PET in Rotation

Extrusion. MRS (multi-rotation system) technology, as an alternative to conventional recycling of PET bottle regrind, is opening up new possibilities in terms of flexibility, quality and energy consumption. It also enables undried material to be processed directly.

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The recycling of post consumer PET bottles to bottle grade chip is common practice today. There is however a clear trend toward ever increasing quality requirements in the future. With the optimum technology, it is possible to recycle PET bottles almost indefinitely, thereby achieving a real recycling cycle.

One special characteristic of PET which can make its processing difficult is its hygroscopic behavior. During storage and during the washing of post consumer bottles, water molecules from airborne moisture or from surface contact diffuse into the PET. During the extrusion process, these water molecules break down the molecule chains (hydrolysis) resulting in a drastic reduction of the viscosity, unless the water is removed.

An Outline of the Process Chain

After collection of the bottles **(Title photo)**, coarse separation of foreign particles and materials takes place. Subsequently, the bottles are ground into flake. These flakes are washed in a hot wash process where dirt, labels and adhesive from the labels is removed. In a floatation bath, polymers are separated according to their specific gravity. The most common foreign polymer, polyprolylene (PP) (bottle caps) are floated off. The PET bottle flakes are then placed in a centrifuge to remove the sur- →

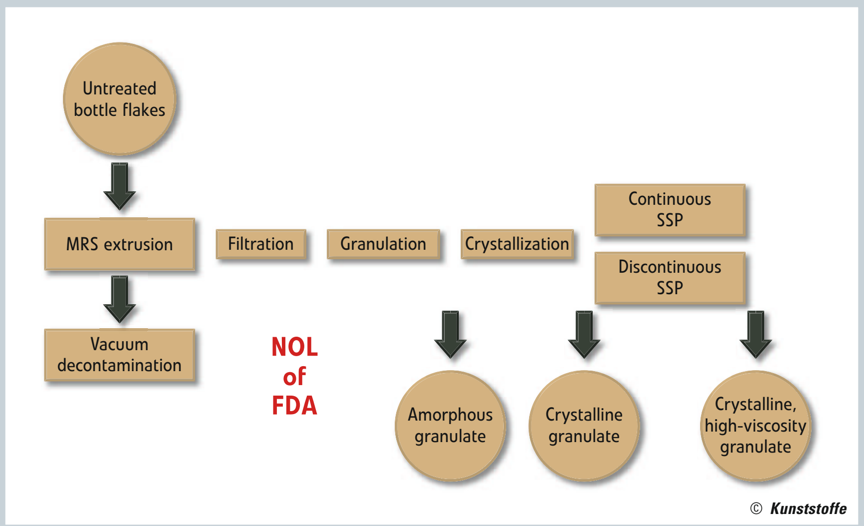

Fig. 1. Overview of possible process steps for PET reprocessing (NOL = Letter of Non-Objection)

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face water. Metals are separated out and further separation of PVC and in most cases, color sorting takes place.

After extrusion, the melt is filtered. The filter system must allow the dirty screen to be exchanged for a clean one without interrupting or hindering the melt flow, and consequently the production process. A melt mixer is used to homogenize the flow profile and ensure melt purity. The mixer is designed to ensure that the melt is subsequently discharged smoothly and uniformly from the die.

These pellets or chips are dried, crystallized and go through an SSP process (solid state polymerization) where the viscosity is raised to the required level. Depending on the throughput rate, this final processing stage can be a continuous process (for larger throughput rates). For smaller throughput rates, typically the more flexible discontinuous processes are used (**Fig. 1**).

The gentle treatment of the polymer in the multi rotation system (MRS) and the fact that the material processed on this extruder means only relatively short residence times in the SSP result in a low amount of yellowness and excellent transparency.

Thanks to its great flexibility, the MRS concept is well suited to the processing of large material streams, as well as smaller batches and batches of variable composition (color, source). The SSP can be performed either batchwise or continuously.

The PET chips of pellets can be used for the most diverse applications: for fibers, sheet for thermoforming and of course for injection molding preforms for bottles. Additionally, it is possible to produce chips or pellets from up to 100 % post consumer bottles for products which come into direct contact with foodstuffs. The MRS extrusion process has a LNO (letter of non objection) from the FDA for processing PET bottle flake to food contact products both with and without a subsequent downstream SSP process.

