The Role of the Rheology in Extrusion Processing & its impact upon Product Texture

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Rheology & Texture

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***

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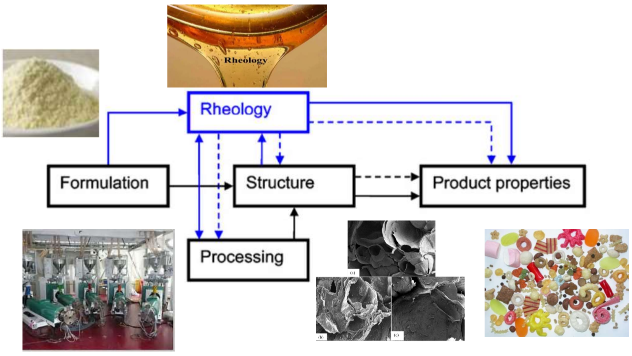

Extrusion is a highly interactive Process and the *Formulation Rheology* plays a pivotal role.

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Viscous Behaviour

"All things flow under the influence of a *Force* or *Stress*."

The perceived differences between the numerous types of fluids that may be encountered relates to the Fluid Rheology and is measured via the *Response Time* of the given fluid to the imposed stress.

This is called the *Relaxation Time*.


Water in a Glass


High DE Glucose Syrup


Nylon Thread being Drawn


Silly Putty Spilling

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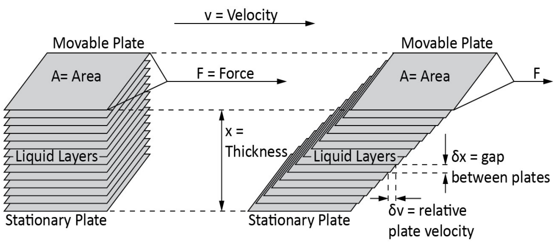
A Thought Experiment - *Fluid Flow*



Whilst Fluids are a *Continuum*, they may be considered as existing as discrete *"Layers"*. The *Frictional Interactions* between these Layers may be considered as resulting in the observed *Rheological Properties* of the Fluid.

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Parameter Definitions

Shear Stress = Force / Area

$$\tau = F / A$$

Shear Rate = Velocity Differential / Gap

$$\gamma = \delta v / \delta x \approx (v_{max} - v_{min}) / x$$

In an Extruder system the most important Shear Rates are:

The *Flight Gap Shear Rate*,

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

[results in *"Cooking"*]

The *Channel Shear Rate*,

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

[results in *"Mixing"*]

The *Die Shear Rate*,

$$\gamma_{die} \approx 8 v_D / D_d = 4 Q_{net} / \pi R^3$$

[results in *"Skin Formation"*]

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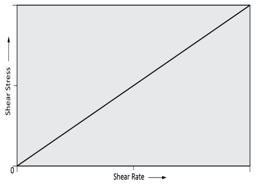
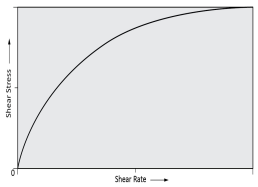
Newtonian Fluid Behaviour



Non-Newtonian Fluid Behaviour



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A Definition for *Fluid Viscosity*

Viscosity = Shear Stress / Shear Rate

$$\mu = \tau / \gamma$$

For *Newtonian Fluids* (at a given Temperature)

$$\mu = \text{constant}$$

For *Non-Newtonian Fluids* (at a given Temperature), the Viscosity is not constant, thus

$$\mu_{apparent} \neq \text{constant, it is } \textit{Shear Rate Dependent}$$

Note: For a Non-Newtonian Fluid we must refer to the *Apparent Viscosity* (at a specified *Shear Rate*).

