Plant Fiber Processing using the Controlled Deformation Dynamic Mixer

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This article highlights the reduced energy consumption required by the Controlled Deformation Dynamic Mixer (CDDM) to process plant fibers. Trials have been performed using current industrial mixers, and the products created compared to those produced using CDDM technology. Increasing pressure leads to a product of greater viscosity, which is more desirable as the fibers have greater structure development and take up more water. This is also observed with the comparison current mixing technologies, but the energy consumption and pressure required to obtain products of equal viscosities is less when using CDDM technology.

Keywords: Fibers, mixing, CDDM, rotor-stator, specific energy

1. Introduction

The American Association of Cereal Chemists describes dietary fibers as being *carbohydrates that are indigestible or nonabsorbable by the small intestine but partially or fully fermentable in the colon* [1]. Food containing high levels of dietary fiber have been identified as being one method of treating and preventing obesity [2,3], reducing cholesterol levels through promoting excretion of bile acids [4], reducing the incidence of depression [5,6], decreasing the risk of both cardiovascular disease and diabetes [7,8] and reducing moderate and severe knee pain by reducing inflammation [9]. Finally, a recent meta-analysis of previously published meta-analyses regarding the effectiveness of the role of dietary fiber as a therapeutic agent for cardiovascular disease concluded that those who consume the highest amounts of dietary fiber, *can significantly reduce their incidence of and mortality from cardiovascular disease* [10].

The health benefits dietary fibers are of significant interest to the foodstuffs industry and increasing their content within products would lead to healthier products, and the amount required is, in actuality, quite small. Trumbo et al., (2002) recommend that males aged 14-50 years old consume 38 grams of fiber per day, and females aged 19-50 years old consume 25 grams of fiber per day [11].

The processing of fibers however, presents some significant challenges. During high-shear mixing, the structure of the fibers will rearrange, including disintegration of cells and cell wall fragments, and the formation of a three-dimensional network will occur [12]. The resulting dispersions are thick and in order to cope with these “networks”, previous work has used homogenizers, devices which are known to use a substantial amount of energy [13]. Consequently, there is considerable interest in finding more energy efficient mixers as although rotor-stator mixers are capable of operating well in batch mode, there is no clear consensus on the optimum settings for how to efficiently operate in-line rotor-stator mixers [14].

The Controlled Deformation Dynamic Mixer (CDDM) is a novel mixing technology which has been designed and developed to allow for both distributive and dispersive mixing [15]. By adding shims of specific sizes in between the stator and the home position causes the stator to be displaced relative to the rotor and move through the different mixing

modes (Figure 1). The mixer comprises of two spaced-apart mutually rotatable confronting surfaces containing cavities and Figure 1 displays the different methods of alignment of these surfaces [15]. When the cavities are substantially overlapping, they are defined as being in CTM mode. When the cavities are substantially lined up, then the mixer is classed as being in CDDM mode. The CDDM "knife edge" set-up is ideal as it has the small gap like a homogenizer, and large cavity overlap which allows for the fibers to be distributed. This provides both dispersive mixing due to the small gap fluid is forced to pass through, and distributive mixing due to rotation of the rotor. The mixing technology has been designed so that the bulk fluid flow within the mixing apparatus is in the plane of the surface of at least one cavity, causing the fluid to be consistently sheared, and never static [16].

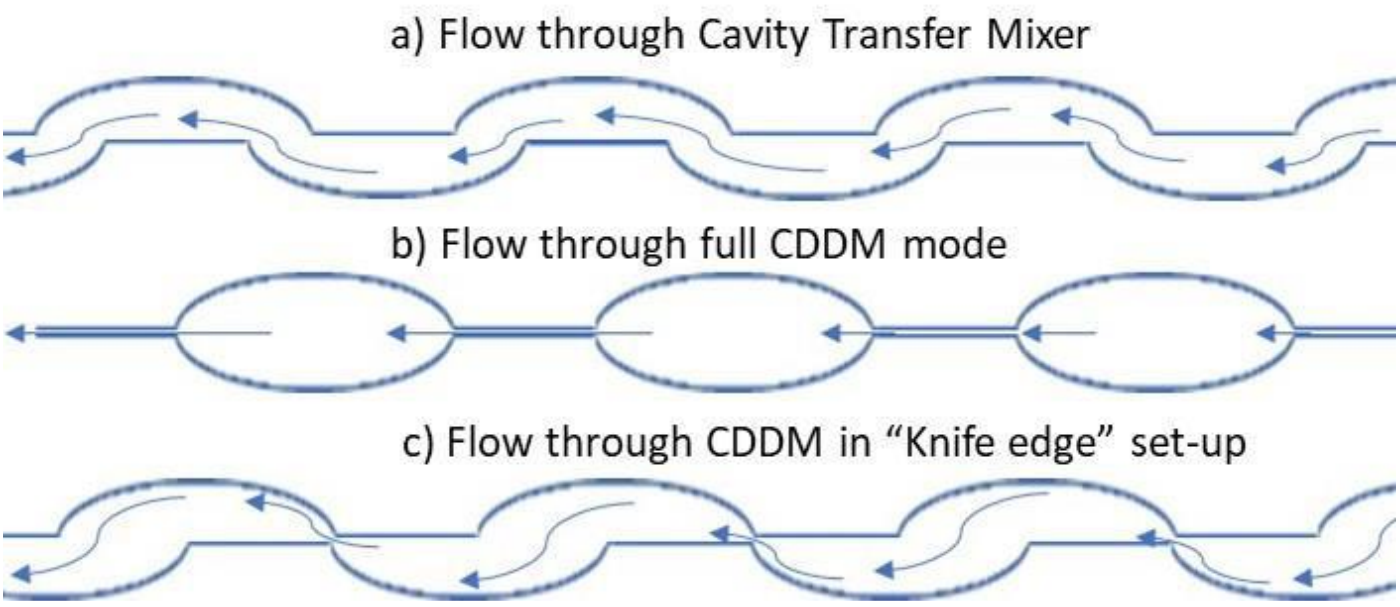

Figure 1. Fluid flow through CDDM when in a) cavity transfer mixer (CTM) mode b) full CDDM mode and c) CDDM "knife edge" mode.

