0.999
	4	80	2.47	0.475	0.994
	1	85	2.12	0.512	1.000
	2	85	2.15	0.504	0.998
	3	85	2.19	0.511	1.000
	1	92	0.87	0.686	0.989
	2	92	0.53	0.469	0.992
	3	92	0.23	0.576	0.989
	4	92	0.54	0.515	0.999
Turkey and rice	1	74	6.80	0.461	1.000
	2	74	6.29	0.466	1.000
	3	74	6.47	0.454	1.000
	4	72	3.84	0.527	0.995
	1	80	3.72	0.459	1.000
	2	81	4.75	0.482	1.000
	3	80	4.48	0.451	1.000
	4	80	3.50	0.472	1.000
	1	86	1.73	0.470	0.995
	2	86	2.13	0.460	0.998
	3	87	1.89	0.482	0.997
	4	86	1.92	0.432	0.996
	1	92	0.53	0.616	0.976
	2	93	0.43	0.595	0.964
	3	91	0.41	0.458	0.998
	4	92	0.75	0.450	0.999

APPENDIX C

THE APPARENT VISCOSITY AS A FUNCTION OF THE SHEAR RATE AT DIFFERENT TEMPERATURES FOR THE DIFFERENT PRODUCTS (RAW DATA)

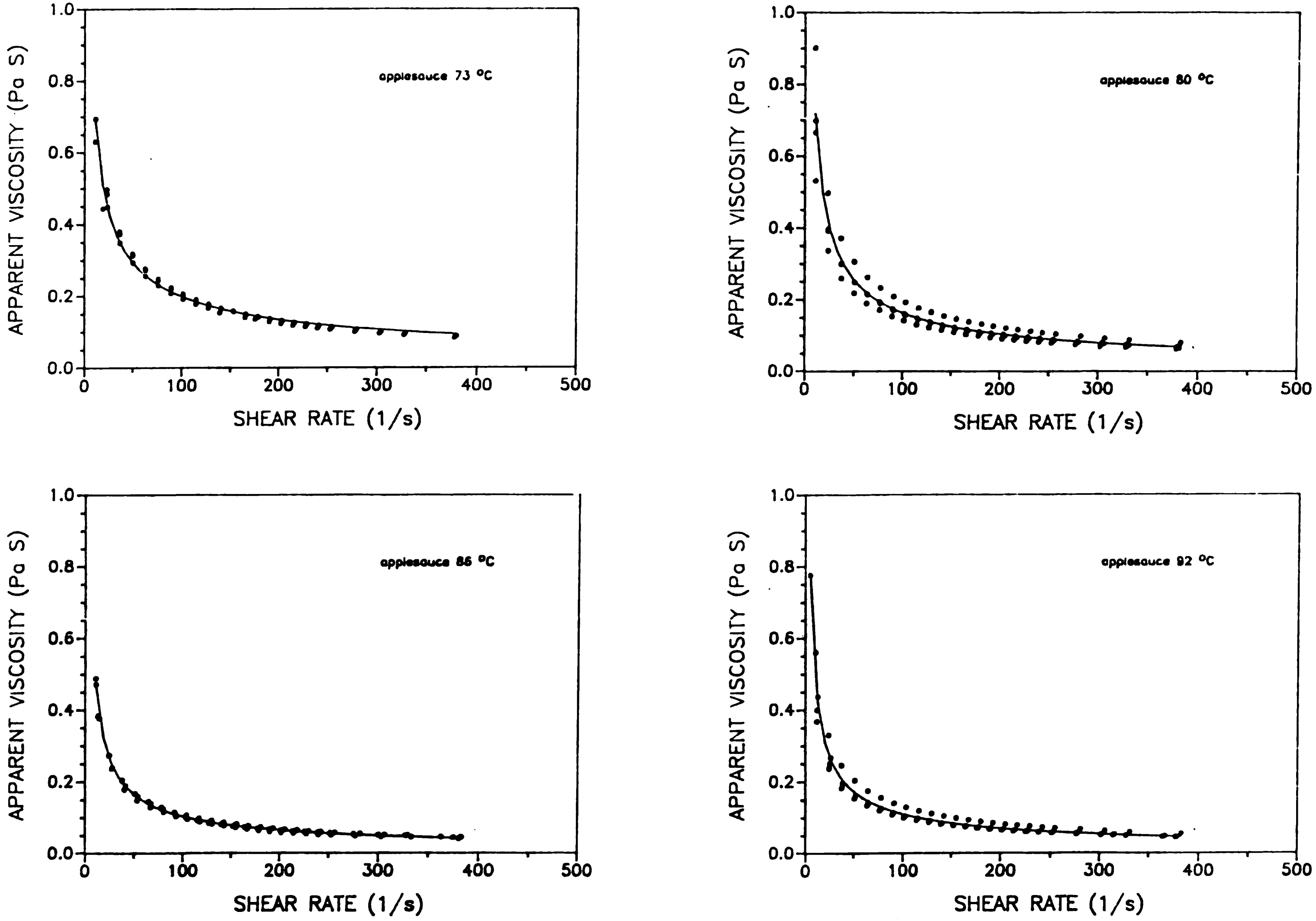


Figure C.1. The apparent viscosity as a function of the shear rate at different temperatures for applesauce (raw data).

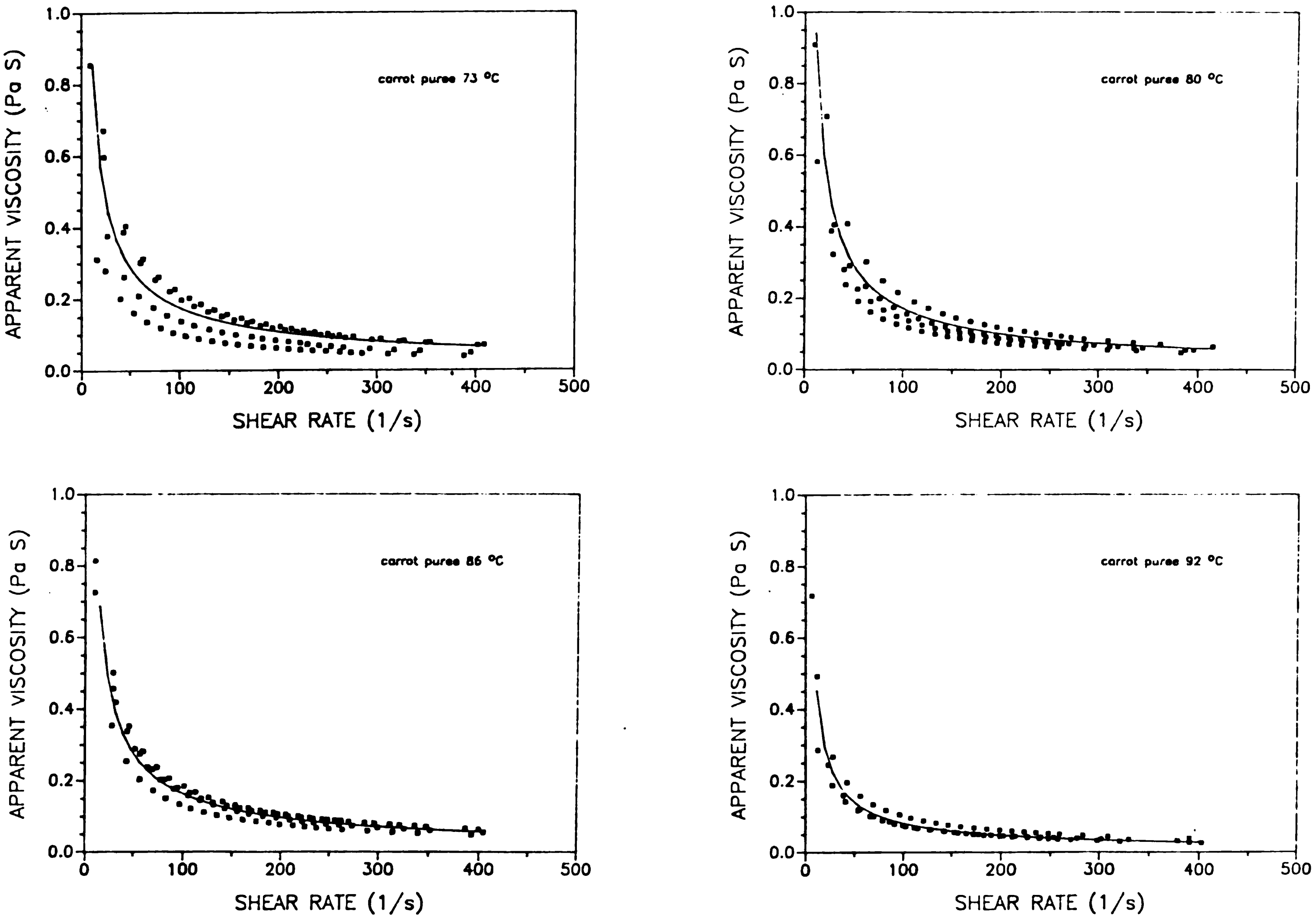


Figure C.2. The apparent viscosity as a function of the shear rate at different temperatures for carrot puree (raw data).

