

Viscosity of concentrated potato-starch pastes

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A new viscosity equation for the description of the viscosity of concentrated aqueous starch pastes is proposed:

$$\eta_{\text{app}} = Ke^{[Bm_{\text{starch}} + (C/T) - DW + (n-1) \ln \dot{\gamma}]}$$

with: m_{starch} = mass fraction starch in paste, T = temperature, W = amount of work performed on the starch, n = power-law index, $K = 3.063 \times 10^{-4}$ Pa s, $B = 12.03$ [—], $C = 4.134 \times 10^3$ K⁻¹, $D = 2.83 \times 10^{-2}$ kg dry starch/kJ, and $n = 0.494$.

The relation describes experimental results of viscosity measurements of potato starch both in a Couette viscometer and in a static mixer for: $0.2 \leq m_{\text{starch}} \leq 0.35$, $343 \text{ K} \leq T \leq 363 \text{ K}$, $3.3 \text{ kJ/kg dry starch} \leq W \leq 29.74 \text{ kJ/kg dry starch}$, and $2.71 \text{ s}^{-1} \leq \dot{\gamma} \leq 10.84 \text{ s}^{-1}$.

NOTATION

B	constant, describing the dependence of apparent viscosity on starch concentration (—)
C	constant describing the dependence of apparent viscosity on temperature (1/K)
D	constant describing the dependence of the apparent viscosity on the amount of work performed (kg dry starch/kJ)
d_t	inner diameter of tube (m)
K	factor in eqn (3) (Pa s)
L_t	tube length (m)
MARR	$\frac{\sum_{i=1}^p y - \hat{y} }{p} \times 100\%$ mean average relative residual
m_{starch}	mass fraction of starch in mixture (—)
n	power-law index (—)
$NeRe_d$	constant used in pressure-drop calculations for Sulzer static mixers, value: 1290 (—)
p	number of experimental points
t	time (s)
T	temperature (K)
v	superficial velocity of fluid (m/s)
W	work performed on starch paste (kJ/kg dry starch)
y	experimental value

\hat{y}	value from model calculation
Δp	pressure drop (Pa)
$\dot{\gamma}$	shear rate (s ⁻¹)
η_0	constant used in eqn (2) (Pa s)
η_{app}	apparent viscosity (Pa s)
$\eta(t)$	time dependent viscosity (Pa s)
ρ_p	density of starch paste (kg/m ³)

INTRODUCTION

The majority of viscosity data for aqueous starch pastes concern relatively diluted starch pastes in the concentration range from 1 to 10%, mass (Zobel 1984), often measured in a Brabender Amylograph. Since the shear rates in this apparatus are not clearly defined, the viscosity can only be expressed in the arbitrary Brabender units. Wong and Lelievre (1982) measured viscosities of wheat-starch pastes at concentrations ranging from 1 to 10% by mass using a cone-and-plate viscometer. Their results show both a distinct shear-thinning behaviour and a sharp increase in viscosity with increasing starch concentrations.

A model for the description of the viscosity of concentrated starch pastes was presented by Dolan and Steffe (1990). They distinguished five independent parameters affecting the apparent viscosity of these pastes:

shear rate;
temperature;
water content;
gelatinisation; and
strain history.

The experimental data of Dolan and Steffe (1990) are limited to starch concentrations of 13.7% mass.

In this paper a new viscosity equation is proposed on the basis of measurements with potato-starch paste up to 35% with respect to weight starch. Results from viscosity measurements with a Brabender Couette viscometer are compared with data obtained from pressure-drop measurements in a static mixer.