The Importance of Moisture Extraction

The moisture content tends to shorten the molecular chains during extrusion, resulting in a decrease in viscosity and worsening the mechanical properties of the end product.

To avoid this, the pellet stock is conventionally dried with dry air at temperatures up to 180 °C and residence times up to 8 h. As a result, moisture is removed prior to extrusion, so that hydrolysis does not take place.

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 (Δn) will increase in relation to the residence time (Δt) 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

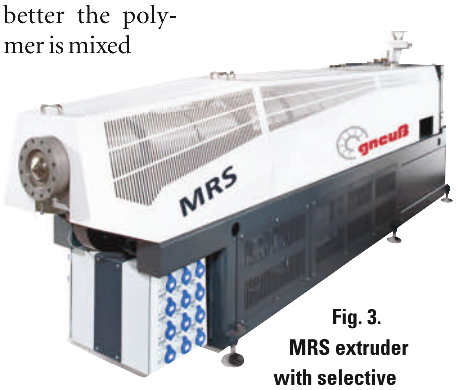

Fig. 3. MRS extruder with selective melt temperature control

Devolatilization with the MRS Extrusion Concept

With the MRS extruder, PET pellets are processed direct, without pre-drying the material. During extrusion (in the melt phase) the polymer surface is greatly enlarged and exchanged at an extremely high rate, thereby enabling volatiles to be extracted (Fick's law of diffusion).

To illustrate this, the mode of operation of the MRS process is described below.

The MRS 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 (**Fig. 2**). The drum contains eight small extruder barrels, parallel to the main screw axis.

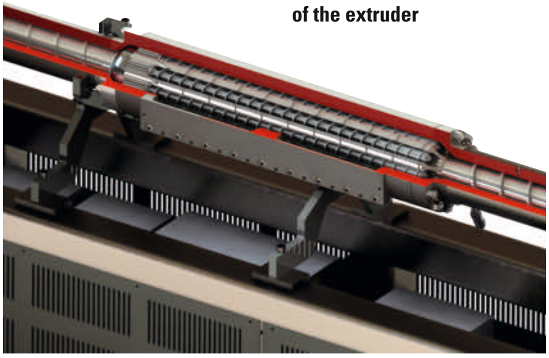

Fig. 2. The multi rotation section of the extruder

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. 3**).

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. For example, the melt exchange surface area generated by MRS is about 25 times greater than that of a conventional co-rotating twin-screw extruder (**Fig. 4**). As a result, it can process undried flakes or pellets with up to 1 % moisture content.

Thanks to its construction, 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.

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. The position, length and design of the modules of the MRS can be varied.

Advantages of the MRS Technology

In bottle2bottle recycling, the MRS extrusion system can be used to produce both amorphous and crystalline materials with different viscosities – depending on the customers' requirements. The material can be discharged directly downstream of the pelletizer, amorphous pellets with a viscosity adjustable within a wide range by volatilization can thus be produced. It is also possible to connect a crystallizer or SSP downstream to achieve very high viscosities.

Measurement and Control of the Processing Parameters

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 complain 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.

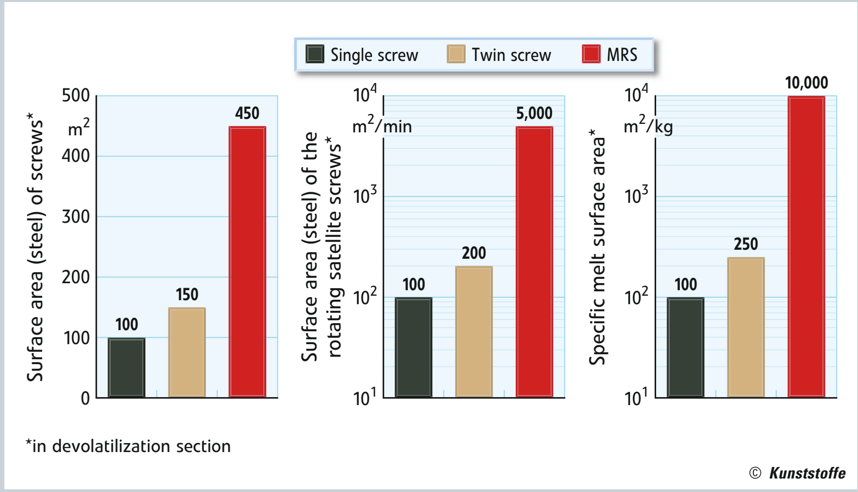

Fig. 4 Comparison of the efficiency of different extrusion concepts

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.