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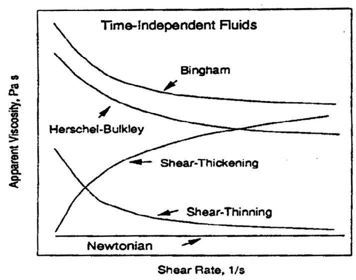
General Behaviour of Time-independent Fluids



Pseudoplastic Fluids

Bingham Plastic Fluids

Yield Stress in a Pana Cotta

Dilatant Fluids

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Some typical values of Fluid Viscosity for various Materials

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The Herschel-Bulkley Model

$$\tau = \tau_y + m\,\gamma^n$$

and

$$\mu_{apparent} = [\,\tau_y / \gamma\,] + [\,m\,\gamma^{n-1}\,]$$

where,

τ_y = The *Yield Stress*
m = The *Consistency Index*
n = The *Flow Behaviour Index*
$\mu_{apparent}$ = The *Apparent Viscosity*

For most *Food Extrusion Melts*, 0.3 < n < 0.5

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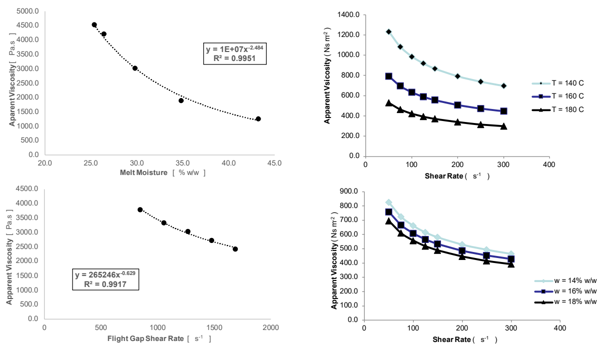
Effect of w_M, γ_{gap} & T_M on Apparent Viscosity

Whole Wheat Flour — **Maize Grits**



Note: This Data was obtained using *Single Ingredients* at *Laboratory Scale* [D ≈ 10 kg hr^{-1}]

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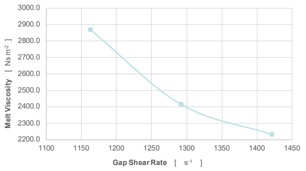
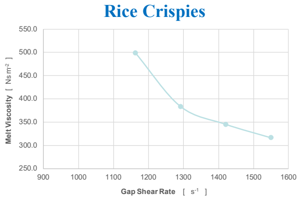
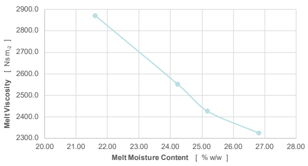
Effect of w_M & γ_{gap} on Apparent Viscosity

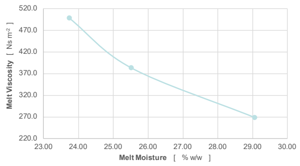
Cocoa Shells



Rice Crispies







Note: This Data was obtained using *Formulated Products* at *Industrial Scale* [D ≈ 600 kg hr⁻¹]

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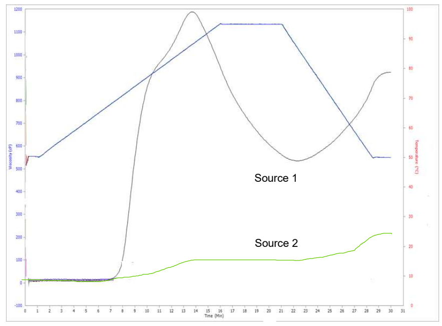
The use of *Cooking Viscometers*

Soy Protein Isolates – *Two different SPI Sources*

Perten Instruments RVA

Brabender Micro Visco –Amylograph



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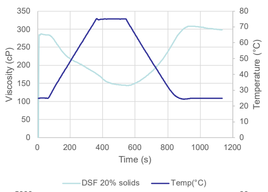
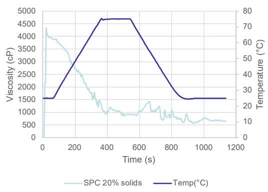
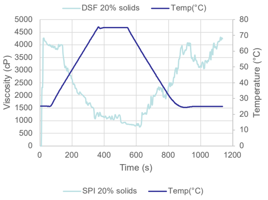
The use of *Cooking Viscometers*

Soya-based Products – *Recipe Blending*







RVA Pasting Profiles for a number of *Soya-based Materials*.

[All Samples tested using "non-standard" Test Parameters.]

