Master Thesis

Wood Plastic Composites: determination and comparison of the specific energy consumption for WPC compounding methods based on two state-of-the-art formulations

Written by

Sonja Christina Kahr

Handed in

Institute of Polymer Processing

Head of institute: Univ.- Prof. Dr. Clemens Holzer

Montanuniversitaet Leoben

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Affidavit

Affidavit: I declare in lieu of oath, that I wrote this thesis and performed the associated research myself, using only literature cited in this volume.

Date	Signature

Acknowledgement

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Kurzfassung

Diese Arbeit beschäftigt sich mit dem energetischen und qualitativen Vergleich dreier unterschiedlicher Aufbereitungsmethoden für Wood Plastic Composites, unter Verwendung zweier gebräuchlicher Rezepturen. Ein gegenläufiger Doppelschneckenextruder (DSE), ein gleichläufiger DSE und ein Heiz-Kühlmischer Konzept wurden mit einer Polypropylen (PP) 40-90 und einer Polyvinylchlorid (PVC) 50/50 Mischung getestet. Die Messungen wurden alle mit Hilfe der Software WarpNet und speziellen Stromwandlern zur Transformation des Stroms durchgeführt. Zur Bestimmung der Granulatqualität wurden Schüttdichte-, Rieselfähigkeit- und REM- (Rasterelektronenmikroskop) Messungen durchgeführt. Es wurden zwei Ausstoßraten pro Test gemessen um industriell relevante Prozessbedingungen zu gewährleisten.

Es wurden in dieser Arbeit signifikante Unterschiede zwischen den Materialien gefunden. PP weist hier einen höheren spezifischen Energie Verbrauch und einen höheren Wirkungsgrad auf. Höhere Ausstoßraten führen generell zu besserer Auslastung des Hauptmotors und folglich zu niedrigeren unerwünschten Prozessverlusten. In Bezug auf thermische und mechanische Verluste findet man bei PVC höhere Werte als bei PP.

Der gleichläufige DSE und der Heiz-Kühlmischer führen zu Problemen bei der Prozesskontrolle. Betrachtet man PP, so liefert eine Aufbereitung mittels Gegenläufer die ökonomischsten Ergebnisse gefolgt vom Gleichläufer und dem Heiz-Kühlmischer. Für PVC ist der Heiz-Kühlmischer die wirtschaftlichste Alternative, gefolgt vom Gegenläufer.

Es wurden signifikante Unterschiede bei allen definierten Qualitätsmerkmalen für die verschieden aufbereiteten Materialen festgestellt. Die höchsten Werte für Schüttgewicht und Rieselfähigkeit wies der Gleichläufer auf, gefolgt vom Gegenläufer und dem Heiz-Kühlmischer. Die niedrigste Restfeuchte mit 1% ± 0,38% r.h. wies das Granulat des Gegenläufers auf, dessen Werte um 1% niedriger liegen als jene der beiden anderen Technologien. Alle Prozesse führten zu einer zufriedenstellenden Homogenität der Granulate, wobei jenes des Gleichläufers eine starke Beeinflussung bzw. Zerkleinerung der Fasern, sowie eine starke dunkle Verfärbung aufweist.

Diese Arbeit soll, durch den Vergleich der wichtigsten Compoundiermethoden, eine Entscheidungshilfe für zukünftige Kunden bzw. Markteinsteiger darstellen.

Abstract

This work focuses on the economic and qualitative comparison of three compounding methods for Wood Plastic Compounds (WPC), using two state-of-the-art formulations. In detail a counter-rotating twin screw extruder (TSE), compounder and one heating-cooling mixer concept were tested processing a Polypropylene (PP) 40-90 and a Polyvinylchloride (PVC) 50/50 formulation. The measurements were done with the software WarpNet using ring- and flap-converters for the current transformation. To analyze the qualitative aspects of the granules bulk density-, flowability- and SEM- (Scanning electron microscope) tests were done. All tests were done with two output rates to ensure industrial relevant processing ranges.

Differences between the two materials were detected. PP leads to higher specific energy consumptions and a higher degree of efficiency than PVC. The higher output rates result in a better workload of the main drive and consequently to lower, unwanted process losses. Regarding the thermal and mechanical losses, PVC shows higher values than PP.

The compounder and the heating-cooling mixer lead to difficulties in the process control. Focusing on PP, the counter-rotating TSE showed the most economic results, followed by the co-rotator and the heating-cooling mixer. For PVC, the heating-cooling mixer is the most economic technology followed by the counter-rotator.

Regarding the quality, significant differences were detected for all defined quality standards. The highest value for bulk density and flowability shows the co-rotator followed by the counter-rotator and the heating-cooling mixer. The lowest moisture level with 1% ± 0,38% r. h. was achieved by the counter-rotator which was 1% lower than with the other two machines. The homogeneity was given for all compounds, whereas the co-rotator led to a high degree of fiber manipulation and a darkening of the material.

The aim of this work is, to provide a decision aid for future customers or newcomers on the WPC market.

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1 SCOPE AND OVERALL OBJECTIVE

Wood Plastic Composites (WPCs) represent one of the youngest and fastest growing group of materials these days, not only due to their high variety of applications but also because of their “green” and eco-friendly image. WPC products are contrivable in single- and two-step processes, so either direct-extrusion or processing after previous compounding, of which the latter seems to dominate the market.

The reason for this preponderance lies in the better thermal homogeneity, achievable by the two step process, which results in better mechanical and physical properties. This work is focused on the first step, the compounding process. There are several technologies available for compounding WPCs, which shall be compared in respect of their specific performance and quality of the emerging compound, the intermediate product. In this particular thesis, the counter-rotating and co-rotating twin screw extruder, heating/-cooling mixer shall be examined by using the most commonly processed mixtures on the market. The measuring equipment, a so called Ducati device, records all necessary data (voltage, current, idle power, active power) so that the specific energy consumption as well as the degree of efficiency and the proportion of the active power can be calculated. Furthermore an energy balance (energy input broken down to the single components) shall be drawn for every procedure, as long as the comparison of the different procedures is reasonable. Therefore, the measuring apparatus contains ten control points which can be attached to the phase of a load (e.g., motor, heating, cooling, granulator, …). To assure the comparability of the measurements the quality of the compound regarding the flowability, the bulk density as well as the homogeneity and the moisture content will be evaluated and compared.

