Role of Rheology in Extrusion –

Determining the Effective Viscosity in the Screw

Dennis Forte & Associates Pty. Ltd.
P.O. Box 20
Greensborough, 3088
Victoria - Australia.
Phone +61 416 261 726
Email: forte1@iinet.net.au

Effective Viscosity in the Screw

Influence of Rheology on Extrusion

The *Rheology* of an *Extrusion Melt* considers both the *Viscous Effects* and also the *Elastic Effects* associated with the *Melt Flow*.

The Rheology has a direct influence on the *Product Characteristics* via:

- **Control of the *Bubble Growth Rate***
- **Control of the *Degree of Expansion***
- **Control of the *Degree of Curvature***

The Rheology has a direct influence on the *Process Design* via:

- **Control of the *Die Pressure Drop***
- **Control of the *Screw Flow Dynamics***
- **Control of the *Screw Energy Consumption***

Effective Viscosity in the Screw

Extrusion System Volumetric Flow Components

$$Q_{net} = Q_{drag} - Q_{pressure} - Q_{leakage} = Q_{net} = K\,\Delta P / \mu_{apparent}$$

Screw Characteristic — **Die Characteristic**

$Q_{net,in} \approx M / \rho_B$ — $Q_{net,out} = Q_{net,in} - Q_{gas} = M / \rho_M$

where,

Q_{net} = Total Melt Flow / Melt Density $[\rho_M = f[\text{Recipe}, w_M, T_M]]$

$Q_{drag} = f[N, \text{Screw Geometry}, \text{Recipe}, COF_{barrel}]$

$Q_{pressure} = f[\Delta P, H^3, 1/\mu_{apparent}]$

$Q_{leakage} = f[\Delta P, \text{Flight Gap}, 1/\mu_{apparent}]$

$K = f[A, L, S, COF_{die}]$

Note: Sufficient *Recirculation* must occur or the Product won't be *Cooked*.

Effective Viscosity in the Screw

How can we define the Viscosity in the Screw?

If we could look inside an *Operating Extruder* (in *Steady-State*) we would find a *Substrate* (i.e. the *Formulation* plus all the *Additives*) which is in a continual state of "*flux*" or "*transformation*" (i.e. it's being *Cooked*!). The question most often asked is:

"Which is the most relevant "*Component*" of the Rheology?"

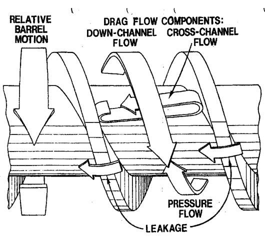
Powder Rheology	Dough Rheology	Transitional Rheology	Melt Rheology	Expanded Foam Rheology

The answer is that "the Extruder (i.e., the *Motor Drive*) *"sees" all of them, at the same time!*"

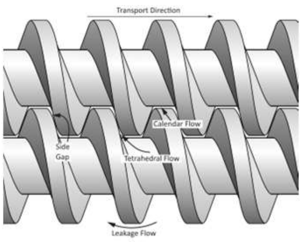
Effective Viscosity in the Screw

Flow Components within the Extruder System

Single Screw Extruders



Co-Rotating TSE



The *Flow Components* (and hence the *Cooking Reactions*) involved in the different types of Extruders are also very different.

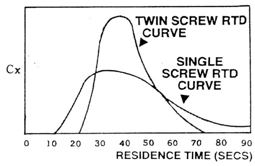
Effective Viscosity in the Screw

The *Filled Length* of the Extruder

The "balance point" between the various Flow Components, ultimately determines the *Filled Length* (or the *Choke Point*) of the Extruder This determines the *Operating Volume* and hence, the magnitude of the *Mean Residence Time*, t_R.

$$t_R = V_{total} / Q_{net} = L_f A_x / Q_{net}$$

The magnitude of t_R for the TSE is typically slightly "lower" (and the RTD is "narrower") than that for a SSE.