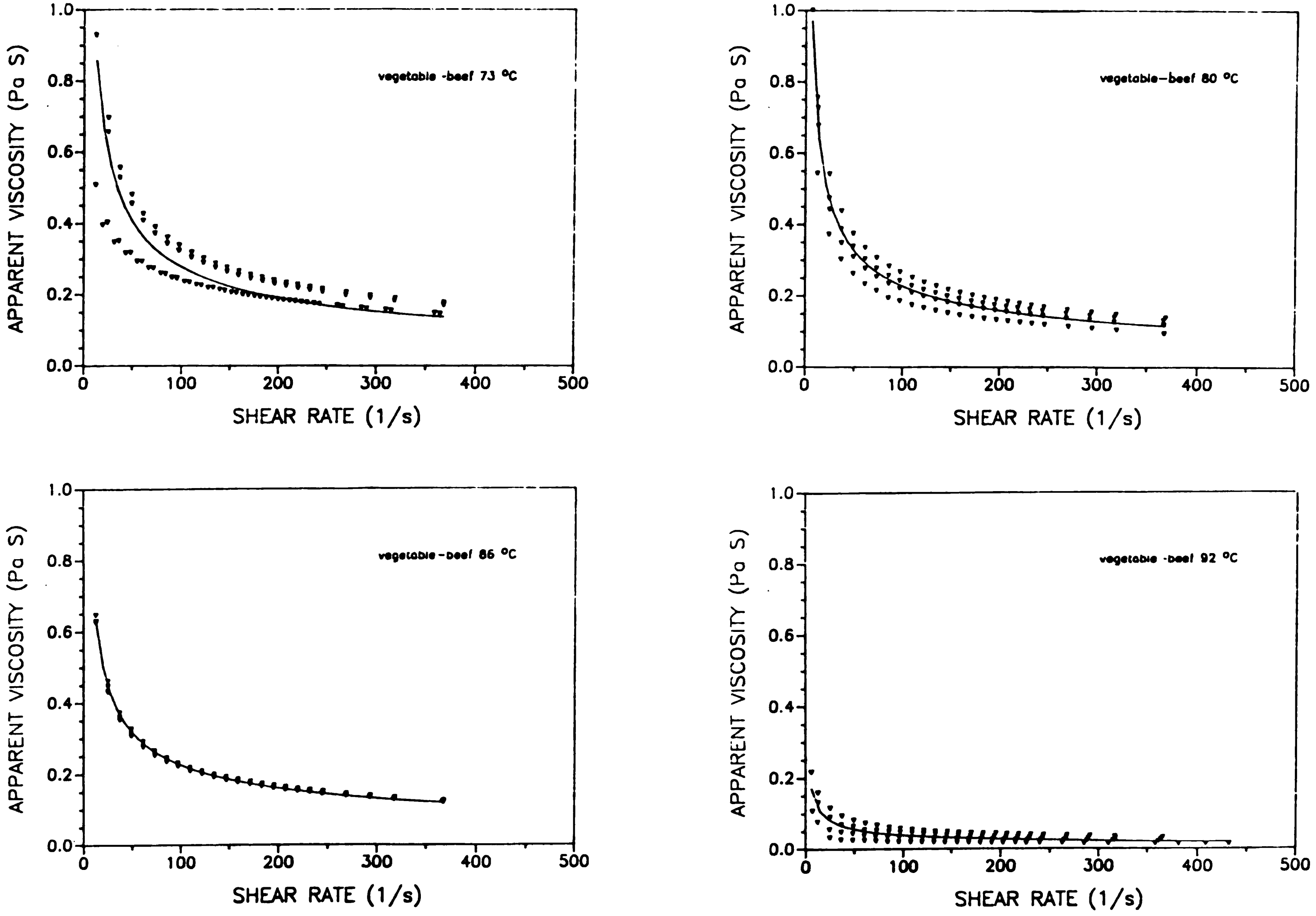


Figure C.3. The apparent viscosity as a function of the shear rate at different temperatures for vegetable and beef dinner (raw data).