EXPERIMENTAL

Couette viscometer

Starch-paste viscosities were measured by using a Brabender Rheotron Couette viscometer (see Fig. 1). The outer diameter of the inner cylinder was 17 mm, and the length was 40 mm. The inner diameter of the outer cylinder was 21.7 mm. The samples were prepared by suspending native potato starch in a diluted aqueous potato-starch solution containing 3% starch by weight. The viscosity of the diluted starch solution was sufficient to prevent sedimentation of the starch during the experiments. Samples with a total starch concentration of 20, 25, 30, and 35% mass were tested in the viscometer (thermostatted at 343.15 K). The sample was allowed to gelatinise before the actual measurement started. In our experiments, shear rates ranged from 2.71 to 10.84 s⁻¹.

Static mixer

In addition, viscosities were determined from the pressure drop in a static-mixer reactor designed for the chemical derivation of aqueous starch solutions (see

Fig. 2) (Lammers *et al.*, 1993). In the description of the pilot plant, we follow the same path as the reactants.

A stirred tank is available for the preparation of starch slurries with a capacity of 50 dm³ (1). The starch slurry can be pumped into the reactor by using a Mohno pump (2). The starch slurry then flows through a heating coil (3), where it can be preheated. From the heating coil, the starch slurry flows to the premixer (4). Just prior to this, an aqueous sodium hydroxide solution can be added to the starch slurry with a metering pump. In the premixer, starch slurry and sodium hydroxide are mixed by the action of ten Sulzer SMX mixers. The amount of sodium hydroxide was always sufficiently high to cause gelatinisation of starch immediately after the premixer. From the premixer (with an internal diameter of 4.5 mm), the paste flows via a conical adapter to the heating section (5) (internal diameter 20 mm). This consists of a ceramic tube, which is inserted in the wave pipe of a microwave oven (6). The power output of the microwave oven can be varied between 0 and 1.2 kW. From the heating section, the paste flows via a conical adapter to the first of five measurement sections (7) (internal diameter 27.3 mm). Each section is equipped with a Pt 100 temperature sensor and a pressure sensor. From the measurement section, the paste flows to the first of four so-called SMX sections (8). These sections consist of a jacketed tube, filled with Sulzer SMX static-mixer elements to induce plug flow and to enhance heat transfer. The tube is thermostatted with water. The paste leaves the reactor via a pressure-controlling pneumatic valve (9).

The viscosity measurements were carried out for starch concentrations of 20–30% mass at 343, 353, and 363 K. The shear rates could be varied by changing the flow rate. The amount of sodium hydroxide added to achieve gelatinisation was 0.15 mol per mol anhydroglucose unit.

RESULTS AND DISCUSSION

Couette measurements

Figure 3 shows the typical time-dependent apparent-viscosity behaviour of a starch paste as measured in the Couette viscometer. The temperature was not varied in our experiments, and the relatively short time in which the viscosity of a potato-starch paste is built up owing to gelatinisation was not considered. In this case, viscosity depends on:

starch concentration (m_{starch});
shear rate ($\dot{\gamma}$); and
strain history ($W(t)$).

The strain history ($W(t)$) for the points in Fig. 3 was introduced into the viscosity equation by using an exponential dependence of the apparent viscosity on the

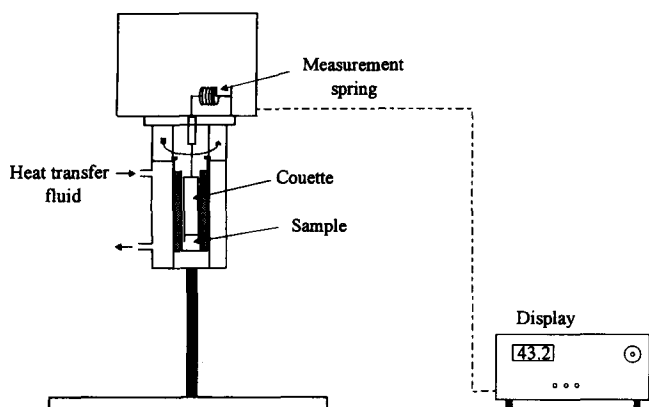


Fig. 1. Brabender Rheotron Couette viscometer.