Effective Viscosity in the Screw

Energy Inputs

$$E_{total} = E_{mechanical} + E_{convective} + E_{conductive}$$

Total Energy Input	Net Power Input	Latent Energy Input / Removal	Barrel Heat Transfer
[Typically	40 to 90%	0 to 30%	10 to 30%]

where

$E_{mechanical}$ = *f* [Rheology, Strain]

$E_{convective}$ = *f* [Volatiles* Injection / Removal] (Typically Steam)

$E_{conductive}$ = *f* [Barrel Temperature]

Note : The Energy Inputs are NOT directly interchangeable! The Energy Inputs determine the *Product Attributes*.

Effective Viscosity in the Screw

Manifestations of the Energy

$$E_{total} = E_{sensible} + E_{cook} + E_{pump} + E_{screw} + E_{radiant}$$

Total Energy Outputs	Temperature Rise	Ingredients Modifications	Pressure Rise	Screw Flow Dynamics	Energy Losses

[Typically only 1% to 2% of E_{total}]

where,

$E_{sensible}$ = *f* [Formulation, $T_{ambient}$, $T_{preconditioner}$, T_{final}]

E_{cook} = *f* [Formulation, Cooking Enthalpy]

E_{pump} = *f* [Q_{net}, ΔP]

$E_{radiant}$ = *f* [T_{barrel} - $T_{ambient}$]

Note: Achieving these *Process Parameters* is confirmation that we have made the "right" Product.

Effective Viscosity in the Screw

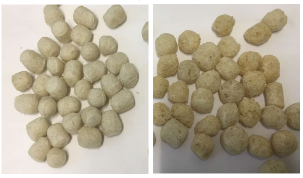
Viscous Dissipation and the RTD

It can be shown (via *Weighted Average Total Strain Analysis*) that the *Power Dissipation* within the Extruder is a function of the *Rheology of the Formulation*, the *Residence Time* and the *Shear Rate* developed within the Extruder Screw.

As a result of the complex *Flow Dynamics* developed within the various types of Extrusion systems, the *Product Melt* will experience a *Residence Time Distribution* (RTD) rather than a single value of Residence Time.

The significantly different *Extruder Geometry* in the various parts of the Extruder also results in different *Shear Rates* (both in terms of magnitude and direction.

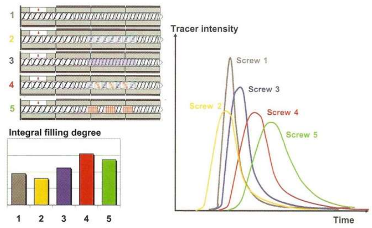
This can result in very "different" looking Products being prepared from alternative Extruders, even with the same *Ingredients*.



Two very different looking Products prepared using the same Extruder and the same Formulation.

Effective Viscosity in the Screw

The *Residence Time Distribution* (or RTD), however, is determined by the specific *Screw Geometry* and the *Screw Speed*.



Each different *Screw Design* results in a different *Degree of Fill* (or *Filled Length*, L_f) and hence a different *Average Residence Time*, t_{ave}) and a different RTD and different *Power Dissipation*.

Average Residence Time	$\theta_{ave} \approx [\theta_{min} + \theta_{max}] / 2$
Standard Deviation	$\sigma \approx [\theta_{max} - \theta_{min}] / 4$
Coefficient of Variance	$COV = \sigma / \theta_{ave}$

Effective Viscosity in the Screw

Shear Rates in the different Parts of the Screw

In a given Extruder System the most important *Shear Rates* are:

The *Flight Gap Shear Rate*,

$$\gamma_{gap} \approx \pi D_s N / g = \Omega_g N$$

[results in "*Cooking*"]

The (*Minimum*) *Channel Shear Rate*,

$$\gamma_{channel,min} \approx \pi D_s N / H$$

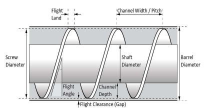
[results in "*Mixing*"]