The goal of this thesis is to provide an aid for the initial purchase decision of future customers who want to enter the WPC market, by giving an overview of the cost-benefit equation of the investigated machines.

2 BASIC CONSIDERATIONS

The following chapter will further explain the term WPC (Wood Plastic Composite) on the one hand and describe the tested machines and the Ducati device on the other hand. Furthermore the quality standards will be defined and the necessary measurement devices explained.

2.1 WPCs (Wood Plastic Composites)

WPCs are a very young segment of the polymer industry with a great potential. Not only due to its flexible ratio of mixture and as a consequence, a flexible setting of mechanical properties, but also because of numerous benefits compared with pure wood. WPC is a mixture of wood flour/spans/fibers and polymers. As a result it combines the properties of both material groups resulting in a material, which has the optical and even increased mechanical properties of wood and can additionally be processed by commonly used plastics processing methods (injection molding, extrusion…), which gives a tremendous freedom of form and geometry. Another benefit is the flexibility in optical appearance of WPC products achieved by post-manufactured brushing, embossing or shaping [8 ,39, 43].

Furthermore products of WPC have a higher biological, UV-radiation and weathering resistance and lower water absorption than conventional wood products and are less likely to be harmed by fungi, which results in lower maintenance costs. This gives a broad variety of possibilities regarding the shape of the product, the setting of additives (e.g. fire retardants, UV-radiation protectors, color stabilizers, …) and as a consequence the application. Depending on the polymer component, mixture ratios ranging from 20/80 to 80/20 wood/polymer are possible. The most commonly used polymers are PE (65%), PVC (16%), PP (14%) and PS (5%) of which PVC has the least eco-friendly image. The challenge of extruding WPC is its moisture content, which varies from 30% r. h. in summer to 50% r. h. in winter and challenges the extruder's/compounder's venting system, especially because the product's moisture limit should be about 2-3% r. h. [22, 32, 39, 43].

The main application and volume of processed WPCs is in the railing and decking industry, even though the range of applications broadens steadily. The WPC market develops constantly. In North America the market is, with 700.000 tons sold material in 2005, already well-established as you can see in Fig. 1, where the main applications are shown related to their market share. The largest production scale lies in outdoor applications like railing and decking (see Fig. 2) [8, 25, 39].

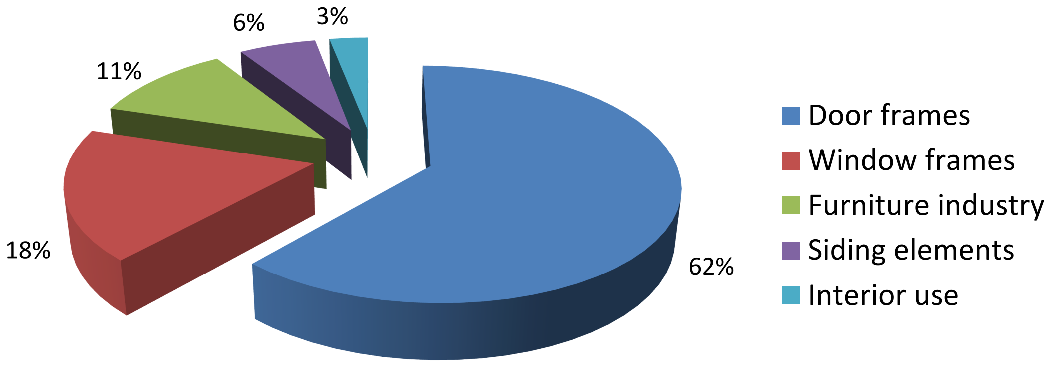


Figure 1: WPC Market overview – USA [39].

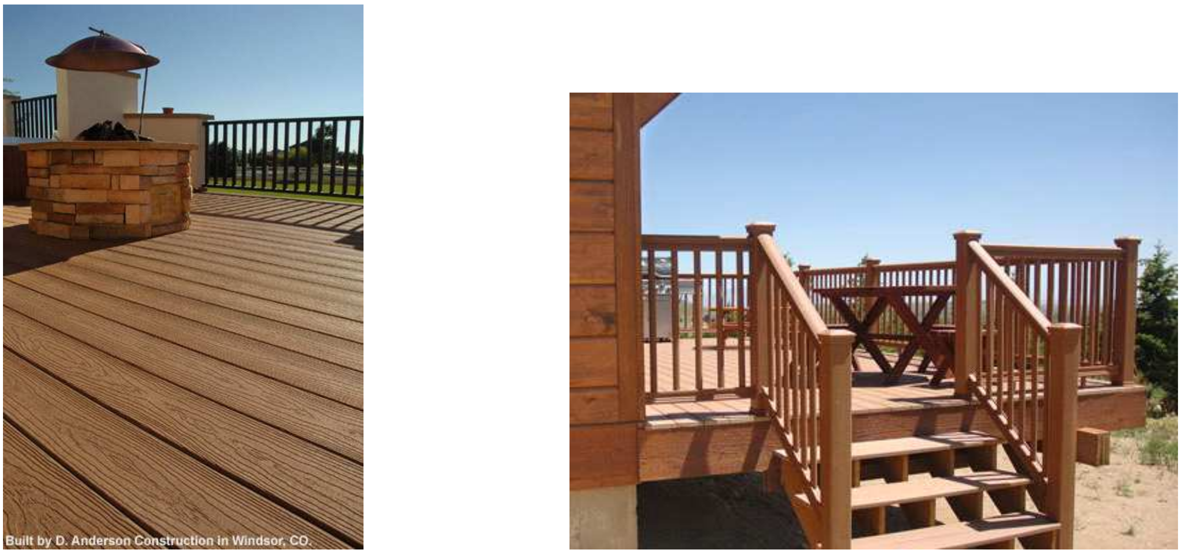


Figure 2: Outdoor application: decking (left) and railing (right) application [13].