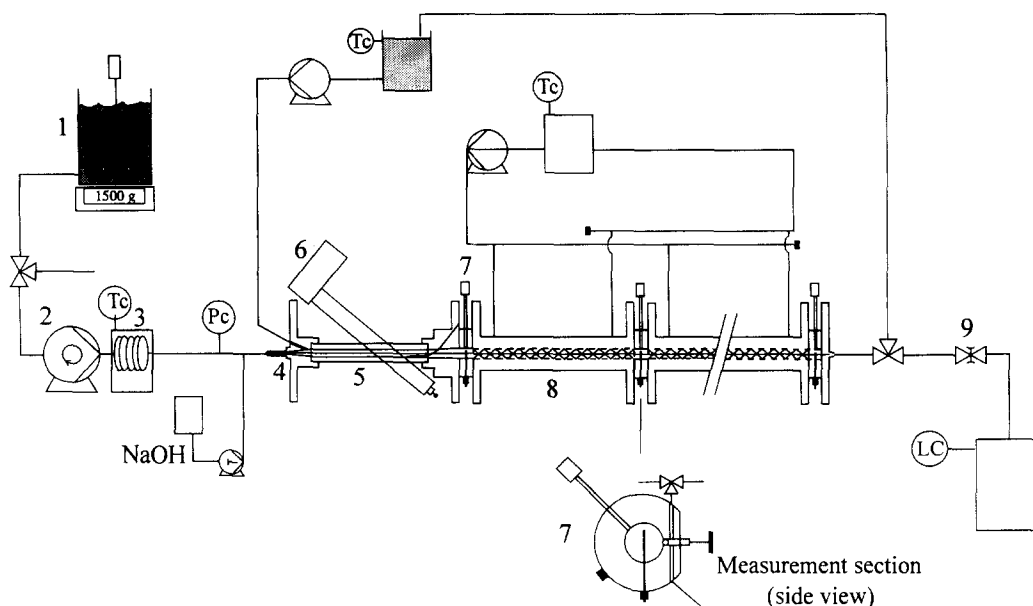


Fig. 2. Flow sheet of the static-mixer reactor used for viscosity measurements.

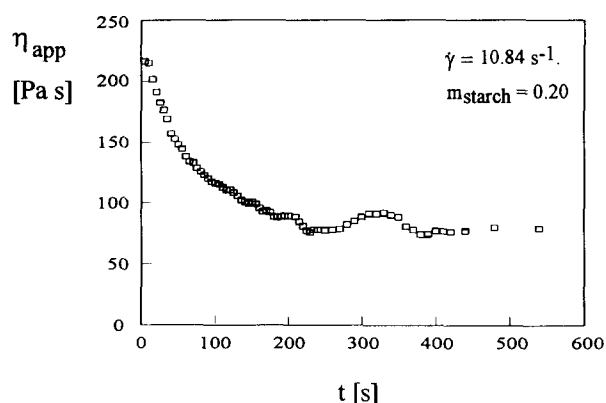


Fig. 3. Viscosity of a starch paste as a function of time.

amount of work performed on the paste. The value of $W(t)$ can be calculated from:

$$W(t) = \frac{1}{\rho_p m_{\text{starch}}} \int_0^t \eta(t) \dot{\gamma}^2 dt \quad (\text{kJ/kg dry starch}). \quad (1)$$

In modelling our experimental data (see Table 1), we modified the equation presented by Dolan and Steffe (1990) further by omitting the temperature-dependence and the gelatinisation term. The result is:

$$\eta_{\text{app}} = \eta_0 e^{(Bm_{\text{starch}}) - DW(t) + (n-1) \ln \dot{\gamma}}. \quad (2)$$

The experimental data were fitted to eqn (2) by using the Marquadt-Levenberg method (Press *et al.*, 1989). Table 2 shows values of the parameters η_0 , B , D , and n obtained from this fit.