The (*Average*) *Channel Shear Rate*,

$$\gamma_{channel,ave} \approx \pi N (R_s + S) / (R_s - S) = \Omega_c N$$

The *Apparent Viscosity* in the various parts of the Screw will be proportional to

$$\mu_g / \mu_c = [\Omega_c / \Omega_c]^{(1 - n)}$$



Typical Single Screw Geometry

Effective Viscosity in the Screw

Estimation of the Viscous Power Dissipation - *SSE*

For a *Single Screw Extruder* (SSE), the *Viscous Power Dissipation*, P_{net}, within the Extruder Screw may be estimated via the following simple expression

$$P_{net} \approx \pi^3 N^2 D^3 \{ [\pi D \mu_c / (2 H)] + [\#_f e \mu_g / g] \} L_f$$

where,

P_{net} = Power (W), N = Screw Speed (Hz), D = Screw Diameter (m), H = Channel Depth (m), $\#_f$ = Flight Starts (-), g = Flight Gap (m), e = Flight Thickness (m), μ_c = Channel Melt Viscosity (Ns m^{-2}), μ_g = Flight Gap Melt Viscosity, (Ns m^{-2}) and L_f = Screw Filled Length (m)

For a Screw of known *Geometry* this may be simplified to

$$P_{net} \approx \Psi_1 \{ [\Psi_2 \mu_c] + [\Psi_3 \mu_g] \}$$

where,

$\Psi_1 = [\pi^3 N^2 D^3 L_f]$, $\Psi_2 = [\pi D / (2 H)]$ and $\Psi_3 = [\#_f e / g]$

A *Process-dependent Term* (Ψ_1)

Purely *Geometric Terms* (Ψ_2, Ψ_3)

Effective Viscosity in the Screw

Estimation of the Viscous Power Dissipation - *SSE*

Based upon the expression presented above, it is clear that if we know the *Screw Geometry*, the *Screw Speed*, the *Product Rheology* and the *Filled Length*, it is possible to determine the *Viscous Power Dissipation*.

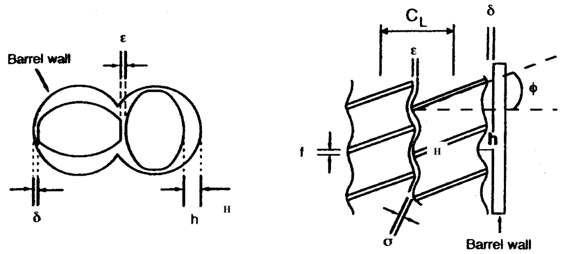
Conversely, if we know the Screw Geometry and the Screw Speed and then if we measure the Filled Length and the Viscous Power Dissipation, then it should possible to determine the Product Rheology.

Effective Viscosity in the Screw

Estimation of the Viscous Power Dissipation - *TSE*

Due to the significantly different *Geometry* for a TSE, the estimation of the Power requires an alternative approach.

The relevant Geometry is shown.



Effective Viscosity in the Screw

Estimation of the Viscous Power Dissipation – *TSE*

Determination of the Volume and the Shear Rate TSE

Zone	Volume	Shear Rate
Screw Channel	$V_{channel} = n\,\pi^2\,D_e\,D_s\,H\,\tan\Phi / 2$	$\gamma_{channel} = \pi\,D_e\,N / H$
Flight Gap	$V_{gap} = n\,f\,C_e\,\delta$	$\gamma_{gap} = \pi\,D_e\,N / \delta$
Tip to Channel Bottom	$V_{tip} = 2\,n\,f\,C_L\,\varepsilon$	$\gamma_{tip} = 2\,\pi\,C_L\,N / \varepsilon$
Flight Flanks	$V_{flanks} = n\,[\,(\,D_s^2 - C_L^2\,)\,)\,]^{0.5}\,H\,\sigma / 2$	$\gamma_{flanks} = \pi\,C_L\,N / \sigma$

where,

Equivalent Screw Diameter, $D_e = [\,2\,D_s\,] - [\,0.9003\,(\,D_s\,H\,)^{0.5}\,]$