Formulation Blend

DSF = 40%, SPC = 24%, SPI = 36%

What will the Pasting Curve Parameters be?

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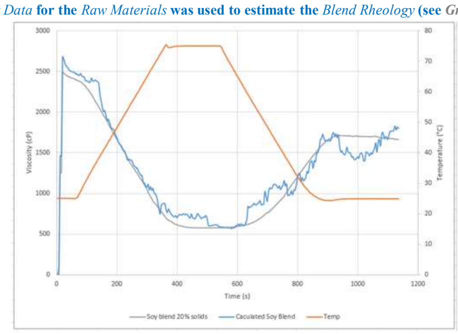
Use of Cooking Viscometers

Soya-based Products – *Recipe Blending*

These *Soya-based Materials* were then *Blended* and the *Mixture* was subsequently Tested (using "non-standard" Test Parameters).

[The *Test Data* for the *Raw Materials* was used to estimate the *Blend Rheology* (see *Grey Curve*).]



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Effect of Temperature, Moisture and Fat on the Melt Viscosity

In general, for Non-Newtonian Fluids

$$\mu_{apparent} = m_o\, e^{[a1/T]}\, e^{[a2\, w]}\, e^{[a3\, f]}\, \gamma^{n-1}$$

For an Extruder the *Die Pressure Drop* is related to the *Melt Viscosity* thus,

$$\Delta P \;\alpha\; \mu_{app}$$

so,

$$\Delta P \;\alpha\; e^{[a1/T]}\, e^{[a2\, w]}\, e^{[a3\, f]}$$

(if all else is constant)

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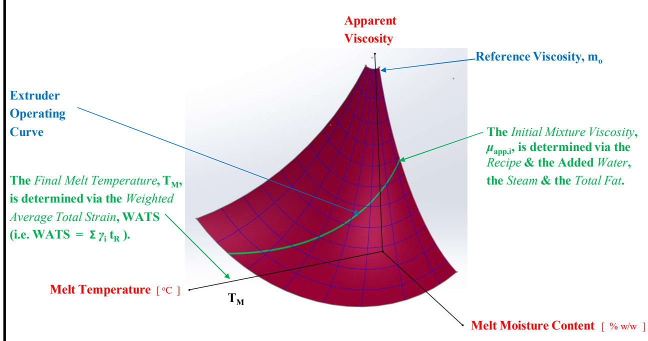
Extruder Operating Curve – *Melt Rheology*



$$\mu_{apparent} = m_o\, e^{[a1/T]}\, e^{[a2\, w]}\, e^{[a3\, f]}\, \gamma^{n-1}$$

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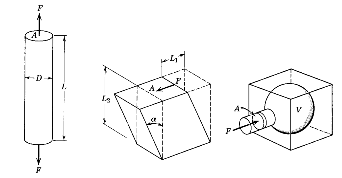
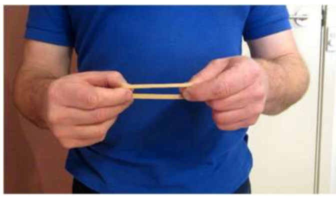
Elastic Behaviour





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Visco-Elastic Behaviour

Memory Foam”

Selection of Extruded Products exhibiting Elastic Effects

“The Golden Rules of Extrusion Technology”

Golden Rule # 1

Extrusion System Flow Components

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

Screw Characteristic — Die Characteristic

where,

Q_{net} = Total Melt Flow / Melt Density

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

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

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

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

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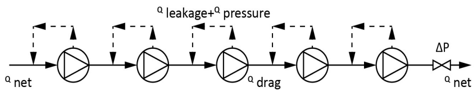
Extruder Behavior Explained -

An Analogy for Extruder Operation

The operation of an extruder may therefore be considered as being equivalent to that of a *Multi-stage Pump* with *Slip*.



The *Pump* (or *Extruder*) will utilize as many *Stages* (or *Screw Elements*) as needed to deliver the *Required Volumetric Output*, Q_{net}, against the *Operating Pressure*, ΔP.