A parity plot (see Fig. 4) shows a Mean Average Relative Residual (MARR) of 16.5% between the experimental data and eqn (2), with the parameters of

Table 2. Deviations occur because the viscoelastic properties of the starch pastes force it to flow upwards from the outer Couette cylinder to the shaft of the inner cylinder. This effect limits the experimental accuracy of the measurement of the apparent viscosities of highly concentrated starch pastes at high shear rates.

Static-mixer measurements

In analysing the viscosity measurements in the static mixer, the temperature was added as an independent variable. We again neglected the gelatinisation term, since the build-up of viscosity due to gelatinisation is almost instantaneous owing to the addition of sodium hydroxide. The equation describing apparent viscosity in the static mixer then reads:

$$\eta_{\text{app}} = K e^{[Bm_{\text{starch}} + (C/T) - DW + (n-1) \ln \dot{\gamma}]}. \quad (3)$$

The apparent viscosity of the pastes was determined from the pressure drop between two successive measurement sections, by using the pressure-drop relations of the SMX type of static mixer as given by Sulzer (1987):

$$\eta_{\text{app}} = \frac{\Delta p d_t^2}{Ne Re_d v L_t}. \quad (4)$$

The shear rate in the SMX static mixer can be calculated (Streiff, Sulzer AG, personal communication) from:

$$\dot{\gamma} = \frac{64v}{d_t}. \quad (5)$$

The work performed on a starch paste flowing through the static mixer was calculated from the over-all pres-

Table 1. Experimentally determined potato-starch paste viscosities for $0.1988 < m_{\text{starch}} < 0.3532$, $2.71 \text{ s}^{-1} < \dot{\gamma} < 10.84 \text{ s}^{-1}$, $3.3 \text{ kJ/kg dry starch} < W(t) < 29.74 \text{ kJ/kg dry starch}$

Experiment no.	m_{starch}	γ (1/s)	W (kJ/kg)	η_{app} (Pa s)
1	0.307	5.42	4.73	736.00
2	0.307	5.42	10.10	554.00
3	0.307	5.42	15.17	445.00
4	0.307	5.42	20.70	359.60
5	0.307	5.42	25.30	377.94
6	0.2436	5.42	5.10	352.00
7	0.2436	5.42	9.81	256.00
8	0.2436	5.42	13.06	285.00
9	0.2436	5.42	19.41	241.15
10	0.2436	5.42	27.34	243.97
11	0.2436	10.84	5.12	159.80
12	0.2436	10.84	10.26	107.20
13	0.1988	5.42	5.01	212.94
14	0.1988	5.42	10.26	143.83
15	0.1988	5.42	14.98	121.28
16	0.1988	5.42	19.65	98.71
17	0.1988	10.84	5.04	148.07
18	0.1988	10.84	10.14	112.11
19	0.1988	10.84	15.26	98.71
20	0.1988	10.84	19.97	88.84
21	0.1988	10.84	25.19	77.56
22	0.1988	10.84	29.74	90.96
23	0.2501	5.42	4.90	341.27
24	0.2501	5.42	10.00	245.38
25	0.2501	5.42	8.36	269.35
26	0.2501	10.84	4.94	256.00
27	0.2501	10.84	10.20	145.72
28	0.3003	5.43	5.00	644.00
29	0.3003	5.43	10.13	423.06
30	0.3003	10.84	4.90	432.23
31	0.3003	10.84	9.95	258.07
32	0.3003	10.84	15.33	169.93
33	0.3497	10.84	5.13	773.27
34	0.3497	10.84	10.13	629.89
35	0.3497	10.84	15.16	552.33
36	0.3497	10.84	20.38	491.22
37	0.1996	2.71	5.29	347.85
38	0.1996	2.71	10.47	240.68
39	0.1996	7.64	5.34	247.37
40	0.1996	7.64	10.10	106.68
41	0.2514	2.71	5.24	468.19
42	0.2514	7.64	5.49	270.04
43	0.2514	7.64	10.06	186.03
44	0.2956	2.71	5.44	916.64
45	0.3532	2.71	3.30	1767.46

sure drop. For a starch paste flowing in a particular reaction section, the pressure drop was calculated from the head of the Mohno pump as indicated by the pressure sensor in the discharge tube (Fig. 2) and the arithmetic mean of the pressure readings from both adjacent measurement sections. The work performed on this starch follows from:

$$W = \frac{\Delta p}{\rho_p m_{\text{starch}}}.$$

(6)