While detailed market analyses are available for North America, the data situation for Europe and Asia, the next important markets, are rather meager. Experts estimated a production of 30.000 tons for the year 2005. These markets offer the biggest potential and the greatest growth rates with the focus on indoor use like door frames, skirting- or window profiles (see Fig. 3). In Fig. 4 the main applications for European market are shown related to their market share. Thus the furniture industry makes use of the enlarged possibilities of WPCs. An additional field of applications for the future is seen in the automotive industry [5, 8, 22, 25, 42].

Figure 3: Indoor applications: doorframe (left), window sill (middle) and skirting profile (right) [8].

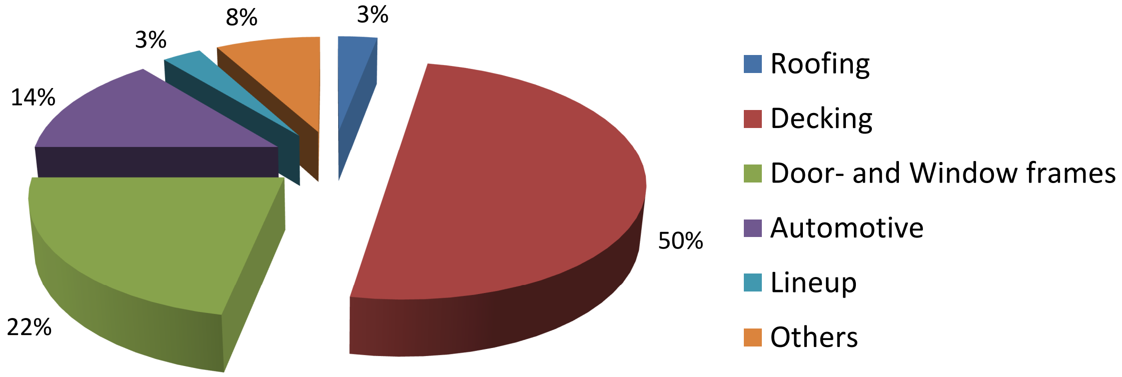


Figure 4: Market overview – Europe [39].

Beside the broad range of applications and the flexible properties, another advantage of WPC is the environmental and economic aspect. The benefit of using WPC instead of plastic or wood products lies in the substitution of exotic wood species, the contribution to reduce the greenhouse effect, the easy recycling/burning and energy valorization involved, as well as the reduced dependency on energy cost fluctuation [8, 22, 32, 43].

2.2 Compounding

In the field of polymer engineering the term compounding is defined as the refinement or dressing process of polymers by mixing them with additives (thermal- and UV stabilizers, lubricants, flame retardants etc.) and/or filler materials (talcum, carbon, ceramics, wood fibers etc.) to achieve the desired properties. Since the development of new polymers is decreasing, the trend goes to adjusting the known polymers property profile with additives and the field of compounding constantly gains importance. The compounding process covers six operation steps: the conveyance of the solid material, the melting, the dispersing and mixing of the material, as well as the venting. The last step is the pressure build-up to press the material through the die. These process steps manage all necessary tasks like the decrease of agglomerations, the homogenous incorporation of additives and the removal of volatile and moisture components [1, 4, 20, 24].

When talking about post processing, there is a difference between hot-cut and cold-cut pelletizing technologies. While the hot-cut pelletizer separates the extrusion strand directly after the die by using a rotating, water wetted knife, the cold-cut technology, as the name predicts, chops the cooled, frozen strands with a knife after they were led through a water bed [24, 35].

The key factor of a good compound is its homogeneity which influences the final product properties and has an impact on further processing. The residence time of the material in the preparation machine, the use of mixing and kneading parts as well as the venting sections, which are especially important for WPCs due to their relatively high moisture content, is decisive factors for homogeneity. A big challenge in compounding WPCs is the small operation window, which is defined by a minimum and maximum process temperature. The bottom level is the melting point of the thermoplast (PP 150℃, PVC 180℃) while the upper level is the temperature where lignin separates itself from the wood and causes irreparable damage. The degradation of lignin lies within a wide range of temperature starting at 200℃ to 450℃. It is a complex structure buildup of phenolic hydroxyl, carbonyl groups and benzylichydroxyl, which are connected by straight links [9, 15, 24, 40].

The current market demands regarding compounding are the increase of throughput, product variety, quality requirements, filler contents and the decrease of batch size. Conventionally co-rotating twin screw extruders (TSE) are applied for the compounding process, but also counter-rotating TSE as well as ko-kneaders and heating-cooling mixers are used. In this work, three categories of compounding machines are used for measurements and discussed in the following paragraphs [24, 45].

2.3 Extruders

Extruders are continuously working screw conveyors, which are not only applied in the plastics industry, but also for example in the food industry. This technique, inspired by the food industry, was realized at first by the cable industry, when the first concept was drawn by Phoenix Gummiwerke A.G. Since then tremendous developments made extruder machines to the most important continuously working plastic processing machines worldwide. The plastics industry uses extruders to produce e.g. pipes, sheets, profiles, hoses, cable coatings and in fact all products, which can be produced as an endless semi-finished part with following final cutting.