Circumference of Equivalent Screw, $C_e = 2\,[\,(\,\pi\,D_s\,) - (2\,D_s\,H)^{0.5}\,] = \pi\,D_e$

Effective Viscosity in the Screw

Estimation of the Viscous Power Dissipation - *TSE*

(1) The Power Dissipated in the *Screw Channels*, $Z_{channel}$, is given by

$$Z_{channel} = [\,\mu_{ave}\,\#_F\,N^2\,]\,[\,n\,\pi^4\,D_s^3\,D_e\,\tan\varphi\ /\,2\,H\,]$$

(2) The Power Dissipated in the *Flight Gap*, Z_{gap}, is given by

$$Z_{gap} = [\,\mu_{ave}\,\#_F\,N^2\,]\,[\,n\,\pi^2\,D_e^2\,f\,C_e / \delta\,]$$

(3) The Power Dissipated in the *Calender Gap*, $Z_{calender}$, is given by

$$Z_{calender} = [\,\mu_{ave}\,\#_F\,N^2\,]\,[\,8\,n\,\pi^2\,C_L^3\,f / \varepsilon\,]$$

(4) The Power Dissipated in the *Screw Flanks*, Z_{flanks}, is given by

$$Z_{flanks} = [\,\mu_{ave}\,\#_F\,N^2\,]\,[\,n\,\pi^2\,C_L^2\,H\,\{\,D_s^2 - C_L^2\,\}\,/\,(\,2\,\sigma$$

Similar (but more complex) arguments, as above for the SSE, can be made for the TSE, which shows that the Power is simply a function of *Screw Speed*, *Geometry* and *Rheology*.

Effective Viscosity in the Screw

Equivalence of Electrical and Mechanical Energy

Many *Food Processing Operations* involve the use of *Mechanical / Electrical* methods to input Energy e.g. *Rotating Shafts* or *Compression Rolls*. The *Mechanical Energy Input* are normally described via either *Motor Load* or *Motor Current* or *Torque Loading*.

Due to the *Inefficiencies* involved with the various alternative *System Designs*, the *Energy Consumption under No Load* must also be allowed for.

The *Specific Mechanical Energy* (SME) is the parameter typically used to report the Mechanical Energy Input.

Effective Viscosity in the Screw

Equivalence of Electrical and Mechanical Energy

The *Net Energy Input*, P_{net} (kW), can be estimated via

$$E_{mechanical} = \sqrt{3}\,V\,[\,(\,\phi\,\eta\,I\,) - (\,\phi_0\,\eta_0\,I_0\,)\,] / 1000$$ **for AC Power**

where,

ϕ = Power Factor (-) η = Efficiency (%)
V = Supply Voltage (V) I = Current (Amps)
Subscript 0 = No Load

Motor Current Meter

$$E_{mechanical} = 2\,\pi\,(\tau - \tau_0)\,N / 60000$$

for DC Power

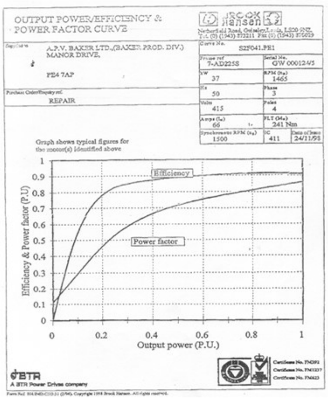
$$E_{mechanical} = V\,[\,(\eta\,I\,) - (\eta_0\,I_0)\,] / 1000$$

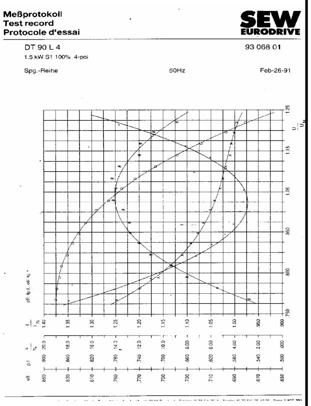
where,

τ = Torque (N m) N = Shaft Speed (rpm)