Plant fibers are able to both absorb and store water, as a result of their structure. It is the *structural integrity of the cell wall* which determines the quantity of water the fiber can absorb and store [17]. The more water taken up by the fiber, the higher the viscosity of the dispersion, and this is promoted by shearing and mixing of the suspension. In this work comparison of the energy efficiency of the CDDM with two other mixers is examined, where effective dispersion is determined by the final viscosity.

2. Methodology

2.1 Materials and Methods

Three different high shear mixers were evaluated in these trials; Controlled Deformation Dynamic Mixing (TecExec ltd, UK), a Tetra Alex S05 High-Pressure Homogenizer (Tetra Pak Group) and a Silverson rotor-stator mixer (Silverson Machines Ltd, UK). In all cases a 2% premix of the plant fiber in water was prepared batch wise, and thoroughly mixed with a low shear impeller.

Trials involving use of the CDDM required 5 kg premix batches to be made up. Plant fibers were dispersed within water at 2 w.t.% concentration in 5 kg batches; 100g of powdered plant fiber was added to a 5 litre vessel, 4900 g of distilled water was added, and the resultant mixture was then stirred gently for 10 minutes using an overhead IKA Stirrer

fitted with a Jiffy Mixer (HS-1) [O.D. 67mm shaft length 260mm stirrer] at 1200 rpm. This dispersion produced a free-flowing slurry, which was then processed. The CDDM used was a small laboratory scale unit, with a rotor diameter of 12.5mm and 6 cavities around the circumference. Two lengths of mixer were used throughout this work, a short rotor comprising of 5 rows of cavities along shaft of the rotor, and a longer rotor comprising 12 rows of cavities. More details on the CDDM design can be found in [15], [16]. The upper operating pressure is limited by the 210 bar rupture discs, though in practice work was performed away from this limit. The premix was fed from a triplex plunger pump (Cat Pumps ltd, UK) which could deliver up to 285 gs^{-1} with pressure measured by both digital and analogue pressure gauges at the mixer entry, and flow rate measured by weighing a timed sample (Fig. 2a). The offset between the cavities on the rotor and stator was varied by the use of shims placed between the stator housing, and the bearing housing which held the rotor. A shim size equal to 0.0mm (i.e. an absence of any shim) corresponded to an overlap in the land between cavities of 0.25mm. A shim of 0.50mm corresponded to the cavities in the knife position (Figure 1c), and larger shims moving the arrangement to a CTM. When the mixer was stationary pressure spikes were observed which caused the rupture disc to open, but if the rotor was rotating, then pressure spikes were not observed. Consequently, by experience and through some testing, it was determined that a rotor speed of 250 rpm was sufficient to prevent pressure spikes. The pressure generated was a consequence of the shim, flow rate and mixer length with smaller shims, higher flow rates and a longer mixer resulting in higher pressures. To obtain total pressure drops above $150x10^5$ Pa (i.e. 150 bar) and closer to the $300x10^5$ Pa (i.e. 300 bar) possible in the HPH, the fiber premix was passed through the CDDM once at a fixed condition (typically at $80*10^5$ Pa) collected and passed through the mixer a second, and even third, time.

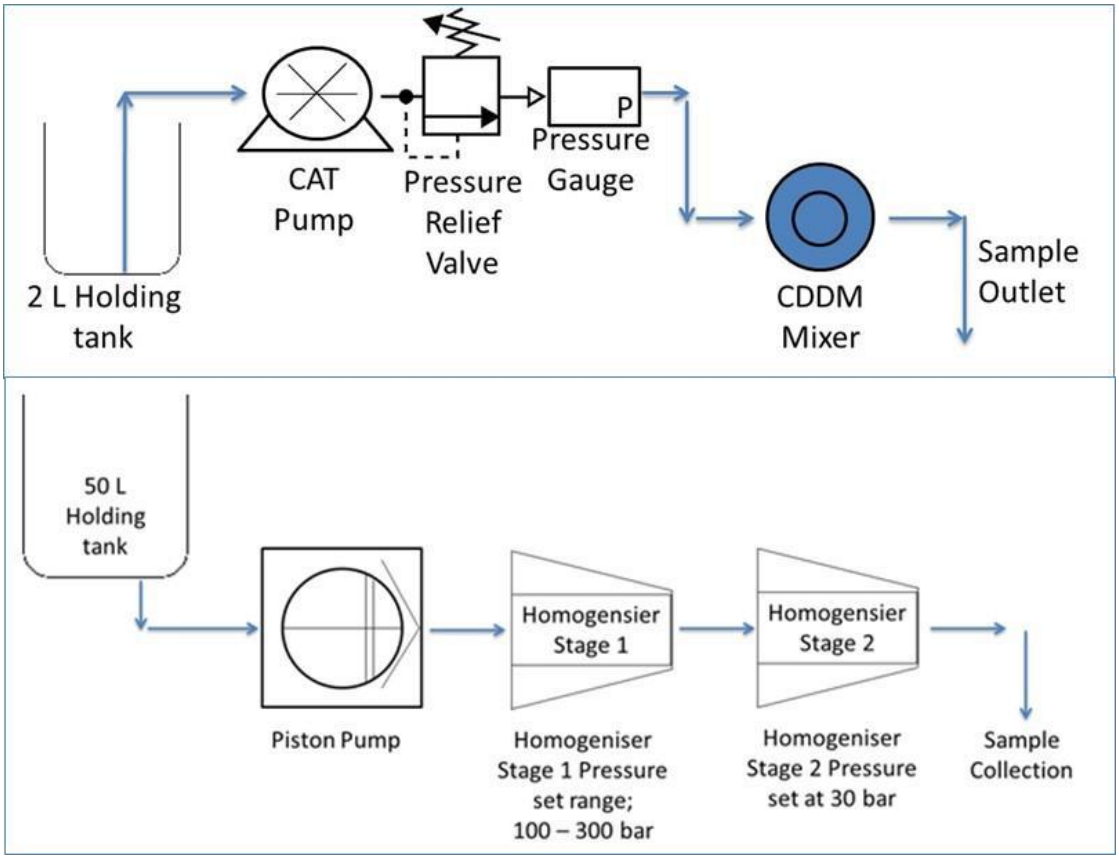

Figure 2. a) Fluid flow from holding tank, through CDDM mixer and out. b) Fluid flow from holding tank, through HPH and out.