We made 120 viscosity measurements with shear rates ranging from 2.8 to 8.3 s⁻¹ and did work on starch

Table 2. Viscosity parameters for concentrated potato-starch gels at $T = 343.15 \text{ K}$; $3.3 \text{ kJ/kg} \leq W \leq 29.74 \text{ kJ/kg}$; $2.71 \text{ s}^{-1} \leq \dot{\gamma} \leq 10.84 \text{ s}^{-1}$; $0.199 \leq m_{\text{starch}} \leq 0.353$

Parameter	Value	Standard deviation
η_0	58.58	8.55
B	11.63	0.409
D	3.32×10^{-2}	3.95×10^{-3}
n	0.422	3.59×10^{-2}

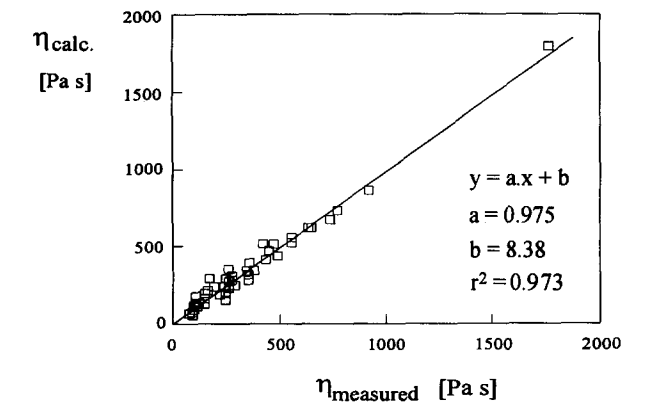


Fig. 4. Parity plot of all Couette starch gel viscosity measurements, $T = 343.14 \text{ K}$, $3.3 \text{ kJ/kg} < W < 29.4 \text{ kJ/kg}$, $2.71 \text{ s}^{-1} < \dot{\gamma} < 10.84 \text{ s}^{-1}$, $0.199 < m_{\text{starch}} < 0.353$.

ranging from 4.2 to 29.0 kJ/kg dry starch. The results were fitted to eqn (3) by using the Marquardt–Levenberg method. Table 3 shows the optimal values of the parameters K , B , C , D , and n obtained from this fit.

Table 3 shows that parameter values can be obtained with a relative error smaller than 2%. To judge whether eqn (3) can describe the viscosity measurements accurately, we made a parity plot of the experimental viscosities and the calculated values with the parameter values from Table 3 (see Fig. 5). It shows a MARR of 6.4% between measured and calculated viscosities, proving that eqn (3) indeed describes the apparent viscosity of starch pastes in the static mixer accurately.

Comparison

Table 4 compares the results of the viscosity measurements in the static mixer with those from the Brabender

Table 3. Values and standard deviations of the parameters K , B , C , D and n found from fitting viscosity measurements to eqn (3)

Parameter	Value	Standard deviation
K	3.063×10^{-4}	4.7×10^{-6}
B	12.03	1×10^{-2}
C	4.134×10^3	5.2
D	2.83×10^{-2}	5×10^{-5}
n	0.494	1×10^{-3}