Process Control with the 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 slot capillary. Melt temperature and melt pressure (at two locations) is measured. Based on internal calculations the online viscometer (VIS) monitors the value of the representative shear rate and the corresponding viscosity.

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.

Thanks to the VIS it is now 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 devolatilizing section of the MRS extruder, thereby guaranteeing constant melt properties (viscosity, molecular weight and therefore the mechanical properties which result from these) **(Fig. 5)**.

The above graph shows the behavior of the vacuum (beige) and the melt viscosity (red) over time. The change of input material at 11:00 h 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 devolatilizing 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.

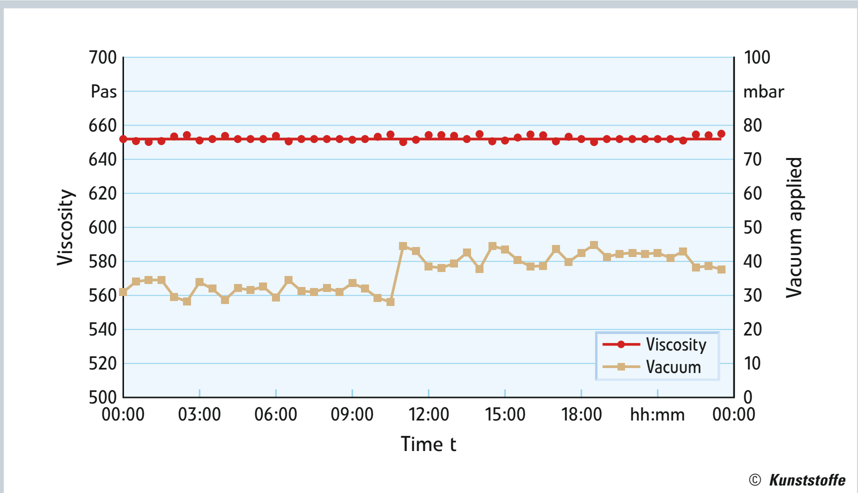

Fig. 5. Constancy of viscosity under fluctuating moisture content

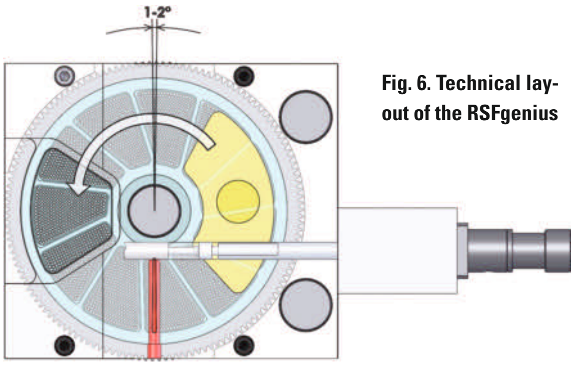

Fig. 6. Technical layout of the RSFgenius

Constant Melt Filtration with Integrated Self-cleaning

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 are particularly suited to this purpose as they operate fully automatically and pressure constant.

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 about 1° **(Fig. 6)**. 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 (Δp) amounts to max. 2 bar.

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 with about 30–80 bar. 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.

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 several months in some applications. Thanks to the RSFgenius, even heavily contaminated polymers can be reprocessed into a high value nonwoven.

Case Example One: Ribbon Production

In a concrete application of the production of ribbons based on 100 % undried bottle flake, the moisture content is up to 12,000 ppm. In this system, the polymer was analyzed to ascertain the viscosity curve during the process. The IV value of undried PET bottle flake was analyzed as was he polymer upstream of the devolatilization zone, directly downstream of it, and in the end product **(Fig. 7)**.

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 by hydrolysis. The more moisture is in the input, the more the 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 **(Fig. 8)**.

The viscosity increase in the devolatilization section is influenced and controlled by the vacuum level. The influence of the vacuum on the viscosity is considerable.

The increase in viscosity in response to the increasing vacuum level can be seen clearly.