The High-Pressure Homogenizer (HPH) used was an industrial scale two-stage homogenizer capable of processing at pressures in excess of $300x10^5$ Pa and flow rates of up to 75 gs^{-1}. The first stage of the two-stage homogenizer is where the majority of the pressure was applied during processing (Fig. 2b). Pressures were set between $100x10^5$ Pa and $300x10^5$ Pa. The second stage was set to $30x10^5$ Pa throughout all trials performed and the flow rate kept constant at 66.7 gs^{-1} (240 kg/h). This allowed exploration of cumulative pressure impact from $130x10^5$ Pa to $330x10^5$ Pa.

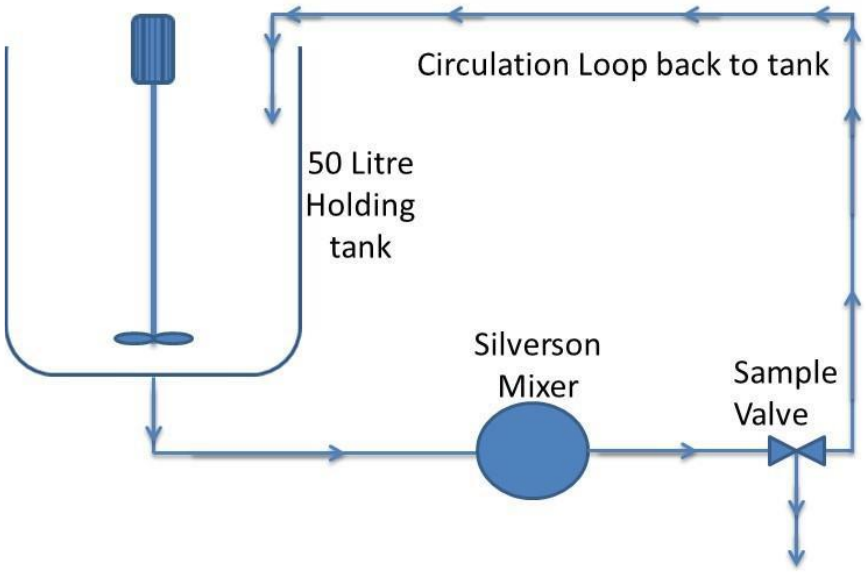

Figure 3. Fluid flow from holding tank, through mixer and back. When trials were completed, sample valve was opened and system drained.

The Silverson trials were performed on the Silverson MS 150/250 inline mixer which is a pilot plant scale mixer capable of high flow rates ranging from 100-1000 kg/hr (28 to 277.8 gs^{-1}). This required 50 kg batches to be made up prior to processing. For these trials, ten separate 5 kg batches were made up using the same method as described above to ensure consistency. To conduct the trials these batches were combined to form a single 50 kg batch which was stirred gently in the holding tank to prevent settling of the dispersion. The 50 L premix was recirculated from the holding tank, through the mixer, and back to the tank, via a circulation loop (Fig. 3). Two Silverson rotor speeds were used of 6,000 and 11,000 rpm with a flow rate of 1,080 kg/hr (300 gs^{-1}), with samples taken regularly for up to 4.5 hours. An illustration of this is provided in Figure 3.

Table 1. Mixers and the settings used for processing fiber slurry.

Mixer	**Flow Rates (gs^{-1})**	**Impeller Speeds (rpm)**	**Tip Speed (ms^{-1})**	**Pressure (Pa)**
High-Pressure Homogenizer (HPH)	66.7	n/a	n/a	1.3×10^7 to 3.3×10^7
Short CDDM	0.33 to 176	250 to 10,000	0.16 to 6.28	0 to 3.2×10^7
Long CDDM	0.80 to 78	500 to 12,500	0.31 to 7.85	0 to 1.4×10^7
Silverson MS 150/250 Inline mixer	300	6,000 & 11,000	19.95 to 36.6	0 to 8.5×10^5

The data displayed in Table 4 details the range of flow rates and impeller speeds that were set for the CDDM mixers and the Silverson MS 150/250 in-line mixer. For these mixers the pressure cannot be set, it was a result of the flow

rates, impeller speeds and the position of the CDDM mixer [CTM, CDDM, or "knife edge" setting]. The pressure was set for the High-Pressure Homogenizer (HPH) and there is no impeller speed as it does not rotate.

The processed fiber solution yield stress and viscosity at 200 s^{-1} was measured on an Anton Paar Dynamic Shear Rheometer (DSR 301 with RHEOPLUS/32 V3.62) capable of measuring 32 samples placed in a carousel. Initial analysis was performed at 5°C with a ST14-4V-35 vane, however this was replaced with an ST12.5 -4V – 25 vane when it was determined that analysis should be performed at 25°C. An example of some flow curves is presented in Figure 4 for samples with increasing viscosity as a result of more intense processes.

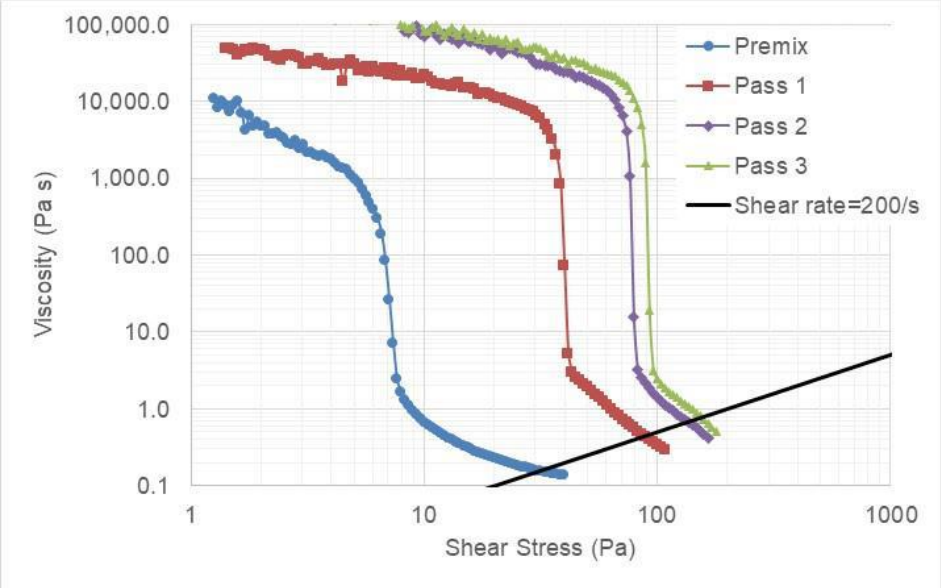

Figure 4. Rheology profiles of slurry passed through the mixer. NB: These samples were analysed using the 25°C rheology method. Dashed line indicates shear rate of 200 s^{-1}.

