Thermoforming Sheet Manufacture with the MRS Extrusion Concept

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1. Introduction

The importance of sheet for thermoforming made from PET in the packaging industry is growing rapidly. This is on the one hand due to its excellent mechanical properties and on the other hand due to the relatively simple processing and the low material costs, particularly if post consumer “bottle flake” is used. Thanks to new processes, it is possible to transform this “waste” to the point where a sheet can be manufactured, which can be used in direct contact with food products.

With the correct processing technologies, sheet with excellent thermoforming properties can be made thinner, saving weight and therefore material. Further, the temperature stability of PET packaging is significantly better than that made from other polymers so that food can be heated in the container (for example in a microwave oven).

![Fig. 1: Microwave – ready meal](image)

A further advantage of PET packaging is the good transparency and high gloss, so that optically the product makes the best possible impression. To quote one manufacturer of PET thermoformed containers: “The packaging is part of the buying experience”

![Fig. 2: Fruit and salad containers, thermoformed from PET sheet](image)

There is however a problem when processing PET to thermoformed containers, or to be more specific when processing the sheet used for thermoforming the containers. The problem is the hygroscopic properties of PET. During storage, water molecules present in the air diffuse into the pellets which subsequently work their way into the polymer chains, resulting in degradation of the material which in turn drastically damages the mechanical properties of the material and to poor thermoforming performance.
2. Key processing technical influences in the processing of PET

Drying (moisture extraction) and extrusion

2.1.1. The importance of moisture extraction in the PET extrusion process

Today, the established technology for the minimisation of degradation of the PET is to dry the material before processing it on a single screw extruder. The drying of PET is complicated, maintenance intensive and expensive in terms of investment costs, factory space and running costs due to the high energy consumption as the material is typically dried using dry air at 180°C. The fact that the material has to be dried for up to 8 hours also reduces the PET processor’s flexibility.

In the processing of PET with an extruder at normal processing temperatures, a chemical process takes place in that any water molecules which may be present reduce the PET chain lengths which results in a reduction in the viscosity which in turn reduces the mechanical properties of the final product. This process is known as hydrolysis.

Fig. 3: The chemistry of polyester: hydrolysis and polycondensation

In order to avoid this problem, the pellets are conventionally pre-dried over a long time period in order to remove the moisture prior to extrusion in order to prevent hydrolysis.

This chemical reaction is however reversible and the point of equilibrium can be driven to one or the other side by reducing or increasing the water content.

This phenomenon can be used to positive effect during extrusion. By removing the water molecules during processing, the damaged PET molecule chains can rebuild themselves.
The physical prerequisites for the removal of water molecules are described by the diffusion process, which can be formulated with the help of the Fick’s first law:

\[
\frac{\Delta n}{\Delta t} = - D \cdot F \frac{dc}{dx}
\]

This law shows that the quantity of water removed (\(\Delta n\)) will increase in relation to the residence time (\(\Delta t\)) the larger the melt surface area (\(F\)) and the driving concentration incline (\(dc\)) and the thinner the polymer layer (\(dx\)). In other words, the better the polymer is mixed and the better the surface is exchanged, the more the chemical equilibrium will move toward long chain molecules with better mechanical properties.

### 2.1.2. Melt phase moisture removal with the MRS extrusion concept

The main function of the new extrusion concept is to increase the polymer surface during extrusion, i.e. in the melt phase and to exchange this area as rapidly as possible to enable volatiles to escape, thereby taking account of Fick’s law.

The MRS (Multi Rotation System) extruder can be described in general as a single screw extruder with a very special degassing section. The polymer melt is delivered into a large single screw drum.

The drum contains 8 or 10 (depending on the model size) small extruder barrels, parallel to the main screw axis. Installed in these small extruder barrels are the "satellite" screws, which are driven by a ring gear in the main barrel. The satellite screws rotate in the opposite direction to the main screw while they rotate around the screw axis. This disproportionately increases the surface exchange of the polymer melt. The extruder barrels which are cut into the drum of the multi rotation system are approximately 30% open to ensure the optimum melt transfer into the barrels and so that the evacuation can take place without restrictions. Further, precise control of the melt temperature is possible as the temperatures of all the surfaces in contact with the melt can be controlled accurately.