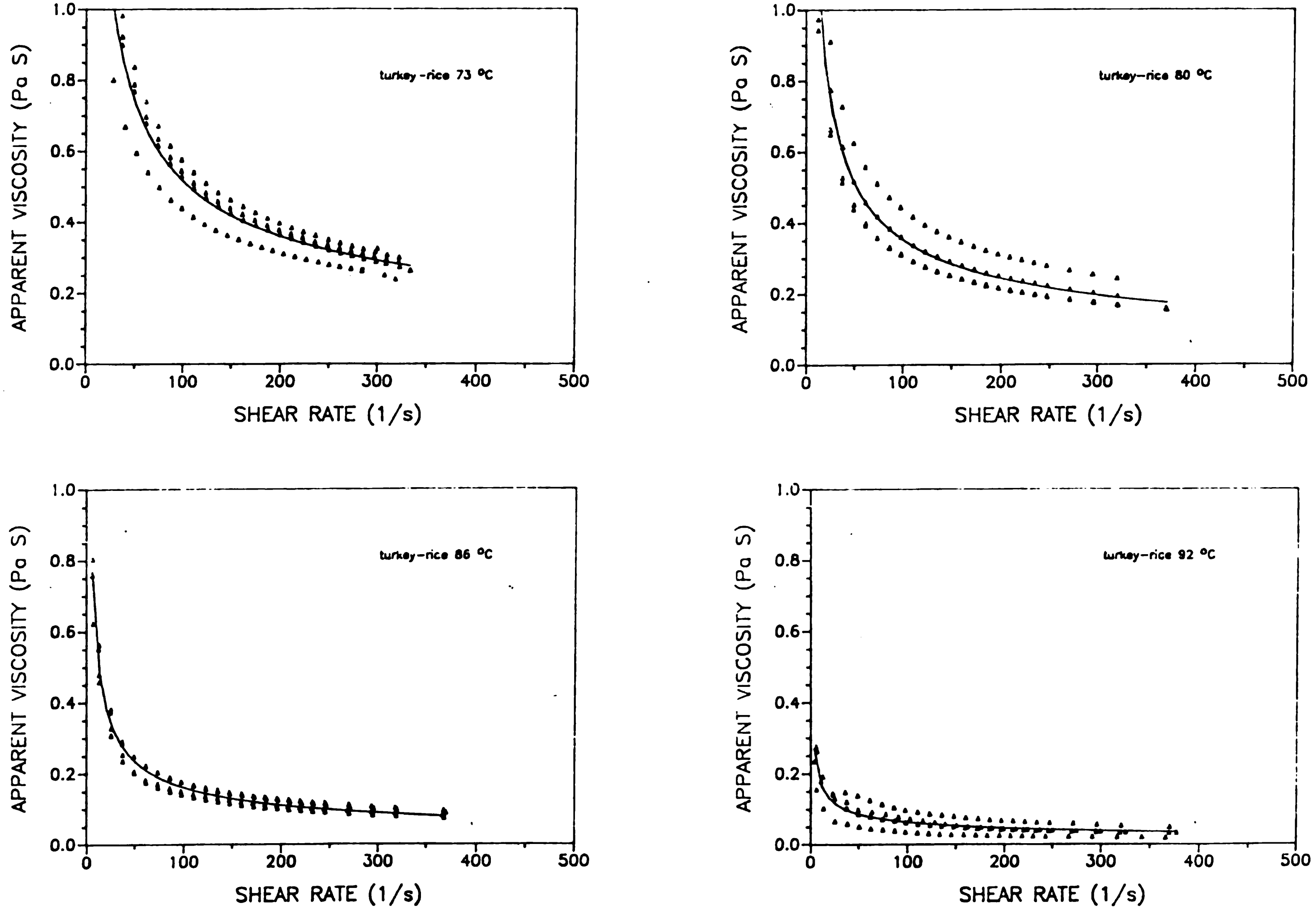


Figure C.4. The apparent viscosity as a function of the shear rate at different temperatures for turkey and rice dinner (raw data).

APPENDIX D

PRESSURE DROP , FLOWRATE AND TEMPERATURE DATA FOR THE DIFFERENT TUBE VISCOMETERS

Table D.1. Pressure drop, flowrate and temperature data for the tube viscometer with a diameter of 0.0127 m at 73 °C and 80 °C.