The initial trials did not contain preservative, so immediately after manufacture they were placed in a refrigerated environment, to prevent microbial growth and to ensure consistency the viscosity was measured at 5°C. An unexpected consequence was the additional time (12hrs) required for the water bath to cool the whole rheometer, leading to analytical times in excess of 24 hours. In later experiments the temperature was increased to 25°C and the vane was changed. These alterations significantly reduced the overall time required and allowed more samples to be characterised; the alterations also resulted in the samples analysed appearing to have a higher viscosity during analysis. To ensure the accurate reporting of results, a series of tests were performed using the same samples. The samples were analysed at 5°C with a ST14-4V-35 vane, and at 25°C with a ST12.5 -4V – 25 vane. The linear conversion between the samples is displayed in Fig. 5 and shows a linear relationship which allows the results between the methods to be transposed.

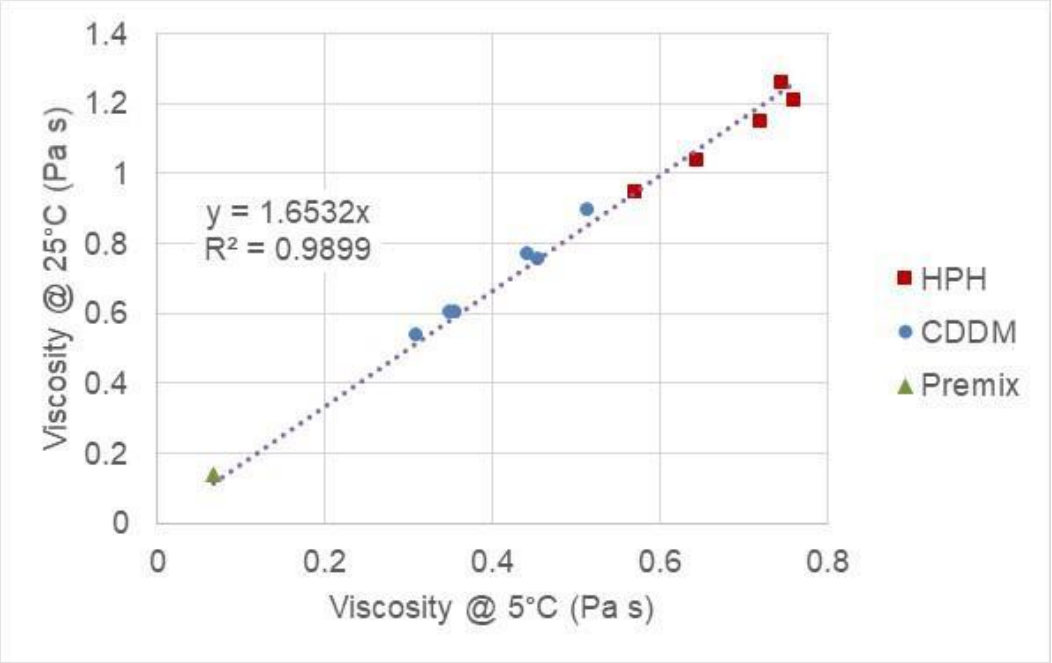

Figure 5. Viscosity measurements at 200 Pa.s using both method 1 and method 2.

To ensure that there was no microbial growth the samples were preserved with 0.1% proxel. Comparative samples were prepared with and without preservative and these had the same viscosity and yield stress (not shown). In this paper data from both protocols are used but the conversion between them is linear (Figure 5). The latter technique is primarily presented in this paper and the one figure presenting data using the former technique (Fig. 6) has a second axis with the equivalent scale on the 25°C method. Multiple samples were made under certain conditions and these indicated a variability of about +/-10%.