Effective Viscosity in the Screw

AC Motor Performance Curves





Effective Viscosity in the Screw

Typical Performance Data for DC Motors

Power		Efficiency			
(hp)	(kW)	0.25	0.5	0.75	1
0.25	0.186	58.0	62.0	65.0	68.0
0.50	0.373	61.0	65.0	70.0	72.0
1.00	0.746	66.0	70.0	73.0	75.0
1.50	1.119	67.0	72.0	76.0	78.0
2.00	1.491	68.0	72.0	77.5	81.0
3.00	2.237	69.0	72.0	77.0	79.0
5.00	3.728	71.0	77.0	81.0	81.0
7.50	5.593	73.0	79.0	82.0	83.0
10.00	7.457	76.0	81.0	83.0	85.0
15.00	11.185	77.0	81.5	84.5	86.0

For Baldor Electric Motors

Effective Viscosity in the Screw

Calculating the SME

The calculation of the SME requires that the *Total Mass Flow* (M_{Total}) be determined via

$$M_{Total} = M_{Dry\ Powder} + M_{Water} + M_{Steam} + M_{Oil} + M_{Addtives}$$

where,

$M_{Dry\ Powder}$ = Mass Flow of Dry Powder (kg / hr)
M_{Water} = Mass Flow of Water (kg / hr)
M_{Steam} = Mass Flow of Steam (kg / hr)
M_{Oil} = Mass Flow of Oil (kg / hr)
$M_{Additives}$ = Mass Flow of other Additives (kg / hr)

The SME is then given by

$$SME_1 = P_{net} / M_{Total} \quad (\text{ kW hr / kg })$$

or

$$SME_2 = 3600\ SME_1 \quad (\text{ kJ / kg })$$

Effective Viscosity in the Screw

Experimental Methodology

In order to determine the *Effective Viscosity*, μ_{eff}, of the Material within the Extruder Screw, follow these steps:

Step 1- **Operate the Extruder (of known *Geometry*) in *Steady-State*, at a given *Processing Rate*, M_1, with a known *Recipe* [D, W, w_M, T_M, etc.], a given *Screw Speed*, N_A.**

Step 2 - **Determine the *Net Power*, $P_{net,1}$ and the *Specific Mechanical Energy*, SME_1.**

Step 3 - **Measure the *Average Residence Time*, $t_{ave,1}$ and from this determine the *Filled Length*, L_{f1}.**

Step 4 – **Increase the Processing Rate (to $M_2 \approx 1.2M_1$), whilst keeping the Recipe and Screw Speed the same.**

Step 5 – **Repeat Steps 2 and 3 to obtain $P_{net,2}$, SME_2, $t_{ave,2}$ and L_{f2}.**

Effective Viscosity in the Screw

Experimental Methodology, cont., ….

Step 6 – **Solve the *Power Equation* for the two unknowns $\mu_{c,A}$ and $\mu_{g,A}$ (at Screw Speed, N_A).**

Step 7 – **Increase the Screw Speed (to $N_B \approx 1.2\ N_A$), then repeat Steps 2 to 6.**

Step 8 – **Increase the Screw Speed (to $N_C \approx 1.2\ N_B$), then repeat Steps 2 to 6.**

Step 9 - **By repeating this procedure over a range of Screw Speeds, it will be possible to gather sufficient Data to make a *Plot* of ln[μ_{eff}] vs. ln[N], which will be a *Straight Line*. The *Slope* of the Line will be equal to the value (n – 1), where n is the *Flow Behaviour Index*.**

Step 10 – **Determine the magnitude of the *Consistency Index*, m.**

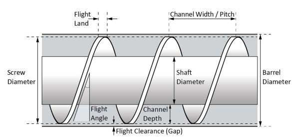
Note: The *Product Quality* generated (i.e., the *Shape*, *Size*, *Density*, etc.) is of no consequence during this study.