T_1 (°C)	T_2 (°C)	T_3 (°C)	T_4 (°C)	ΔP (Pa)	Q $(m^3/s)*10^{-4}$
73.5	74.7	99.4	99.4	97284.2	1.8036
73.2	74.5	99.4	99.4	95284.8	1.8352
72.8	74.0	99.0	98.9	96112.1	1.8688
73.0	74.1	99.1	99.0	99559.5	1.8896
73.5	77.0	92.0	96.1	81357.5	1.3121
70.1	72.4	91.2	101.9	81978.0	1.2311
73.1	77.0	106.4	106.3	76531.2	1.3221
69.5	72.6	109.6	109.6	59570.2	0.8492
72.6	78.0	99.0	100.7	57846.5	0.8183
69.9	74.0	110.4	110.3	60259.7	0.7847
73.2	74.6	100.9	103.9	35163.0	0.3303
74.8	75.0	104.3	104.3	29647.2	0.2809
75.8	75.9	103.7	103.8	25510.4	0.1627
80.9	82.7	105.1	106.1	84391.1	1.5063
81.0	84.9	110.7	110.6	82391.7	1.4346
80.8	85.8	111.6	111.5	79495.9	1.3508
77.5	81.0	110.3	110.2	96112.1	1.6589
77.4	80.4	105.1	105.0	81426.4	1.1630
77.4	81.2	109.7	109.6	78599.6	1.1243
78.3	83.6	117.8	117.7	78185.9	1.1437
74.9	78.3	109.7	110.4	50745.0	0.4758
80.5	84.5	113.7	114.5	77841.2	1.0125
77.3	79.9	114.8	114.7	44057.1	0.3483
81.9	81.2	124.1	124.0	20959.9	0.0609

Table D.2. Pressure drop, flowrate and temperature data for the tube viscometer with a diameter of 0.00635 m at 73 ^{o}C and 80 ^{o}C.

T_1 (^{o}C)	T_2 (^{o}C)	T_3 (^{o}C)	T_4 (^{o}C)	ΔP (Pa)	Q (m^3/s)$*10^{-4}$
68.6	69.5	102.5	102.5	604251.5	1.1981
69.5	70.8	103.1	103.1	602665.7	1.2017
70.4	72.0	103.8	103.8	593633.7	1.2110
70.8	73.2	98.3	98.3	542543.9	0.9652
69.7	72.3	98.3	98.2	545370.8	0.9645
68.9	72.4	98.5	98.3	531650.3	0.9172
71.0	74.9	104.1	104.0	393687.4	0.5668
72.8	76.8	105.9	105.8	397617.3	0.6019
73.9	76.1	106.6	106.6	389826.3	0.5847
75.6	76.4	95.7	98.3	299092.1	0.3447
73.8	74.6	88.7	98.2	287302.1	0.3096
72.8	73.3	83.9	98.2	297161.6	0.3124
83.2	83.4	120.7	120.6	543164.5	1.1272
83.4	84.1	120.9	120.8	545508.7	1.1394
83.7	84.8	121.2	121.1	545439.7	1.1387
81.0	84.7	119.2	119.1	481112.2	0.8183
80.8	84.6	118.9	118.9	490764.7	0.8535
80.6	84.8	118.9	118.8	497866.3	0.8606
84.0	85.8	123.6	123.5	373141.2	0.5396
85.5	86.8	124.2	124.1	387551.1	0.5482
85.7	86.8	124.0	123.9	397203.7	0.5496
85.9	80.5	109.7	109.6	215942.0	0.1727
84.7	81.4	109.6	109.5	190431.6	0.1254
84.8	83.8	109.5	109.4	191190.0	0.1376

Table D.3. Pressure drop, flowrate and temperature data for the tube viscometer with a diameter of 0.003175 m at 73 ^{o}C and 80 ^{o}C.

T_1 (^{o}C)	T_2 (^{o}C)	T_3 (^{o}C)	T_4 (^{o}C)	ΔP (Pa)	Q (m^3/s)$*10^{-6}$
78.3	76.0	89.5	98.3	893718.6	9.2439
77.0	74.6	84.3	98.2	897965.7	8.5273
75.2	72.8	79.0	98.2	900358.2	8.3840
74.2	70.3	113.4	113.3	862575.2	8.4557
81.7	78.7	105.4	105.3	858955.5	10.8921
82.4	79.7	101.0	100.9	863457.8	9.8172
80.9	78.3	103.3	103.2	986762.6	11.9669
81.0	78.7	98.5	98.4	963389.5	10.6054
79.0	76.6	98.2	98.1	958942.5	10.3905
77.1	74.4	99.3	99.3	789808.6	6.8792
77.8	75.0	100.1	100.1	806211.1	7.7391
78.6	75.9	100.8	100.7	797013.5	7.7391

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