![Fig. 4: Extrusion drum](image)

Thanks to its patented multiple screw section, the MRS makes a very large area available and permits unmatched degassing performance, even with a vacuum of only 20 to 40 mbar.
The extrusion of undried PET bottle flakes or pellets (for example up to moisture contents of 12,000 ppm H₂O) is therefore possible without making any compromises. This even applies to high viscosity end products such as strapping tape.

This evacuation technology (and the multiple screw section) is based on the robust and proven single screw extruder concept. In this way, the MRS avoids the problems of alternative multiple shaft or screw designs (intermeshing) which are considerably more sensitive to mechanical damage due to their tight clearances. This last point can be decisive in the reprocessing of PET bottle flake which frequently includes coarse contamination.

Fig.5: MRS-Extruder (with vacuum unit)

Further positive effects of the MRS technology are the 100% dehumidification of PET as well as the possibility of increasing the intrinsic viscosity of this material.

Thanks to the multi rotation elements, a melt surface is made available which is far greater than that of conventional extruders. For example: the MRS system creates a melt surface exchange rate which is 25 times greater compared with a co-rotating twin screw extruder.

<table>
<thead>
<tr>
<th></th>
<th>Single screw extruder</th>
<th>Twin screw extruder</th>
<th>MRS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface (cm²)*</td>
<td>100 %</td>
<td>150 %</td>
<td>450 %</td>
</tr>
<tr>
<td>Surface exchange (m²/min)*</td>
<td>100 %</td>
<td>200 %</td>
<td>5,000 %</td>
</tr>
<tr>
<td>Free volume (cm³)*</td>
<td>100 %</td>
<td>150 %</td>
<td>300 %</td>
</tr>
</tbody>
</table>

* in expansion section
Compared with other multi screw systems, the MRS is characterized by its extremely compact and rugged design. The rotating satellite screws run in individual bearings and are therefore comparable with a drum containing a number of single screws.

The evacuation or degassing system is modular and can be ideally matched to the individual requirements, thanks to its remarkable performance. The position, length and design of the modules can be varied. The MRS system can be used as an element of an extruder screw or can be integrated in a polymer melt pipe transfer system.

A South American customer manufactures sheet for thermoforming from 100% post consumer bottle flakes. These are processed without any pre-drying even though the flakes can have a moisture level of up to 10,000 ppm. The I.V. of the material was analysed at various stages along the extruder, upstream and downstream of the devolatilising section, the I.V. of the final product was likewise analysed.

Fig. 6: Viscosity when processing PET–Bottle Flakes

It is obvious that in the very first section of the extruder the viscosity of the polymer is reduced, because the water content is integrated into the chains of the PET. The more moisture is in the input material, the greater the viscosity decrease. In the degassing section these water molecules are extracted by vacuum (driven by diffusion), here the reversed chemical reaction takes place. Therefore the MRS is able to increase the chain length, the molecular weight, the viscosity and the mechanical properties of the polymer.

The melt viscosity is monitored by means of the Gneuss Online Viscometer. This can be equipped with a control loop to raise or lower the vacuum in the devolatilising zone in relation to viscosity changes. The influence of vacuum on the viscosity is significant, enabling this system to be used to control the viscosity with a required bandwidth.
The relationship between viscosity of the polymer immediately before it reaches the die and vacuum can be seen clearly.

2.2. Continuous online measurement and control of the processing parameters

2.2.1. Process control with the continuous measurement of melt pressure, temperature and viscosity

Today, the monitoring, logging and analysis of processing parameters is a key element in plastics processing in order for example to be able to trace problems relating to a customer complaint but also to be able to react as quickly as possible to changes in these parameters. Through this monitoring, a continuously high product quality can be ensured.