Effective Viscosity in the Screw

A Worked Example – *Extruder and Die Geometry*

Extruder Data

Screw Diameter, D_s	130.0	mm		
Total Screw Length, L_s	2080.0	mm	L_s / D_s	16.00
Flight Gap, g	1.5	mm		
Flight Width, e	12.0	mm		
Number of Flight Starts, $\#_F$	2	starts		
Inlet Channel Depth, B_{in}	35.0	mm		
Inlet Length, L_i	900.0	mm		
Transition Length, L_t	580.0	mm		
Metering Channel Depth, B_m	25.0	mm		
Inlet Length, L_i	600.0	mm		
Channel Width, W	50.0	mm		
Flight Angle, α	12.0	deg		
Flow Area for Product, A_x	9.239E-03	m^2		
Geometric Constant 2, ψ_2	7.0013	-		
Geometric Constant 3, ψ_3	16.0000	-		



Die Data

Die Radius, R_h	1.50	mm	D_h	3.00	mm
Land Length, L_D	6.00	mm	L / D	2.00	-
Number of Dies, $\#_D$	120	holes			
Die Hole Conductance, k_h	0.3313	mm^3 per Hole			
Total Conductance, K_T	39.761	mm^3		3.976E-08	m^3
			Die Open Area, A_d	8.482E-04	m^2
			Die Assembly Volume, V_D	2.500E-04	m^3

Effective Viscosity in the Screw

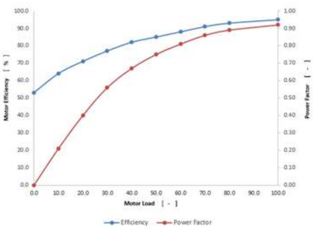
A Worked Example – *Motor Performance Data*

Installed Power, P_{max} 110.0 kW

Power Supply Voltabge, **V** 415 Volts

	Motor Load		Efficiency	Power Factor
	%	Amps	-	-
	0.0	0	53.0	0.00
	10.0	19	64.0	0.21
	20.0	38	71.0	0.40
	30.0	56	77.0	0.56
	40.0	75	82.0	0.67
	50.0	94	85.0	0.75
	60.0	113	88.0	0.81
	70.0	132	91.0	0.86
	80.0	150	93.0	0.89
I_{max}	100.0	188	95.0	0.92

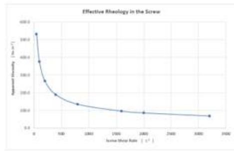
No Load Current, I_o 35 Amps   No Load Power, P_o 12.202 kW

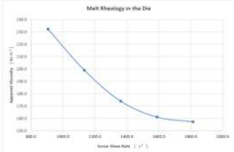


Effective Viscosity in the Screw

A Worked Example – *Trial Summary & Data Analysis*

[illegible]





Effective Viscosity in the Screw

A Worked Example – *Process Data*

The *Recipe* is kept the same throughout the Trial.

The *Processing Rate* is adjusted from M_1 to $M_2 \approx 1.2M_1$.

The *Screw Speed* is adjusted to a number of different Settings.