The Filled Length of an Extruder

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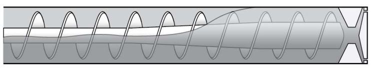
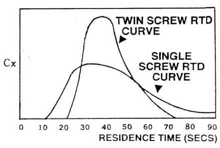
The *Filled Length* of the Extruder

The *Filled Length* (or the *Choke Point*) of the Extruder determines the magnitude of the *Mean Residence Time*, t_R.

The magnitude of t_R of for the TSE is typically slightly lower than that for a SSE.



L_{Fill}



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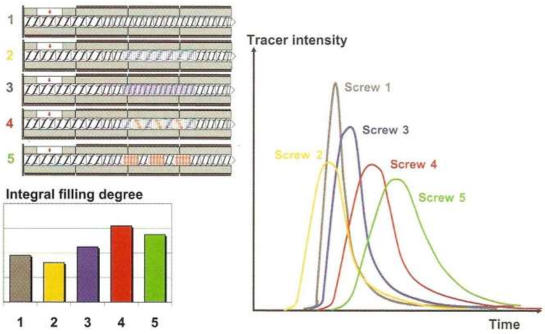
The *Filled Length* of the Extruder

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



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Estimation of the Apparent Viscosity of the Melt

The use of Extruder Operating Data

Dry Feed Rate, D	13.84	kg / hr	
Water Flow Rate, W	6.13	kg / hr	
Melt Flow Rate, M	19.97	kg / hr	
Melt Density, ρ_M	1200	kg / m^3	
Volume Flow, Q_{net}	4.623E-06	m^3 / s	$Q_{net} = M / \rho_M$
Die Diameter, d	1.50	mm	Radius, R 7.500E-04 m
Die Land Length, L	3.00	mm	3.000E-03 m
Die Conductance, k	4.142E-11	m^3 per Hole	$k = \pi R^4 / 8 L$
Number of Die Holes	6		
Total Conductance, K	2.485E-10	m^3	
Die Pressue, ΔP	2600	kPa	2600000 N /m^2
			$\mu_{app} = K \Delta P / Q_{net}$
Apparent Melt Viscosity, μ_{app}	139.77	Ns / m^2	139770 cP

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Numerous types of *Product Textures* may be defined:

Hard

Fibrous

Friable - **Crumb Structures**

- **Crisp Structures**

Soft, Moist

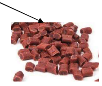
Brittle

TVP

Boiled Confectionery

Granola

Expanded Rice



Semi-Moist Pet Food

Pasta

The development of the *Product Texture* is associated with the *Formulation*, the *Process History* and the *Expansion Process*.

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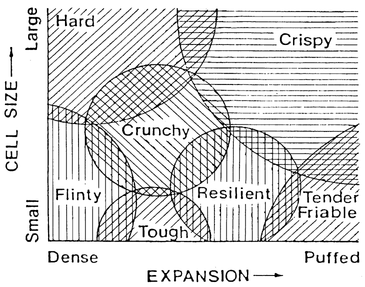
Relationship between Structure and Expansion



Typical Direct Expanded Cereal Products

Internal Porous Structure

The *Bubble Morphology* (i.e. *Bubble Size*, *Number of Bubbles* and the *Cell Wall Thickness*) is critical in determining the *Final Product Texture*.

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The Extrusion Cooking Process

If we consider any "*Cooking Process*" then we can say that

Cook = *f* (Time, Temperature, Pressure & Shear)

Pressure alone cannot "cook", however, it does allow the Process to operate at an *Elevated Temperature* (i.e. > 100°C), which significantly increases the *Rate of Cooking*, thereby reducing the *Cook Time*. In the simplest of terms we can therefore say that

Formulation + Energy → Product

Clearly, it is the *Energy Input* that results in the *Transformation* (or *Cooking*) of the *Ingredients* within the *Formulation* into the *Product*.