Today we know many different kinds of extruders, beginning with the simplest concept of the single screw extruder, over the intermeshing and non-intermeshing twin screw extruders to the special ko-kneaders and planetary roller extruder. For simple applications and moderate outputs, the single screw extruder is still state-of-the-art, but for more complex processes and higher output rates, where single screw extruders are technologically insufficient, multi screw extruders, like the counter-rotating and the co-rotating twin screw extruders are applied. One of these fields is the compounding of polymers, where ideal dispersing, mixing and high outputs are required [20, 35, 45].

2.3.1 Counter-rotating twin screw extruder

The development of counter-rotating TSEs began in the 1930s and was inspired by the demand to create an extruder for certain polymer types, whose conveying characteristics are independent on the one hand of the backpressure and additionally of the friction coefficient between polymer and barrel. The counter-rotating TSE is, other than the single screw extruder or the compounder, an axially closed system. The first engineering analysis of this construction dating back to 1963 by Schenkel found, that this type of extruder can be seen as a positive displacement pump. This characteristic appears due to the C-chambers (see Fig. 5) formed by the two intermeshing screws and the axially closed system having the positive effect of a very good feeding behavior [4, 6, 35, 45].

There are two types of parallel counter-rotating TSE, the intermeshing- and the non-intermeshing construction. The non-intermeshing machines can, due to their characteristics, be seen as two single-screw extruders which influence each other, but they are not focus of this work. In intermeshing counter-rotating TSE (see Fig. 6), the screws, as the name predicts, move counter wise and have the same pitch [6, 35, 45].

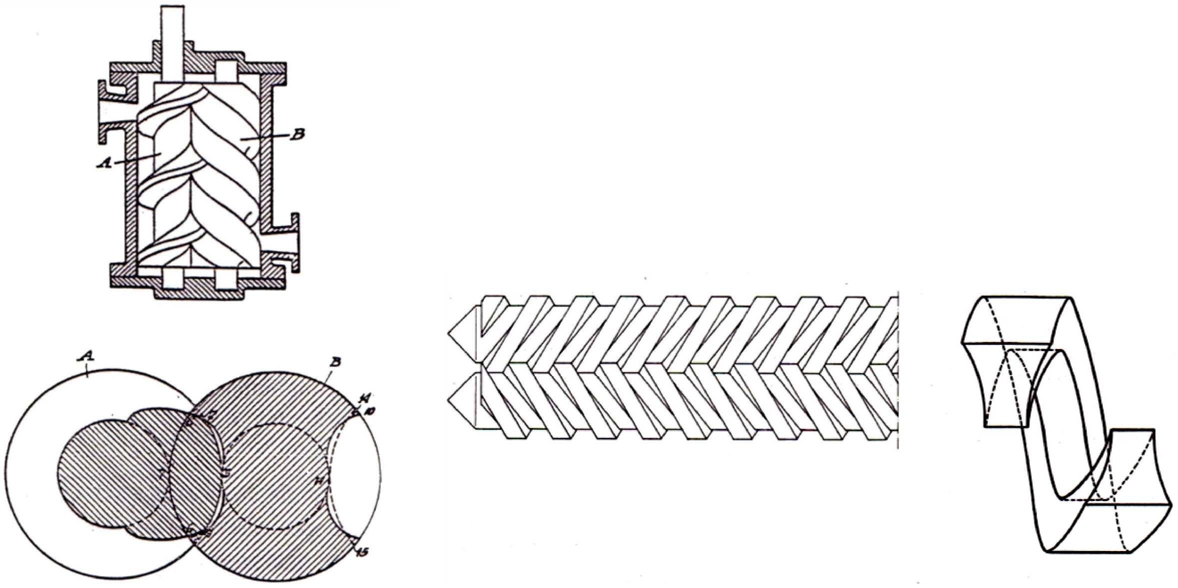


Figure 5: Intermeshing area of two counter-rotating screws (left); C-chamber formed by the two intermeshing screws [6, 45].

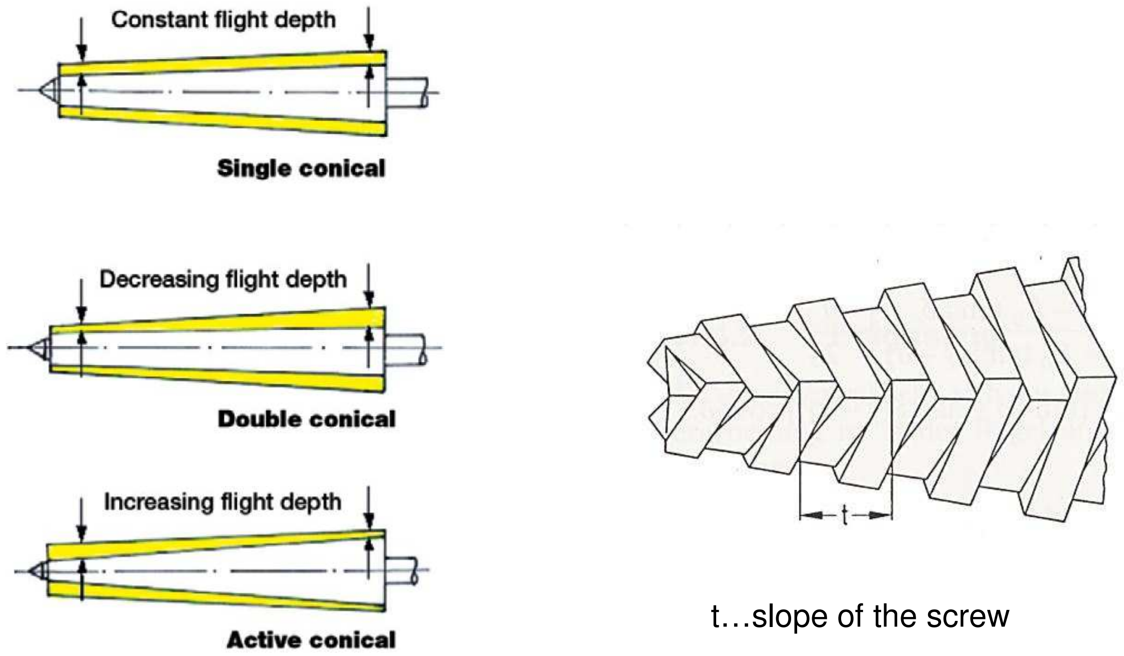
A very important construction among the counter-rotating TSEs is the conical design, developed by AGM (Anton Anger Allgemeine Maschinenbau GmbH) in 1964 and Cincinnati Extrusion GmbH in 1969. The development was pushed by big problems concerning the driven shafts. Due to the narrow axial distances and the bearing technology back then, it was impossible to accommodate long-term radial and axial forces, by means of appropriate dimensioning technology. This problem was solved through an improved bearing technology available at the end of the 1960s and through the development of the conical TSE, which provided more space for the whole driven shaft, the bearings and the distributor drive. The first machines were single conical machines, where the flight depth stays constant throughout the length of the screw (see Fig. 6). In 1964, Krauss-Maffei GmbH filed a patent [27] for a double conical screw, in which the flight depth continuously decreases over the screw length, which leads to higher output rates while retaining barrel lengths and axial angle (see Fig. 6). In 2000, Battenfeld GmbH, back then only known for parallel TSEs, presented the negative-conical screw design, today better known as the "active" conical design (see Fig. 6). The benefit of this design is that higher output at lower screw speed can be realized and consequently the lifetime of the screw is prolonged [18, 19, 26, 27].