Process Data		Data Set A			Data Set B		Data Set C		Data Set D		Data Set E	
		1		2	1	2	1	2	1	2	1	2
Dry Feed Rate, D	kg hr⁻¹	1600.0		1920	1600	1920	1600	1920	1600	1920	1600	1920
Water Addition Rate, **W**	kg hr⁻¹	160	10.0% D	192	160	192	160	192	160	192	160	192
Steam Addition Rate, **S**	kg hr⁻¹	96	6.0% D	115.2	96	115.2	96	115.2	96	115.2	96	115.2
Oil Addition Rate, O	kg hr⁻¹	32	2.0% D	38.4	32	38.4	32	38.4	32	38.4	32	38.4
Melt Flow Rate, **M**	kg hr⁻¹	1888		2265.6	1888	2265.6	1888	2265.6	1888	2265.6	1888	2265.6
Volume Flow Rate, Q_{net}	m³ s⁻¹	4.389E-04		5.266E-04	4.389E-04	5.266E-04	4.389E-04	5.266E-04	4.389E-04	5.266E-04	4.389E-04	5.266E-04
Screw Speed, **N**	rpm	200		200	250	250	300	300	350	350	400	400
Flight Gap Shear Rate, γ_g	s⁻¹	907.6		907.6	1134.5	1134.5	1361.4	1361.4	1588.2	1588.2	1815.1	1815.1
Channel Shear Rate, γ_c	s⁻¹	46.7		46.7	58.3	58.3	70.0	70.0	81.7	81.7	93.4	93.4
Operating Pressure, ΔP	bar	27.0		29.0	23.0	25.0	20.0	22.0	18.0	21.0	18.0	20.0
Motor Current, **I**	Amps	61		64	64	67	68	72	71	76	74	80

The *Process Response* (i.e., *Motor Load*, *ΔP* and t_{ave}) is noted.

Effective Viscosity in the Screw

A Worked Example – *Data Analysis*

The *Net Power* is determined as outlined above.

The *Pumping Power* is determined via $P_{pump} = Q_{net}\,\Delta P$

The *Apparent Viscosity* is determined via $\mu_{app} = K_T\,\Delta P\,/\,Q_{net}$

The *Average Residence Time* is determined via $t_{ave} = (t_{min} + t_{max})\,/\,2$

The *Filled Length* is determined via $L_f = Q_{net}\,t_{ave}\,/\,A_x$

Motor Current, **I**	Amps	61	64	64	67	68	72	71	76	74	80
% Load	%	32.45	34.04	34.04	35.64	36.17	38.30	37.77	40.43	39.36	42.55
Power Factor, φ	-	0.581	0.603	0.603	0.625	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.712
Motor Efficiency, ψ	%	77.37	78.23	78.23	79.07	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	82.43
Net Power, P_{net}	kW	7.504	9.499	9.499	11.581	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	21.558
Pumping Power, P_{pump}	kW	1.185	1.527	1.009	1.317	0.878	1.159	0.790	1.106	0.790	1.053
Screw Power, P_{screw}	kW	6.319	7.971	8.489	10.264	11.416	14.082	13.700	17.225	15.978	20.505
Specific Mechanical Energy, **SME**	kW hr kg⁻¹	0.00335	0.00352	0.00450	0.00453	0.00605	0.00622	0.00726	0.00760	0.00846	0.00905
	kJ kg⁻¹	12.0	12.7	16.2	16.3	21.8	22.4	26.1	27.4	30.5	32.6
Apparent Melt Viscosity, μ_{app}	Ns m⁻²	244.6	218.9	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	163.1	151.0
	cP	244617	218948	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	163078	150998
Minimum Residence Time, t_{min}	s	31.0	32.0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	26.0	28.0
Maximum Residence Time, t_{max}	s	37.0	39.0	35.0	36.0	33.0	34.0	32.0	34.0	32.0	33.0
Average Residence Time, t_{ave}	s	34.0	35.5	32.5	33	31	32	29.5	31.5	29	30.5
Standard Deviation, σ	-	1.50	1.75	1.25	1.5	1	1	1.25	1.25	1.5	1.25
Coefficient of Variance, COV	-	0.044	0.049	0.038	0.045	0.032	0.031	0.042	0.040	0.052	0.041
Filled Volume of Extruder, V_E	m³	1.467E-02	1.845E-02	1.401E-02	1.713E-02	1.335E-02	1.660E-02	1.270E-02	1.634E-02	1.248E-02	1.581E-02
Calculated Filled Length, L_f	mm	1587.9	1996.4	1516.7	1853.9	1445.4	1796.9	1374.2	1768.4	1350.4	1711.4