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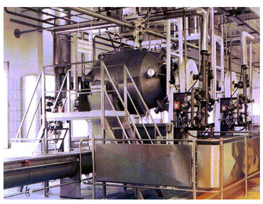
Product Cooking Systems

Atmospheric Batch Cooker

Batch Steam Pressure Cooker



High Shear Extrusion Cooker

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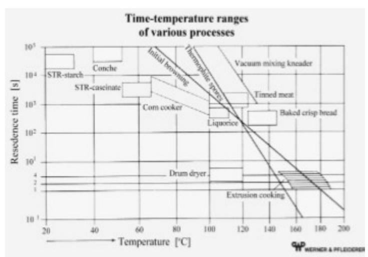
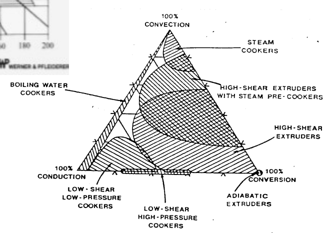
Process Energy Inputs



The *Processing Temperature*, the *Residence Time* and the *Energy Inputs* may be modified to change the *Product Characteristics*.



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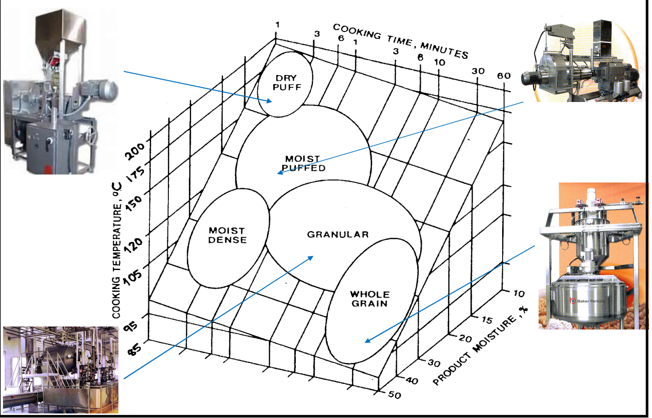
Summary of Cooking Processes



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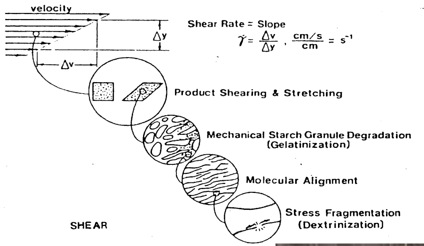
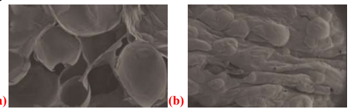
The Role of Shear in the Extrusion Cooking Process





(a) (b)

SEM of an Extruded Corn Snack (a) *Internal Structure* and (b) *Surface Structure* (i.e. *"Skin" Formation*).

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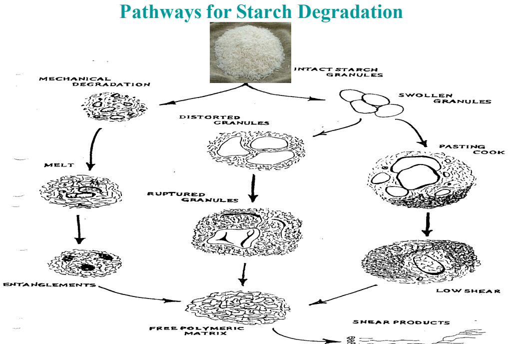
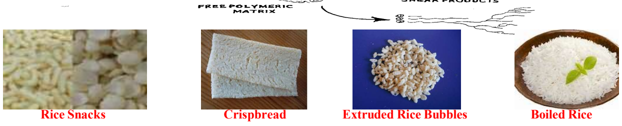
Pathways for Starch Degradation





Rice Snacks | Crispbread | Extruded Rice Bubbles | Boiled Rice

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The Role of Shear in the Extrusion Cooking Process

If we rearrange our definition for *Viscosity*, then we obtain the following expression

$$\tau = \mu_{apparent}\,\dot{\gamma}$$

Thus, for a given *Formulation*, at a given *Total Moisture Content* and *Temperature*, in the presence of a given *Shear Rate* (determined by the *Screw Geometry* and *Screw Speed*), an *Effective Shear Stress* is experienced within the Fluid, resulting in the *Degradation* (or "*Cooking*") of the Ingredients.