The main advantages a conical TSE offers compared to a conventional parallel TSE are:

- Better heat conduction / transmission in the feeding zone due to the bigger outer diameter.

- The decreasing diameter minimizes the shear stress at the end of the screw in the pressure build-up zone and therefore avoids thermal stress and inhomogeneity.
- The conical construction provides more space for the bearings, which therefore can be more robust and massive.
- The force on the pressure bearing is 1,7 – 2 times smaller.
- Better screw temper systems can be applied.
- The smaller front surface of the screw results in lower backpressure forces.
- The big outer diameter in the feeding zone provides more plasticizing capacity.
- Smaller constructions at same performance levels are possible.

On the other hand a conical screw design means higher production costs and more complex construction.



t…slope of the screw

Figure 6: Construction possibilities of conical TSEs (left), Conical TSE – schematic model (right) [6, 36].

The operating sections of a counter-rotating TSE are divided into six parts (see Fig. 7). First section is the so-called solid section, where the solid is compacted through compression and the porous mass is formed to a solid strand. The second section is the melting zone, where the solid mass is melted through inner friction and friction with the barrel. The third section is the mixing part, where the melt is mixed and dispersed by constantly splitting and merging the melt. In this section kneading and mixing parts are applied for an ideal, homogenous product. The mixing zone is followed by a pressure build-up zone for the subsequent venting part, where a decompression through high slope and wide screw channels is realized. The decompression provokes the volatile components to exit the material. As pressure is needed to overcome the die, a second pressure build-up is necessary and realized in the last operating section through a low slope and a diminution of screw channel width [6, 20, 27, 35, 45].

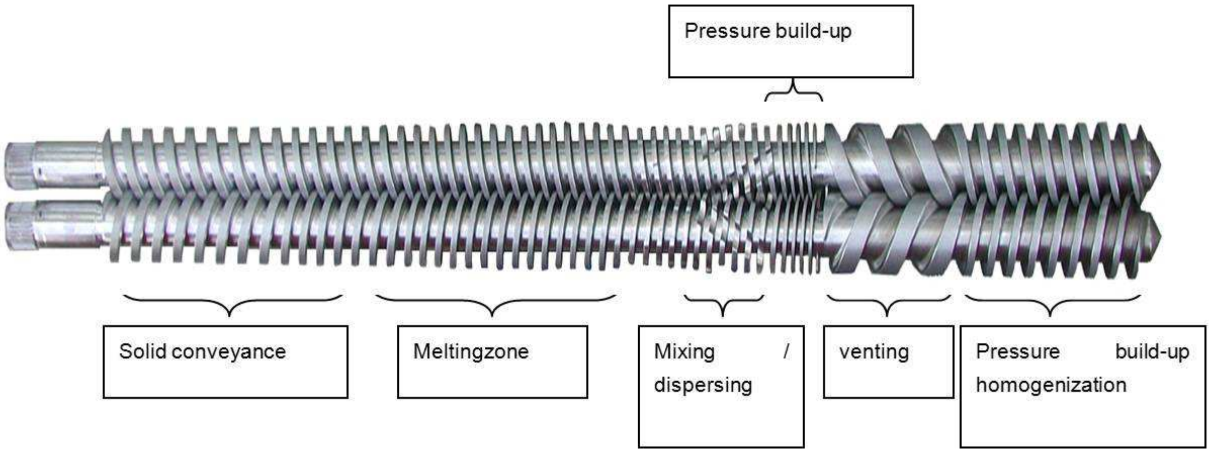


Figure 7: Operating sections of a counter-rotating TSE.

The material is forced along the axis of the screws resulting in a continuous and calm melt flow. The forward pumping capacity is defined after Kiesskalts [21]:

$$Q = NV_c - Q_{leak} \tag{1}$$

Where N represents the number of screw revolutions, V_c stands for the total C-chamber volume and Q_{leak} is the backward leakage flow, which occurs in every extruder, depending on the flow resistance before and between the screws and constitutes of four components shown in Fig. 8 [6, 36].