Effective Viscosity in the Screw

A Worked Example – *Data Analysis cont. ….*

An estimate of the magnitude of the *Flow Behaviour Index*, n, is made

The *Process Constant* is determined via $\Psi_1 = [\,\pi^3\,N^2\,D^3\,L_f\,]$

Calculated Filled Length, L_f	mm	1587.9	1996.4	1516.7	1853.9	1445.4	1796.9	1374.2	1768.4	1350.4	1711.4
Process Constant 1, Ψ_1	m³ s⁻²	1.2019	1.5111	1.7937	2.1926	2.4616	3.0602	3.1854	4.0992	4.0886	5.1815

Estimated Value of the Flow Behaviour Index (in the Screw), n_s 0.50 -   Flight Gap Shear Constant, Ω_g 272.27 -

$[\,\Omega_g\,/\,\Omega_c\,]^{(1-n)}$ 5.099 -   Channel Shear Constant, Ω_c 10.47 -

Apparent Flight Gap Viscosity, μ_g	Ns m⁻²	107.9		96.5		88.1		81.4		76.1	
Apparent Channel Viscosity, μ_c	Ns m⁻²	550.0		492.0		449.0		415.0		388.0	
Estimated Power, P_{calc}	kW	6.703	8.428	8.948	10.938	11.210	13.936	13.430	17.283	16.124	20.435
error	%	6.08%	5.73%	5.41%	6.56%	-1.81%	-1.04%	-1.97%	0.34%	0.92%	-0.34%
Calculated Consistency Index, m_{calc}	Nsⁿ m⁻²	3757.6		3758.1		3756.9		3750.7		3748.8	

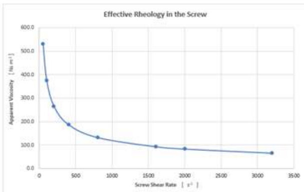
Average Consistency Index (in the Screw), m_s 3754.40 $Ns^n\,m^{-2}$

An estimate of the magnitude of the *Apparent Channel Viscosity*, μ_c, is made, the *Apparent Gap Viscosity*, μ_g, follows and then the *Power*, P_{calc}, is calculated to minimize the *error*.

The *Consistency Index*, m is then determined via $m = \mu_c\,/\,\gamma_c^{(n-1)}$

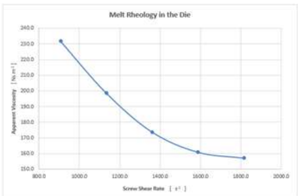
Effective Viscosity in the Screw

A Worked Example – *Formulation Rheology*



Average Consistency Index (in the Screw), m_s 3754.4 $Ns^n\,m^{-2}$

Estimated Value of the Flow Behaviour Index (in the Screw), n_s 0.50 -



Average Melt Consistency Index, m_M 12123.1 $Ns^n\,m^{-2}$

Average Melt Flow Behaviour Index, n_M 0.42 -

Effective Viscosity in the Screw

Summary

The numerous ***Physical & Chemical Transformations*** **of the** ***Formulation*****, which occur within the Extruder Screw, will ultimately result in the formation of the** ***Melt*****.**

These changes are solely dependent upon the interaction of the ***Screw Geometry*****, the** ***Rotational Speed*** **and the** ***Effective Formulation Rheology*** **(which is continuously changing along the** ***Length*** **of the Screw) thereby determining the** ***Strain*** **(or** ***Work Input*****) for the Process.**

A ("simple") ***Methodology*** **for estimating the** ***Effective Viscosity*** **(or the** ***Global Rheological Properties*****) has been presented herein.**

An ***Understanding*** **(and the** ***Control*****) of the** ***Rheological Properties*** **of the** ***Formulation Ingredients*** **(i.e., the** ***Ingredient Quality*****) is therefore of paramount importance to ensure optimal** ***Process Control*** **for any Extrusion Operation.**