[Thus, in simplistic terms, it is the *Shear Stress* within the Fluid (which acts at the *Molecular Level*), that tells the Ingredients how to "break down", that is "how to cook"!]

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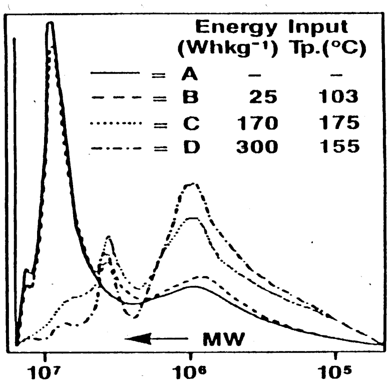
Influence of SME on the Mean Molecular Weight (MMW)

An increase in the SME leads to a significant increase in the *Degree of Degradation* of both the *Starches* (and also the *Proteins*).

SME = P_{net} / M



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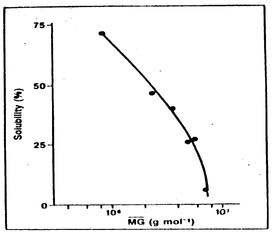
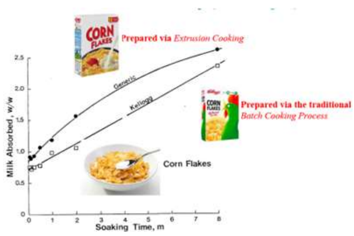
Product Water Solubility





Increasing the SME reduces the MMW, therefore increases the *Water Solubility* (or reduces the *Water Stability*) of *Products*.

The two Products are clearly ***not*** the same! The *Bowl Life* of the *Extruded Cornflake* is significantly reduced.

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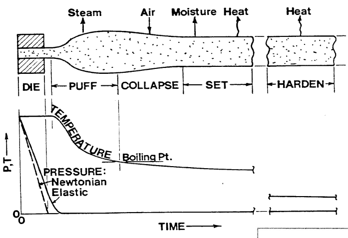
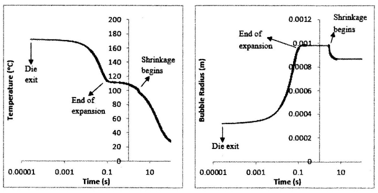
The Direct Expansion Process



The General behavior of an Extrudate during the Direct Expansion Process.



Model Prediction of T_p and R_b for the Extrudate.

"Stochastic Modeling of Expansion of Starchy Melts during Expansion", P.H. Manepalli, et al

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The Product Expansion Process

The *Product Expansion* is influenced via:

- The *Die Pressure Drop*
- The degree of *Superheating*
- The *Elasticity* of the Melt (i.e. the *Formulation*)
- The *Surface Tension* of the Melt
- The amount and type of *Starch / Protein* (i.e. *Ingredients*)
- The *Cooking Process* used (i.e. *STE*, *SME*, etc.)

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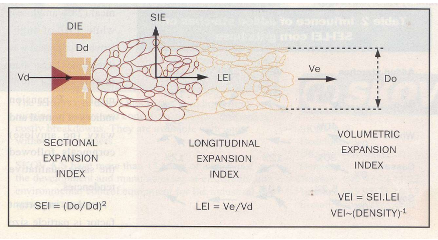
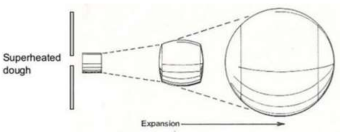
The Expansion Indices





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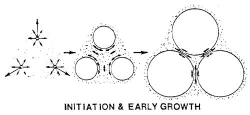
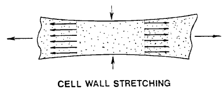
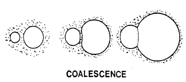
Development of Cellular Structures

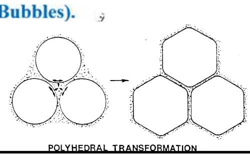




The *Bubble Number*, *Size* and *Shape* directly influence the *Product Texture*.