During extrusion, the most important factors with regard to the properties of the final product are the melt temperature, the melt viscosity and the melt pressure(s) in the machine. With the help of these parameters, the failure of heater zones or cooling fans, variations in the raw material parameters and wear in the line can be monitored. Dangerous situations can be avoided if equipment is for example automatically shut down if a too high pressure increase takes place quickly.

Pressure Transducer:

Melt Pressure transducers used in plastics processing operate using the principle of a medium to transfer the pressure from the hot environment to the sensitive measurement electronics. A diaphragm in contact with the polymer melt deforms due to the melt pressure. This deformation forces a liquid in a capillary to transfer the pressure to a second diaphragm, equipped with a Wheatstone bridge sensor, which translates deformation into an electric signal.

The liquid medium in the capillary is typically mercury; however the use of these sensors in the manufacture of food packaging is not permitted. The Gneuss sensors on the other hand use a mercury–free liquid. Through the replacement of mercury with an environmentally safe
substitute medium, melt pressure measurements with the required accuracy can be obtained in all applications, especially in the area of food contact packaging materials.

![Melt Pressure Transducer DA](image1) ![Sensor tip with Gneuss isolating diaphragm](image2)

**Fig. 8: Melt Pressure Transducer DA**  **Fig.9: Sensor tip with Gneuss isolating diaphragm**

**Melt Temperature Sensor:**
The Gneuss TF range of Melt Temperature Sensors is ideal for the exact measurement of highly sensitive media. The ceramic insulation guarantees a direct measurement of the melt temperature at all times, independent of the temperature of the surrounding steel components, such as a flange barrel or die.

![Melt Temperature Sensor](image3)

**Fig. 10: Melt Temperature Sensor**

**Online Viscometer:**
Through the use of melt pressure and melt temperature sensors and with a known throughput rate and known geometry, the flow resistance of a liquid can be calculated and from this, the dynamic viscosity of the medium can be extrapolated. This is a measurement of the average molecular weight of the polymer which defines its properties such as elasticity and stretch or elongation.

**2.2.2. Process control with the Gneuss Online Viscometer**
A small part of polymer melt is diverted from the main melt channel and with a high precision gear pump it is pumped through a precisely manufactured slot capillary. Melt temperature and melt pressure (at two locations) is measured. Based on internal calculations the viscometer monitors the value of the representative shear rate and the corresponding...
viscosity. Different shear rates can be set and by corresponding corrections the real values for viscosity and shear rate can be derived.

The design is very compact. The viscometer can be fitted between two flange connections. The melt channel can be designed according to customers’ specifications between 0.5 and 2 mm. The unit includes a pump drive, a pump, pressure transducers, temperature sensors and the control and evaluation electronics. The setting of process parameters, the evaluation and the display is realized via a user friendly touch screen panel or alternatively can be integrated into an existing control system.

Through the combination of the Gneuss technologies Measurement and Processing Technology, it is for the first time possible to maintain the melt quality within a very narrow bandwidth in spite of varying input material conditions (residual moisture). The viscosity, measured by means of melt pressure and temperature is used as a control value to automatically adjust the vacuum in the devolatilising section of the MRS extruder, thereby guaranteeing constant melt properties (viscosity, molecular weight and therefore the mechanical properties which result from these).
Fig 12: viscosity in relation to residual moisture variations

The above graph shows the behaviour of the vacuum (red) and the melt viscosity (blue) over time. The change of input material at 11:00h can clearly be seen. The material silo was changed, but prior to this, the material was drawn from the lower section of the silo, this material having relatively high residual moisture content. Immediately after the change, the residual moisture level of the flakes is considerably lower. By increasing the vacuum in the devolatilising section of the MRS extruder, the viscosity and therefore the molecular weight of the material can be maintained, consequently maintaining the mechanical properties i.e. the quality of the final product constant.