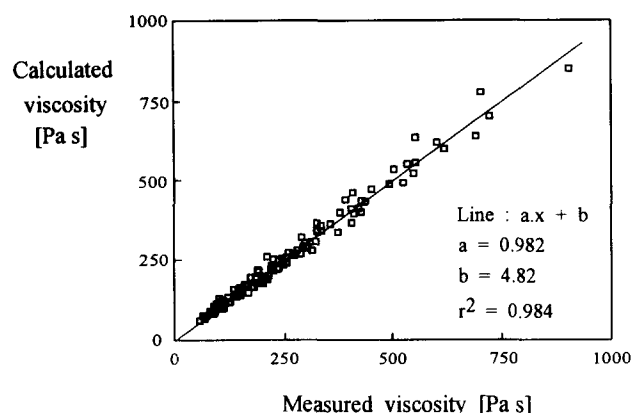


Fig. 5. Parity plot of all static-mixer viscosity measurements, $343\text{ K} < T < 363\text{ K}$, $2.8\text{ s}^{-1} < \dot{\gamma} < 8.3\text{ s}^{-1}$, $0.2 < m_{\text{starch}} < 0.3$ and $4.2\text{ kJ/kg} < W < 29.0\text{ kJ/kg}$.

Table 4. Results from parameter fit for viscosity measurements in a Brabender Couette viscometer and in the static mixer

Measurement method	η_0 (Pa s)	B	D (kg dry starch/kJ)	n
Couette	58.58	11.63	3.32×10^{-2}	0.422
Static mixer	52.26	12.03	2.83×10^{-2}	0.494

Couette viscometer. For the static-mixer data, η_0 was calculated from:

$$\eta_0 = K e^{C/T}, \text{ with } T = 343.15\text{ K}.$$

Table 4 shows that the numerical values of the parameters as obtained from both measurement methods are in fair agreement. To compare the results of viscosity calculations from eqns (2) and (3), apparent viscosities were calculated for $T = 343\text{ K}$, $m_{\text{starch}} = 0.2$ and 0.3 , $W = 0, 5$, and 20 kJ/kg dry starch, and $\dot{\gamma} = 1\text{ s}^{-1}$, 5 s^{-1} , and 10 s^{-1} (see Fig. 6).

Figure 6 shows a MARR of 12.2% between the apparent viscosities calculated from eqns (2) and (3) in the variable ranges tested. It proves that viscosity data obtained from Couette-viscometer experiments can be used in pressure-drop calculations for the design of static mixers.

CONCLUSIONS

A new equation for the description of the viscosity of concentrated starch pastes was derived. The equation gives a fairly good description of viscosity data obtained from experiments in a Couette viscometer with a MARR of 16.5%.

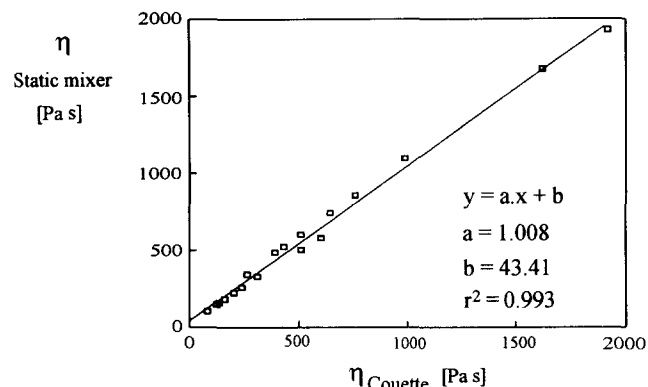


Fig. 6. Parity plot of viscosity eqns (2) and (3), $T = 343\text{ K}$, $m_{\text{starch}} = 0.2$ and 0.3 , $W = 0, 5$ and 20 kJ/kg and $\dot{\gamma} = 1\text{ s}^{-1}$, 5 s^{-1} , and 10 s^{-1} .

Results of viscosity measurements of concentrated starch pastes made in a Brabender Rheotron viscometer and in a static mixer are in fair agreement. The viscosity data of these rheological complex pastes, as obtained from a general-purpose viscometer, can thus be used in the design of process equipment.

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