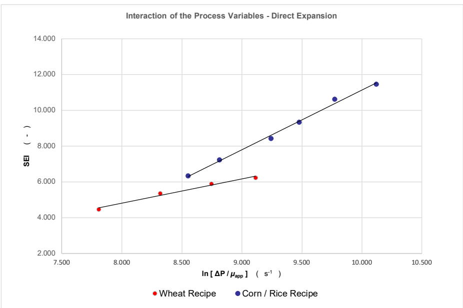
The Texture can also be modified by "pulling" the Product (i.e. by *Stretching / Distorting* the Bubbles).





Rheology & Texture

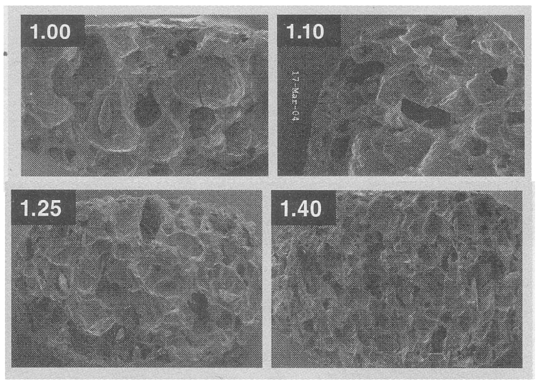
Effect of Ingredients & Process Variables



Alternative *Product Formulations* display significantly different *Expansion Characteristics*, at the same *Operational Conditions* (i.e., T_M and P).

Rheology & Texture

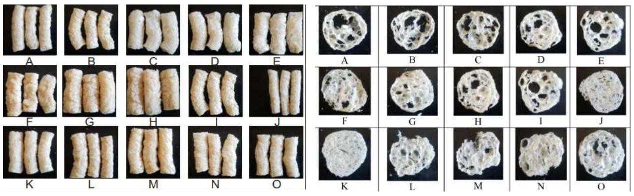
Impact of SME on Cellular Structures



All Product Samples shown have an equivalent *Bulk Density*

Rheology & Texture

Process Interactions with Expansion



Key
(A=100ºC X_1, 15% X_2, 8% X_3), (B=140ºC X_1, 15% X_2, 8% X_3), (C=100ºC X_1, 25% X_2, 8% X_3), (D=140ºC X_1, 25% X_2, 8% X_3) (E=100ºC X_1, 15% X_2, 24% X_3), (F=140ºC X_1, 15% X_2, 24% X_3), (G=100ºC X_1, 25% X_2, 24% X_3), (H=140ºC X_1, 25% X_2, 24% X_3), (I=86.5ºC X_1, 20% X_2, 16% X_3), (J=153.6ºC X_1, 20% X_2, 16% X_3), (K=120ºC X_1, 11.6% X_2, 16% X_3) (L=120ºC X_1, 28.4% X_2, 16% X_3), (M=120ºC X_1, 20% X_2, 2.55% X_3) (N=120ºC X_1, 20% X_2, 24.5% X_3) (O=120ºC X_1, 20% X_2, 16% X_3), X_1 = Barrel temperature, X_2 = Feed moisture content, X_3 = Amount of cowpea added to rice.

"Statistical Modeling and Optimization of Processing Conditions of TSE Extruded Rice-Legume Instant Breakfast Gruel", N. Danbaba, et al.
Arid Zone Journal of Engineering, Technology and Environment, December, 2018; Vol. 14(4): 693-712.

"The Golden Rules of Extrusion Technology"

Golden Rule # 2

Energy Inputs

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

Total Energy Input	Net Power Input	Latent Energy Input / Removal	Barrel Heat Transfer

where

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

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

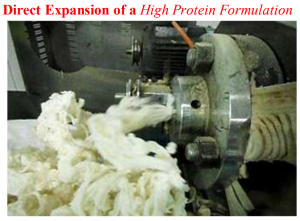
$E_{conductive}$ = f [Barrel Temperature]

Note : The Energy Inputs are not directly interchangeable!

Rheology & Texture

Direct Expansion of a *Modified Starch*
(Prepared via *Chemical Reaction* in the Extruder)

Direct Expansion of a *High Protein Formulation*



Direct Expansion of *Crumpet Flour*