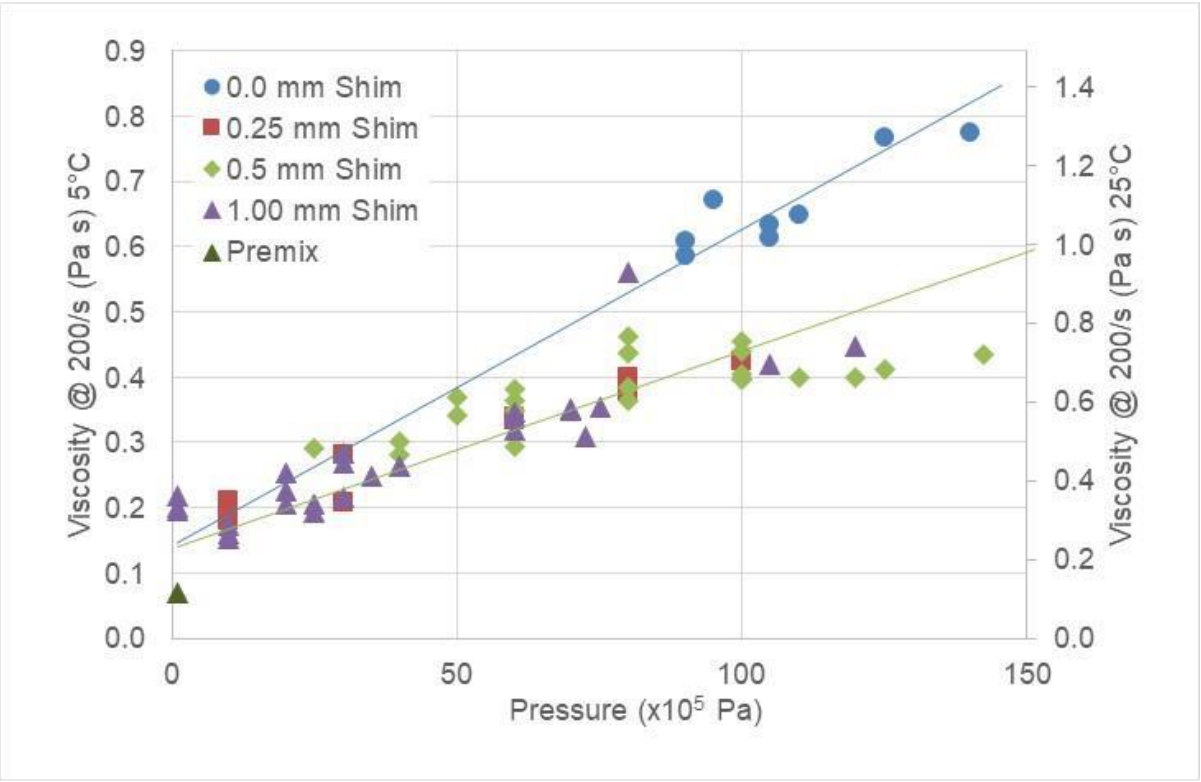

Figure 6. Product viscosity as a result of different shim sizes and pressure during processing. NB: The samples were measured at 5°C but a second y axis is included with the equivalent viscosity at 25°C.

2.2 Specific Energy Equations

The specific energy is the amount of energy required to process each kilogram of product and requires an estimate of the energy from the pressure driven flow and the rotational driven flow. The high-pressure homogenizer (HPH) is the simplest unit to start with since it only has a pressure driven flow and the specific energy is given by the pressure drop divided by the density and has units of J/kg. It is calculated via eq. 1.

$$Specific\ Energy = \frac{\Delta P}{\rho} \qquad \textbf{Equation 1}$$

Where ΔP = change in pressure (Pa), ρ = density (kg/m^3). For a typical HPH pressure of 100x10^5 Pa, the specific energy is therefore 10^4 J/kg.

The Silverson only has a contribution from rotational power [18] and this is calculated using eq. 2:

$$Power\ (W) = P_{oz}\rho N^3 D^5 + k_1 \dot{m} N^2 D^2 \qquad \textbf{Equation 2}$$

where P_{oz} = 0.1, N = rotations per second, D = 0.064 m, k_1 = 10, ṁ = mass flow rate (kg s^{-1}). The power draw for the Silverson operating at the higher rotor speed (11,000 rpm) is about 750 W. Specific energy is then calculated using eq. 3:

$$Specific\ Energy = \frac{Power * Process\ Time}{Mass\ of\ Batch} \qquad \textbf{Equation 3}$$

For an hour of operation at the higher speed, the specific energy for the Silverson mixer is about 5.4x10^4 J/kg which is much greater than the HPH. The CDDM can be classed as a rotor-stator mixer (eq. 2) with a pressure driven component (eq. 1), where the latter is converted into a power (eq. 4) and the two components are added together before being divided by the mass flow rate (eq. 5)

$$Power = \Delta P * \frac{\dot{m}}{\rho} \qquad \textbf{Equation 4}$$

where power is in W,

$$Specific\ Energy = \frac{Total\ Power}{\dot{m}} \qquad \textbf{Equation 5}$$

It was established that rotor speed does not contribute to the development of the structure of the fibers, but a minimum rotor speed is required to prevent pressure spikes. Consequently, to minimise the power it makes sense that the minimum rotor speed (250 rpm) would normally be used. The CDDM has not been fully characterised, and the constants in eq. 2 not determined, but it is instructive to use the Silverson values to make an estimate of the rotational power contribution. Picking a high viscosity sample, a typical flow rate for zero shim is 25 gs^{-1} (0.025 kg s^{-1}), the minimum rotor speed is 250 rpm (~4/s) and the diameter of the mixer is 0.0125 m. The first term in eq. 2 is 2.2x10^{-6}W and the second term is 6x10^{-4}W; however, the power due to the pressure driven flow is 1,000W, therefore the power contribution from the rotational flow is negligible compared to the pressure driven flow.

3. Results and Discussion

Data in Figure 6 is coded by shim size and shows that for the 0mm shim (i.e. no shim), the viscosities are significantly higher than the other shim sizes. Similar representations (not shown) where the data is segmented by flow rate, or by

rotor speed, show no systematic trends; pressure drop across the mixer is the only parameter that shows a distinct difference between the 0mm shim size and the other shims. At zero shim the mixer is in the closed mode of the CDDM (Fig. 1b) whereas the other data represents the knife edge (Fig. 1c) through to the open mode representing the cavity transfer mixer (Fig. 1a). For the zero shim size it was not possible to get low pressures because the pump flow rate could not be turned down sufficiently.

The implication is that the dispersion of plant fibers is much more sensitive to extensional flows, with little dependence on shear flows. Moreover, correlation with pressure drop suggests that the dispersion is driven by specific energy (i.e. energy per kg of processed material), which is proportional to pressure drop, rather than energy dissipation rate (power per unit volume of mixer). The fully closed CDDM position is therefore more energy efficient in dispersing the fiber and producing a higher viscosity product.