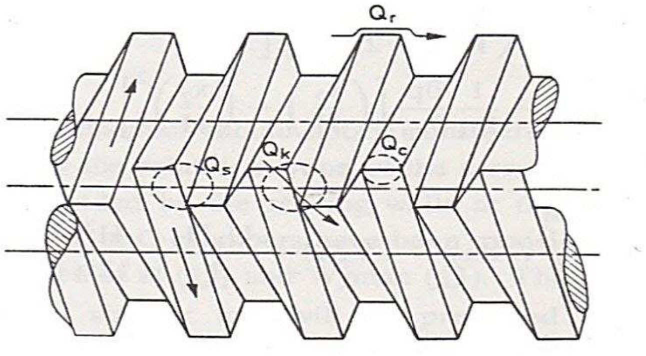


Figure 8: Visualization of leakage flow occurring in the counter-rotating TSE; Q_s and Q_k referring to the pressure leakage between the flanks, Q_c representing the calandering leakage between the screws and Q_r standing for the flight leakage [45].

A very important indicator for thermal homogeneity, mixing performance and dispersing capacity is the residence time spectrum. Many measurements regarding this problem have been carried out by Sakai and are shown in Fig. 9. In general, the residence time spectrum of a counter-rotating TSE is narrower and as a consequence the mixing performance is lower compared to the compounder or the single screw extruder. This fact is associated with, the C-chamber principle of the counter-rotating TSE, the stagnant layers on the screw surface of a single screw extruder, which retain the material longer, and the axially open and self-wiping system of a compounder [18, 19, 20, 35, 45].

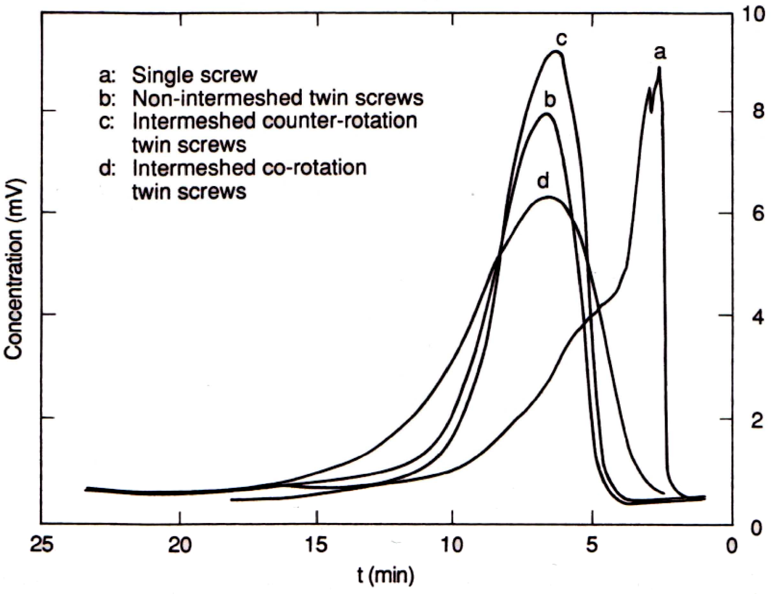


Figure 9: Residence time distribution for single-screw, non-intermeshing twin screws and intermeshing co- and counter-rotating TSEs [45].

This effect can partially be compensated by installing shear and mixing parts in the screws of a counter-rotating TSE. Due to the axially closed system and therefore smaller channel volume of a counter-rotating TSE, the output rates lie under those of a compounder. Moreover is the counter-rotating TSE limited in the numbers of screw revolution, because the counter wise moving screws exert high pressure on the barrel as shown in Fig. 10, which results in a high wear and abrasion of the concerned parts [6, 35, 45].

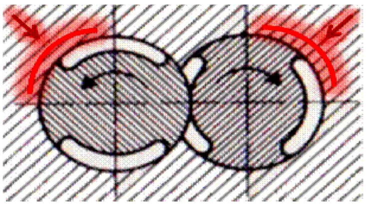


Figure 10: Zones of wear and abrasion in counter-rotating TSEs [18].

Typical main fields of application for a counter-rotating TSE are the compounding and processing of PVC or materials with an explicit thermal sensitivity, flow anomalies and powder materials, which are easier to handle with the characteristics of a counter-rotating TSE.

- PVC-rigid: pipe extrusion, profile and sheet extrusion, blow film extrusion, blow molding, granulation
- PVC-soft: tube extrusion and sheet extrusion, granulation
- Regranulation
- Foam production
- Extrusion of polymers, filled with reactive additives
- Extrusion of fine grained and voluminous HD-PE and PP powder [6, 26].

2.3.2 Co-rotating twin screw extruder

The origins of compounder lie in the beginning of the last century and were fully defined by R.W. Eston 1920 in the U.S. with his patent of fully intermeshing and self-wiping screws. The development was primarily inspired by the demand of independency of rheological properties, which often change when working with fillers, and the desired self-wiping effect, two things, single screw extruders were not appropriate for. Another driver for the development was the need of better mixing and dispersing properties and increased flexibility of the screw design. The TSE meets all these demands and presents today one of the most important and complex screw machines on the market. The screws are build up modularly, where the single screw elements can be variously plugged onto the driven shaft and different screw geometries can be realized. The application of compounders was commercialized in the early 1950s [17, 24, 45].

In a compounder two parallel screws, driven by one common motor, are rotating in the same direction with the same screw speed and the same outer diameter over the length (see Fig. 11 left). As a consequence to the closely intermeshing screws a so-called self-wiping effect occurs, due to the fact that the screws constantly scrape off the material from the opposite flight, so that no stagnation zones can be developed. This self-wiping or self-cleaning effect is illustrated in Fig. 11 (right) [24, 45].