2.3. Not only for recycling: melt filtration as a key element with regard to quality assurance and the economic aspects of the process

Before the polymer enters the die, all kinds of contamination should be removed, in order to achieve the highest quality requirements with regard to transparency (sheet) or tensile strength (sheet for thermoforming, strapping tape) and of course to protect the downstream components from damage. The Rotary Melt Filtration Systems from Gneuss are particularly suited to this purpose as they operate fully automatically and pressure constant.

2.3.1. The RSFgenius: process and pressure constant melt filtration with integrated self-cleaning

The screens in the fully automatic RSFgenius are taking out the contaminations like aluminium, wood, etc. With this equipment it is possible to run an always stable differential pressure across the screens, even during back-flushing the screens or screen change.

The RSFgenius consists of three main parts – an inlet block, an outlet block and a filter disk rotating between them. The system is sealed by a metal to metal sealing with very narrow gaps as well as very hard and flat surfaces. It is guaranteed that all components in contact with melt are not in contact with the environment (e. g. oxygen).

The screen elements are located in a ring pattern on the filter disk, moving through the melt channel. When melt flows through the screen, hard particles get caught and the differential
pressure increases slightly. The control system reacts to this pressure increase and makes the filter disk index by approx. 1 angular degree. Thus, contaminated screen area is continuously moved out of the melt channel and clean screen area is moved into the melt channel without changing the active filter area. Due to this mode of operation, the filtration system operates process- and pressure-constantly. The variation of the pressure differential across the filter ($\Delta p$) amounts to max. 2 bar.

![Fig.13: RSFgenius - Technical Layout](image)

Cleaning of the contaminated screens takes place just before they are re-introduced into the melt channel. The dirt cake is then cleaned via a high-pressure segment purging system. For this purpose, already filtered melt is taken from the outlet block and siphoned into a hydraulically-driven piston and then shot from the back at high pressure, through the filter disk and through the screen into the inlet block. The purging pressure is measured and can be adjusted and optimized. Only a small segment (approx. 1% of the screen area) is cleaned at a time with a defined high impulse. The stroke of the back-flush piston (= melt amount to be used) as well as the speed (= intensity of cleaning) can be adjusted freely and therefore optimized. So on one hand the cleaning is very efficient but on the other hand the melt amount used is minimized (backflush losses are minimal).

Due to this mode of operation the screens can practically be cleaned 100% and can be re-used, depending on the filtration fineness, up to 400 times. This makes a fully-automatic filtration (without any operator attention) possible for up to two months.

Thanks to unique performance characteristics of the RSFgenius, even highly contaminated PET bottle flakes can be used in the manufacture of high quality PET sheet.

2.3.2. The SFXmagnus

The SFXmagnus is basically very similar to the RSFgenius, however without self-cleaning. In the case of the SFXmagnus, the filter elements must be replaced after one use. The SFXmagnus is therefore designed for lower contamination levels than the RSFgenius. The space within the screen changer which is available due to there being no back flushing piston
etc. enables a major enlargement of the melt channel. This makes it possible to use a smaller unit for the same throughput rate, or to use considerably finer filter elements.

**Fig. 14: SFXmagnus in a thermoforming sheet line**

The advantages of the Rotary Filtration Systems are clear: thanks to the fact that the filtration area always remains constant, the variations in pressure differential are kept to a minimum. In this way, permanent melt purity and constant product quality can be **guaranteed**.

### 3. Case Examples

A US American manufacture of sheet for thermoforming and thermoformed containers has – with the help of the MRS extruder concept – successfully dispensed with the expensive and energy intensive processing step of crystallising and drying the material prior to extrusion.

This company operates an extrusion line with a throughput of 1.000 kg/h. PET. Most of the sheet produced is subsequently processed to containers for packaging fruit.

**Fig. 15: Line for thermoforming sheet with throughput of 1000 kg/h**
The MRS extruder plasticises and devolatises the material, the RSF genius filters the material (at a fineness of 56 to 75 microns) the Online Viscometer measures the viscosity immediately upstream of the die and controls the vacuum pump at the devolutilising section of the extruder in order to maintain the viscosity within a narrow range. In this way, not only can the quality of the sheet but also the sheet thickness be maintained at a consistently high level.