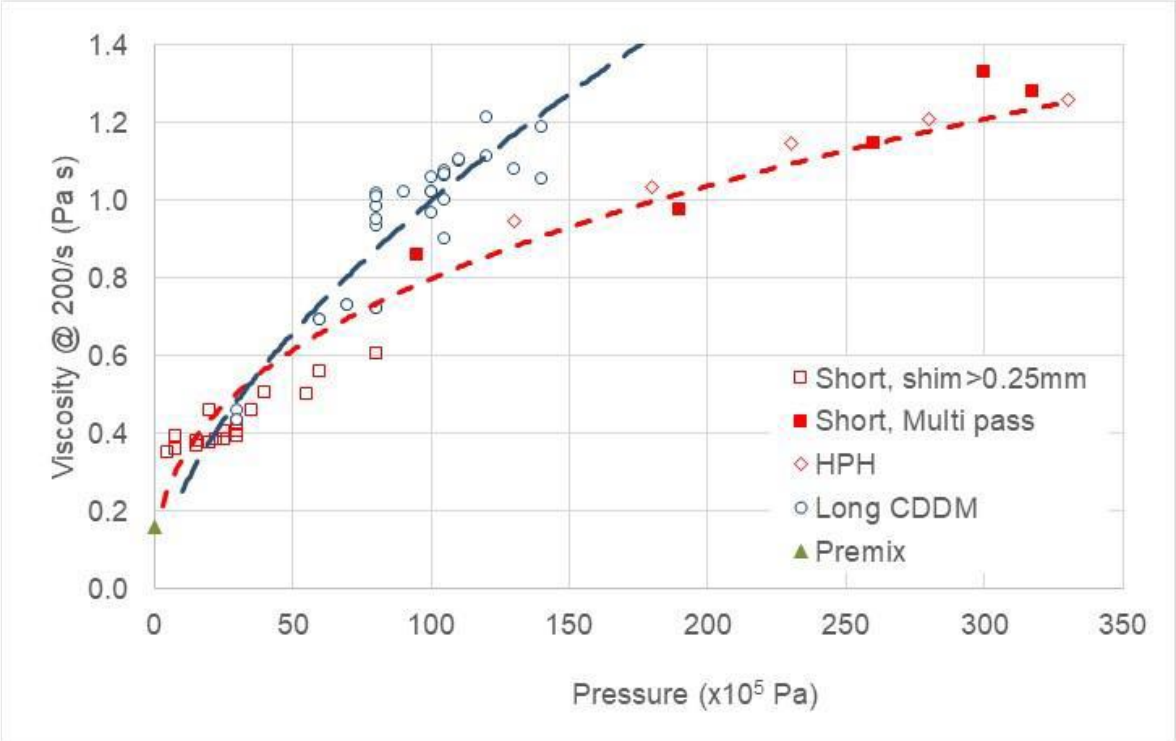

Figure 7. Product viscosity as a result of pressure applied during processing. Dashed lines represent trend line of data set of the same colour. NB: These samples were analysed using the 25°C rheology method.

Figure 7 presents a comparison between the CDDM and the high-pressure homogenizer (HPH). The HPH data is obtained from a single pass, where the backpressure is gradually increased with the lowest pressure that could be achieved at about 130x10^5 Pa. The CDDM data includes different modes of use. Firstly, to achieve similar pressures to those of the HPH, multiple passes through the short CDDM were required, with the cumulative pressure used as the independent variable. The maximum pressure that can be obtained in the CDDM is set by the design constraints; 200 bar as the rating of the pressure relief valve, and 210 bar which is the rating of the rupture disc. As the fibers are dispersed and the suspension thickens, there is a chance that on subsequent passes the pressure will be higher and the relief valve will open, or the rupture disc will open. As a consequence a set of operating conditions were selected to produce a pressure of about 80-100x10^5 Pa, providing a reasonable safety margin. This enables the suspension to be passed through the CDDM under identical conditions for each pass a total of 4 times with a cumulative pressure of ~320x10^5 Pa achieved. The process conditions for the multi-pass experiment are displayed in Table 5 and it can be seen

by the viscosity value that the fiber solution retains the viscosity of the previous pass, each subsequent pass increases the viscosity of the fiber solution further.

Table 2. Processing parameters and resulting product viscosity from multi-pass trial using short rotor CDDM.

Pass number	**Shim Size ($x10^{-3}$ m)**	**Impeller Speed (rpm)**	**Flow Rate (gs^{-1})**	**Tip Speed (ms^{-1})**	**Pressure Drop ($x10^5$ Pa)**	**Cumulative Pressure Drop ($x10^5$ Pa)**	**Viscosity at 200 s^{-1} (Pa.s)**
1	0.50	500	23.5	0.314	95	95	0.858
2	0.50	500	25.5	0.314	95	190	0.974
3	0.50	500	24.0	0.314	70	260	1.146
4	0.50	500	21.3	0.314	40	300	1.329
5	0.50	500	7.1	0.314	17.5	318	1.279

The data (Fig. 7) shows good agreement between the HPH and the CDDM data, indicating that the HPH and the short CDDM rotor provide similar structuring of the fiber suspension. This is consistent with the earlier observation that the viscosity of the product is largely a result of the specific energy, as given by the cumulative pressure drop per pass. Taking the central points on then red trendline shown in Fig. 7, the short CDDM rotor is able to produce a sample of with a viscosity of 0.974 Pa.s following cumulative pressure of 190 bar, and the HPH produces a sample with a viscosity of 1.035 Pa.s following cumulative pressure of 180 bar. For these two samples the one created using the HPH has been subjected to one major extensional flow event at 150 bar and one minor extensional flow event at 30 bar; whereas by comparison the short rotor CDDM has 5 events of roughly equal pressure drop per pass, and in the example discussed this is two passes, therefore it has been subjected to 10 events of roughly equal pressure drop. The development of the fiber structure and the increasing product viscosity depends on the cumulative effect of these extensional flow events (i.e. specific energy), it is not dependent on the magnitude of the biggest event. In this regard it can be determined that the fibers behave differently to emulsions, whereby the drop size depends primarily on the magnitude (e.g. shear rate or energy dissipation rate) of the most intense event.

A further set of trials were performed using a longer rotor CDDM. The long rotor CDDM has an extra 7 cavities compared to the short CDDM rotor, and therefore for the same operating conditions, it is expected that the pressure drop will be higher. The majority of the trials were with a 1mm shim (pressure drop was too large for zero shim) and different flow rates and rotor speeds but as before, it is the pressure drop that is the main correlating factor, and thus the data is shown as one set of data for simplicity. For the longer rotor CDDM mixer, there is enhanced performance (i.e. higher viscosity at lower pressure) to that observed using the short rotor, the HPH and multiple passes through the short rotor. This suggests that there is an advantage to repeated and regular exposure to extensional flow events.