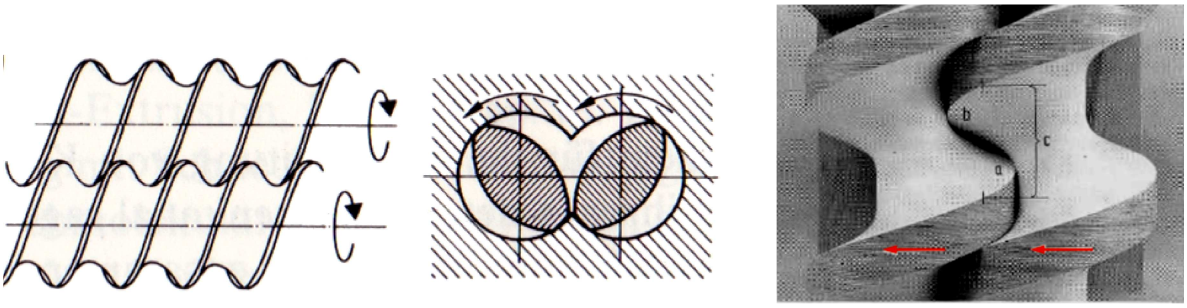


Figure 11: Schematic illustration of compounders and the barrel cross-section (left), self-wiping effect (right) [18].

The operating unit of a compounder forms, in opposite to the counter-rotating TSE, an axially open system. The screws can be built up modularly, after a construction kit system, where the different screw elements, each with a different operating behavior, are tucked on a shaft. This gives a further process parameter, the degree of filling. The pros and cons of fully filled and starved regions in the screw system will be discussed later in the operating sections [6, 21, 24].

Regarding the conveyance characteristic of a compounder, the fluid flows in a figure-of-eight motion along the screw, as shown in Fig. 12 [20, 24, 40].

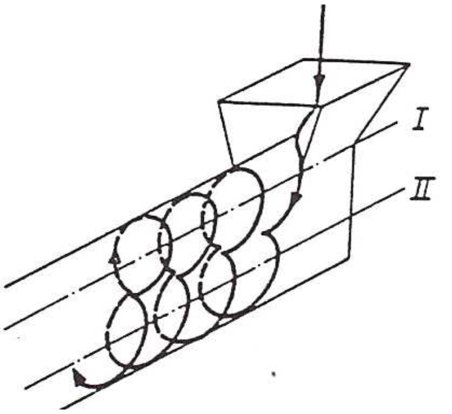


Figure 12: Motion pattern of the fluid inside a compounder [45].

The flowing characteristics inside kneading elements are described to be fluctuating or pulsating. Because of the direct connection between the hopper and the screw tip over the length (axially open system), the compounder is not acting like a positive displacement pump. The one screw conveys the material in the intermeshing area, the crotch, where it is taken over by the second screw and again transported around the barrel into the crotch (see Fig. 13 (right) the yellow area), where processing starts again. The conveyed (displaced) volume per screw revolution is limited to the overlapped region of screw flight and channel (see Fig. 13 (left) the shaded area) [6, 18, 23, 34, 45].

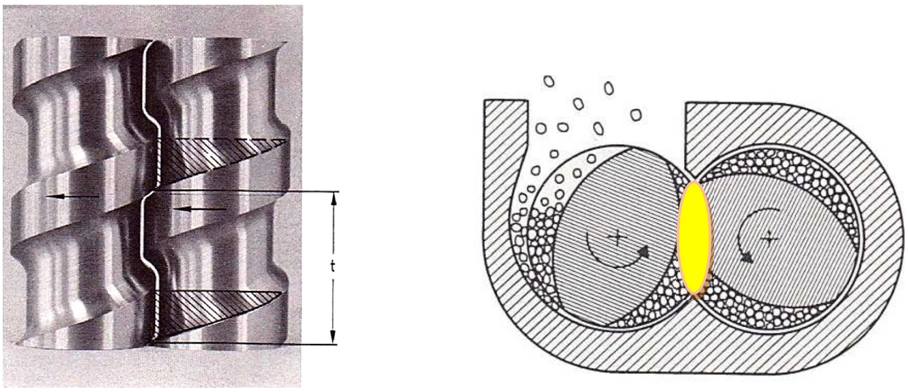


Figure 13: Positive displacement of a part-volume (shaded) during one screw revolution (left), intermeshing area or crotch of co-rotating screws (right) [6].

It is difficult to speak of one conveying pattern or one characteristic within the compounder, because every element has its own characteristics and flow mechanisms. The most important elements are described in the following paragraph.

The construction variety of the co-rotating system is tremendous, due to the construction kit-principle. Every screw in the field is composed differently according to specific needs of the realized process. Generally right-handed and left-handed elements, neutral, conveying and backpumping elements as well as mixing and dispersing elements (kneading elements) are distinguished. In Fig. 14 the pictures A) – C) show conventional conveying screw elements, which have the task to convey the material in the posterior chambers. Elements having their pitch in rotation direction are backpumping (see Fig. 14 b) and pressure consuming, meaning they pump the material back in anterior chambers. Elements with a pitch direction against the rotation direction are conveying elements Fig. 14 a), e), d) and f) and pressure building, like the single- or double-flighted screw element. So right-handed and left-handed elements are operating, depending on the screw's rotation direction, either backpumping or conveying.

Neutral elements, like picture c) in Fig. 14, are neither conveying nor backpumping and cause the material to stagnate, so they have to be overrun to force the material through. Mixing elements (see Fig. 15) mix the material only by distributive processes (splitting and merging the melt) without putting shear stress on the material. Dispersing elements cause shear stress and are therefore applied to melt single solid particles in the melt conveying zone.

Generally speaking, positive working elements (conveying elements) are starved regions, where a certain percentage of the cross-section remains unfilled during the process. This percentage can be varied depending on the output demands on the process. Negative working elements (backpumping) or neutral elements are fully filled regions and are therefore often used to separate or insulate single sections, e.g. the degassing zone. The following figures should help to visualize the differences between the elements [1, 11, 24].