Fig. 16: Example 1 - Thermoforming sheet line in USA, 1000 kg/h

A smaller line of this kind is in operation in Brazil, with an MRS 110 extruder. This line is also used for the production of thermoforming sheet for packaging fruit, however with a somewhat smaller throughput rate of 600 kg/h.

On this line, a mix of reground skeletal waste, reground bottle flake and virgin material is processed, with no pre-drying and with extremely simple vacuum technology, without gas purification and without the corresponding high maintenance requirement.

In comparison with lines which operate with pre-drying, the MRS concept means that no crystallising or pre-drying is required. It was therefore possible to reduce the space requirement by 25 % and the energy requirement by 15 to 25 %, not to mention the reduced maintenance and the fact that the long time required for drying and crystallising the material in advance of processing considerably restricts the flexibility of the whole operation (for example material colour or grade changes).

Fig. 17: Case example 2 – PET thermoforming sheet production in Brazil, 600 kg/h
In the production of PET sheet using post consumer bottle flake, the devolatilising effect of the MRS extruder is not only useful for removing moisture: it is also useful for decontaminating the melt so that the process can be provided with an FDA “letter of no objection” from the American Food and Drug Administration (FDA).

In addition to the good mechanical properties of the sheet, the energy consumption of the whole plant was measured as well.

Compared to conventional single screw processing with crystallisation and pre-drying down to a water content of less than 50 ppm the specific energy consumption is much less, around 20%, because of the immense energy costs for heating the pellets by hot air during the preparation for extrusion.

<table>
<thead>
<tr>
<th></th>
<th>MRS</th>
<th>Twin Screw</th>
<th>Single Screw</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crystallisation</td>
<td>-</td>
<td>-</td>
<td>90 Wh/kg*</td>
</tr>
<tr>
<td>drying &lt; 50 ppm</td>
<td>-</td>
<td>-</td>
<td>120 Wh/kg*</td>
</tr>
<tr>
<td>pre - drying to 1000 ppm</td>
<td>-</td>
<td>60 Wh/kg*</td>
<td>-</td>
</tr>
<tr>
<td>extruder drive and heating</td>
<td>295 Wh/kg</td>
<td>230 Wh/kg*</td>
<td>240 Wh/kg*</td>
</tr>
<tr>
<td>vacuum</td>
<td>45 Wh/kg</td>
<td>90 Wh/kg*</td>
<td>-</td>
</tr>
<tr>
<td>booster pump</td>
<td>-</td>
<td>30 Wh/kg*</td>
<td>-</td>
</tr>
<tr>
<td>total</td>
<td>350 Wh/kg</td>
<td>410 Wh/kg*</td>
<td>450 Wh/kg*</td>
</tr>
</tbody>
</table>

* Specifications given by our customers

**Table 2: PET processing: comparison of energy consumption between extruder types**

In comparison to twin screw processing of the flakes the energy consumption is also less, because a high vacuum of less than 5 mbar is needed with the twin screw and in addition to that normally the flakes have to be pre-dried down to around 1000 ppm, and there is a booster pump needed as well.

The specific energy consumption of the MRS technology is 15% to 25 % less the conventional technologies, not to mention the higher flexibility and less maintenance on dryers and high vacuum systems.

**4. Conclusion**

The new MRS extrusion system offers extremely efficient devolatilisation or degassing of the polymer melt thanks to its high surface renewal rate. The diffusion process is drastically increased by the multiple screw system. Consequently, it is for example easily possible to process PET bottle flake to sheet for thermoforming with excellent quality.

The MRS extrusion system is (including the multi rotation section) based on proven and rugged single screw extruder technology. This system is therefore extremely well suited to the processing of highly contaminated polymers (for example post consumer waste).

Since the MRS extrusion system requires the input material to be neither pre-dried nor crystallised, the system is an economically attractive alternative to the conventional
technologies for processing PET. The MRS has already been proven as a reliable and practically maintenance-free system for over a year on a range of different applications.

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