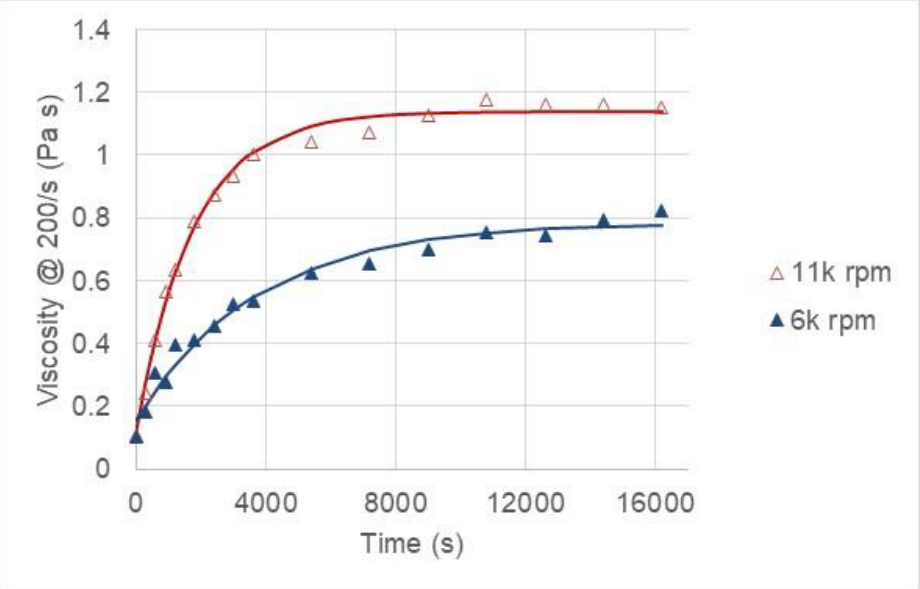

Figure 8. Product viscosity as a function of time at two mixer speeds using Silverson MS 150/250 in-line mixer. NB: These samples were analysed using the 25°C rheology method.

The Silverson MS 150/250 in-line mixer trials (Fig. 8) lasted for 4.5 hours and samples were taken throughout the mixing process. A higher rotor speed leads to a more rapid development of viscosity and a higher plateau similar to that observed with the CDDM and the HPH. The data from the 6,000 rpm trial appears to have not reached a plateau, and the viscosity of the products appears to still be increasing, albeit slowly, over time.

Table 3. Processing parameters for all configurations resulting in the highest product viscosity. Shim size only a variable parameter for CDDM therefore n/a for HPH and Silverson. *Silverson batch process produces 50 kg of product in 10,000 seconds, giving flow rate of 5 gs^{-1} in continuous process.

Mixer	Shim Size ($x10^{-3}$ m)	Impeller Speed (rpm)	Flow Rate (gs^{-1})	Tip Speed (ms^{-1})	Cumulative Pressure Drop ($x10^5$ Pa)	Viscosity at 200 s^{-1} (Pa.s)
Short rotor CDDM 4th Multi-pass	0.50	500	23.5	0.314	300	1.33
Short rotor CDDM 0mm shim	0.00	750	29.5	0.471	125	1.25
Long rotor CDDM	1.00	12500	1.7	7.854	120	1.21
High-Pressure Homogenizer (HPH)	n/a	n/a	66.7	n/a	330	1.26
Silverson	n/a	11000	5.0*	36.573	5.5	1.18

The conditions resulting is the highest viscosities are summarised in Table 6. The short CDDM with 0mm shim setting, and the long CDDM, produce high viscosity products at the lowest pressures. The flow rate for the former is about 17

times larger and so is preferred. The short rotor CDDM which is partially open [has shims inserted] can achieve high viscosity products, but only at high pressure and would require 4 machines in a series. High-Pressure Homogenizer can also produce high viscosity products but at high pressure ($330x10^5$ Pa). The flow rate is also high, but this is a consequence of the size of the machine. A larger diameter CDDM operated at the same pressure drop and 0mm shim would also have a higher flowrate. Finally, the Silverson also has a low flow rate and as such appears to be less suited to processing fibers. Consequently the best operating conditions are the short CDDM with 0mm shim.

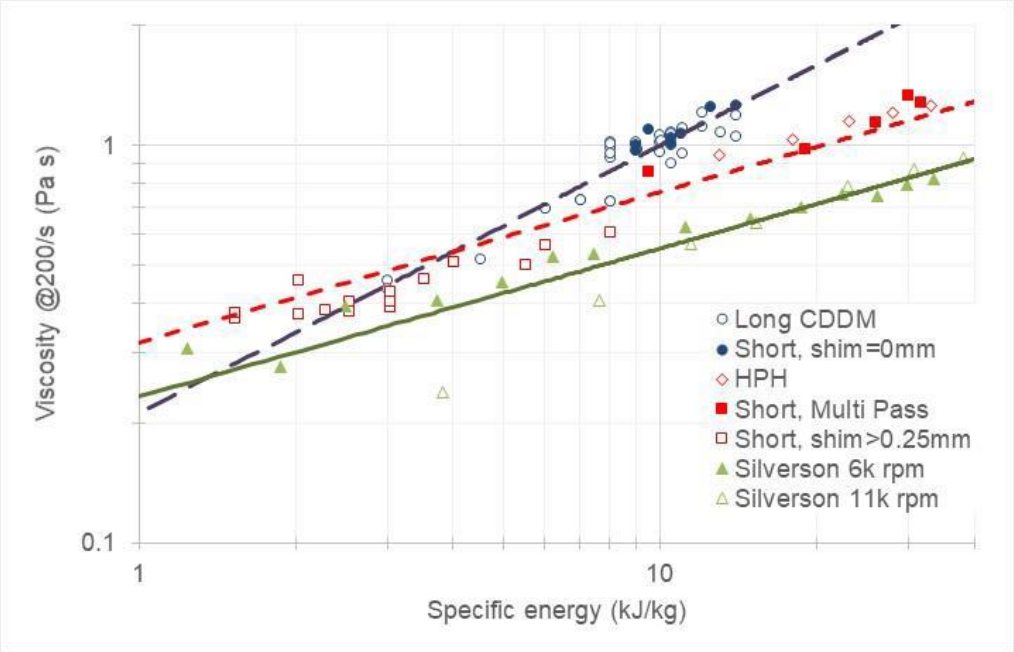

Figure 9. Product viscosity as a result of Specific Energy (kJ/kg). Dashed lines represent trend line of data set of the same colour. NB: These samples were analysed using the 25°C rheology method, except the 0 shim short CDDM data which has been predicted based on its 5°C data.