	MRS [Wh/kg]	Twin screw [Wh/kg]	Single screw [Wh/kg]
Cristallisation	–	–	90 *
Drying < 50 ppm	–	–	120 *
Pre-drying to 1,000 ppm	–	60 *	–
Extruder drive and heating	295	230 *	240 *
Vacuum	45	90 *	–
Booster pump	–	30 *	–
Total	**350**	**410 ***	**450**

Table 1. Comparison of energy consumption between different extruder types (* Specifications given by our customers)

Contact

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Case Example Two: Pellet Production

A manufacturer of PET flakes chose to extend the value addition of his production by installing an extrusion line with a downstream SSP. With the MRS Extrusion concept, this company was able to avoid cost intensive, complicated and potentially damaging pre-treatment of the flakes prior to extrusion.

PET is processed with a throughput rate of up to 2,000 kg/h from washed bottle flake to a high value PET bottle grade chip/pellet. The MRS extruder, operating at a vacuum of only 25 to 30 mbar, permits very short residence times in the downstream SSP. The Melt Filtration System type RSFgenius filters the material from 75 µm to as fine as 30 µm. The Online Viscometer measures the viscosity of the polymer upstream of the die and is equipped with a control loop to regulate the vacuum on the MRS extruder, thereby ensuring that the viscosity is automatically held at a controlled, constant level.

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

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.

The specific energy consumption of the MRS technology is 15 to 25 % less than conventional technologies **(Table 1)**, not to mention the higher flexibility and less maintenance on dryers and high vacuum systems.

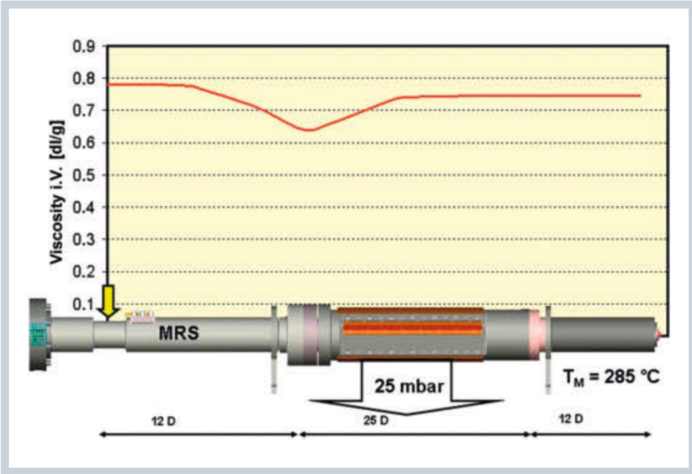

Fig. 7. Viscosity when processing PET bottle flakes

Conclusion

Thanks to the high surface renewal rate of the polymer, the MRS extrusion system achieves efficient devolatilization of the plastic melt. The diffusion process is greatly increased by the use of screws with multi-rotation section; the same applies to the migration mechanisms at the melt surface. Consequently, it is readily possible to produce packaging tape, thermoforming sheet, fibers or bottle pellets of excellent quality, including good yellowing index.

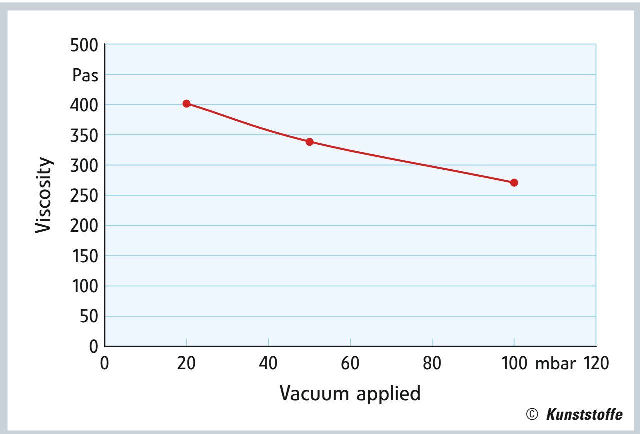

Fig. 8. Correlation between viscosity and vacuum applied (figures and sources: Gneuss)

The MRS Extrusion System (including the Multi Rotation Section) is based on the rugged and simple single screw extruder and is therefore suited to the processing of highly contaminated polymers.

Thanks to the FDA Letter of Non Objection, the MRS Extruder, its Devolatilization System and the Rotary Melt Filtration System permit the processing of up to 100 % unwashed PET bottle flakes to containers for food and beverage contact.

Since the MRS extrusion system requires the input material to be neither pre-dried nor crystallized, the system is an economically attractive alternative to the conventional technologies for processing PET as the factory floor footprint and the energy requirement can be reduced. ■

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