Figure 9 summarises the data from the three mixers in terms of the specific energy. It is usual to present this data on logarithmic axes and the lines are power law fits. The Silverson data from the two different speeds lie on a similar trajectory, which indicates that specific power is the appropriate scaling parameter, and that similar viscosity products can be achieved from both high and low power scenarios by adjusting the exposure times. Unfortunately the development of the same high viscosities as the other two mixers requires a much higher specific energy. The relationship between the CDDM (short and long rotor) and the HPH is the same as seen in Figure 7, since the rotational contribution for the CDDM is small compared to the pressure driven flow. Figure 9 shows that a lower specific energy is required for the long rotor CDDM technology, and the short CDDM with zero shim, to produce products of equal viscosity to those of the HPH, therefore the CDDM is more energy efficient than the HPH.

4. Conclusion

The Controlled Deformation Dynamic Mixer (CDDM) technology has shown to be capable of processing plant fiber slurry and generating a high viscosity suspension comparable to that produced by a high-pressure homogenizer (HPH). The key scaling parameter has been identified as the specific energy (effectively the pressure for the CDDM and HPH).

A long rotor CDDM, and short rotor CDDM with zero shim, produce a higher viscosity product at lower specific energy (and hence lower pressures) than either the HPH, or a short CDDM [fitted with shims]. It is suggested that this is a

consequence of the greater number of cavities along the rotor, and thus more frequent and more regular exposure to extensional flow event in the longer CDDM. This might be tested by increasing the flow rate in the short rotor to access higher pressure drops, but unfortunately this was not possible on the current facility due to the limitations of the pump and the safety devices. Such a test would be useful to achieve a higher production rate with a lower specific energy requirement, than the industrial benchmark of the HPH.

The Silverson mixer requires multiple passes through the mixer to achieve a product of relatively high viscosity, whereas the CDDM and HPH have shown they can create products of a higher viscosity in a single pass.

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Symbols Used

Symbols

D	[m]	Diameter
k_1	[-]	Flow power constant
N	[rps]	Rotations per second
P_{oz}	[-]	Zero flow power constant
P	[Pa]	Pressure

Greek letters

ΔP	[Pa]	Change in Pressure
ρ	[kg/m^3]	Density
$\dot{m}$	[kg s^{-1}]	Mass flow rate

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Collection of Figure Legends

Figure 1. Illustration showing flow of fluid through CDDM when in a) cavity transfer mixer mode b) full CDDM mode and c) CDDM knife edge mode.

Figure 2. a) Schematic showing flow of fluid from holding tank, through CDDM mixer and out. **b)** Schematic showing flow of fluid from holding tank, through HPH and out.

Figure 3. Schematic showing flow of fluid from holding tank, through mixer and back. When trials were completed, sample valve was opened and system drained.

Figure 4. Rheology profiles of slurry passed through the mixer. NB: These samples were analysed using the 25°C rheology method. Dashed line indicates shear rate of 200 s^{-1}.

Figure 5. Viscosity measurements at 200 Pa.s using both method 1 and method 2.

Figure 6. Graph showing the viscosity of the product as a result of different shim sizes and pressure during processing. NB: The samples were measured at 5°C but a second y axis is included with the equivalent viscosity at 25°C.

Figure 7. Graph showing the viscosity of the product as a result of pressure applied during processing. NB: These samples were analysed using the 25°C rheology method.

Figure 8. Graph showing the viscosity of the product as a function of time at two mixer speeds using Silverson MS 150/250 in-line mixer. NB: These samples were analysed using the 25°C rheology method.

Figure 9. Graph showing the viscosity of the product as a result of Specific Energy (kJ/kg). NB: These samples were analysed using the 25°C rheology method, except the 0 shim short CDDM data which has been predicted based on its 5°C data.

Tables and table legends

Table 4. Mixers and the settings used for processing fiber slurry.

Mixer	Flow Rates (gs^{-1})	Impeller Speeds (rpm)	Tip Speed (ms^{-1})	Pressure (Pa)
High-Pressure Homogenizer (HPH)	66.7	n/a	n/a	1.3×10^7 to 3.3×10^7
Short CDDM	0.33 to 176	250 to 10,000	0.16 to 6.28	0 to 3.2×10^7
Long CDDM	0.80 to 78	500 to 12,500	0.31 to 7.85	0 to 1.4×10^7
Silverson MS 150/250 Inline mixer	300	6,000 & 11,000	19.95 to 36.6	0 to 8.5×10^5

Table 5. Processing parameters and resulting product viscosity from multi-pass trial using short rotor CDDM.

Pass number	Shim Size ($x10^{-3}$ m)	Impeller Speed (rpm)	Flow Rate (gs^{-1})	Tip Speed (ms^{-1})	Pressure Drop ($x10^5$ Pa)	Cumulative Pressure Drop ($x10^5$ Pa)	Viscosity at 200 s^{-1} (Pa.s)
1	0.50	500	23.5	0.314	95	95	0.858
2	0.50	500	25.5	0.314	95	190	0.974
3	0.50	500	24.0	0.314	70	260	1.146
4	0.50	500	21.3	0.314	40	300	1.329
5	0.50	500	7.1	0.314	17.5	318	1.279

Table 6. Processing parameters for all configurations resulting in the highest product viscosity. Shim size only a variable parameter for CDDM therefore n/a for HPH and Silverson. *Silverson batch process produces 50 kg of product in 10,000 seconds, giving flow rate of 5 gs^{-1} in continuous process.

Mixer	Shim Size ($x10^{-3}$ m)	Impeller Speed (rpm)	Flow Rate (gs^{-1})	Tip Speed (ms^{-1})	Cumulative Pressure Drop ($x10^5$ Pa)	Viscosity at 200 s^{-1} (Pa.s)
Short rotor CDDM 4th Multi-pass	0.50	500	23.5	0.314	300	1.33
Short rotor CDDM 0mm shim	0.00	750	29.5	0.471	125	1.25
Long rotor CDDM	1.00	12500	1.7	7.854	120	1.21
High-Pressure Homogenizer (HPH)	n/a	n/a	66.7	n/a	330	1.26
Silverson	n/a	11000	5.0*	36.573	5.5	1.18

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A new mixing technology, Controlled Deformation Dynamic Mixer (CDDM), is shown to have lower specific energy requirement that other commercial mixers. Combining high-pressure and a rotor-stator cavity design, the CDDM is shown to be capable of producing products of equal viscosity, at half the pressure of the currently used industrial benchmark.