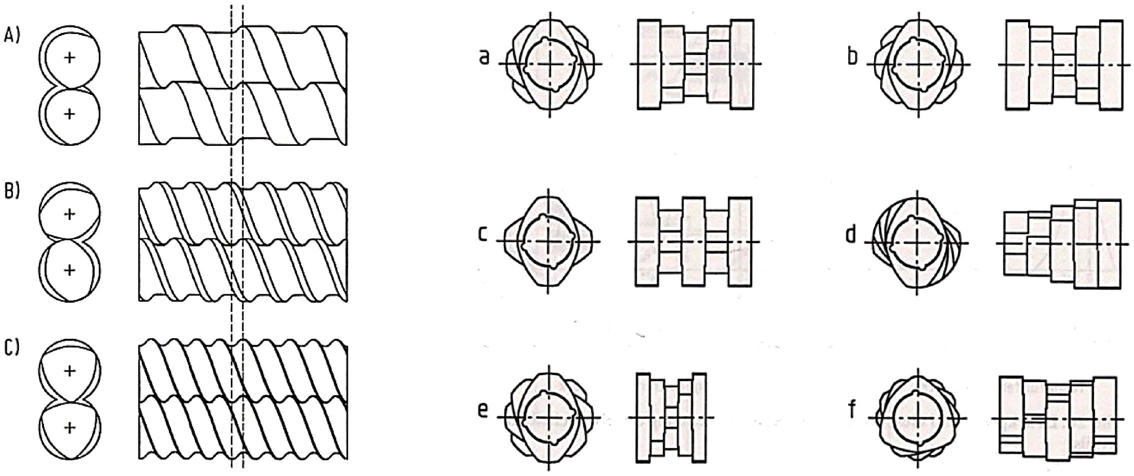


Figure 14: A) B) C) are "normal" conveying elements: A) single flighted, B) double flighted and C) triple fligthed. a) – f) are kneading elements with different characteristics: a) and e) are conveying kneading elements offset angle 45℃, b) backpumping kneading element offset angle 45℃, c) neutral kneading element offset angle 90℃, d) and f) are conveying kneading elements with 22,5℃ and 30℃ offset angle [6, 18].

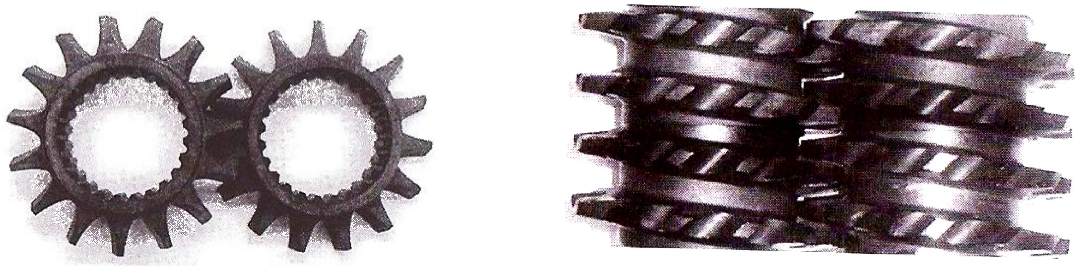


Figure 15: Mixing elements: toothed mixing element (TME) [24].

These elements are used for specific tasks in the compounding process. The working principle and single steps are shown in Fig. 16, where an example of a cross-section of a compounder is simplified.

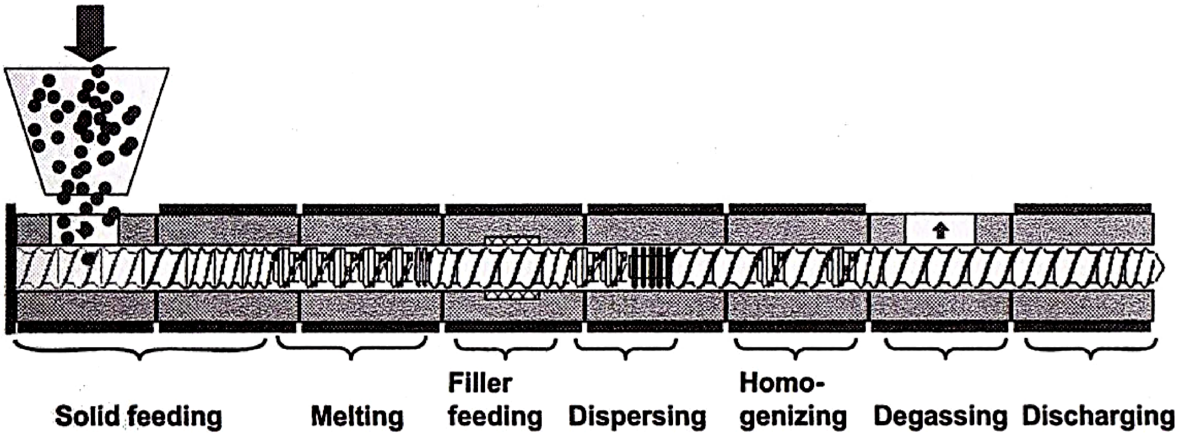


Figure 16: An example of an operating zone of a compounder [24].

The first zone, the solid feeding zone, extends from the hopper to 4 – 6 D and has the task to convey and compress the solids and additionally remove the air drawn in. Because the intake is limited by volume, in most cases, self-wiping screw elements with the maximal number of threads and a low pitch are used to give the largest possible free cross-section and realize a high degree of filling. The following melting zone melts and disperses the solids. Up to 80% of all mechanical energy put in the compounder is consumed in the melting zone, where kneading elements of all shapes are applied. It is the challenge to balance the elements regarding their mixing and conveying capacity by varying the staggering angle, as these two properties behave reciprocal. The next step is the filler feeding section, where fillers like wood fibers are incorporated. This section consists exclusively of forward pumping elements to achieve partial filling, so that fluidization in the solid feeding zone can be guaranteed. Forward pumping elements are e.g., single flight elements or kneading elements with low offset angles. The dispersing zone conveys the melt and disperses the last solid particles, realized through wide kneading discs. The section where the material is homogenized (homogenizing zone) consists of mixing elements, to ensure a homogeneous filler distribution. The degassing zone is insulated by backward feeding kneading elements (fully filled) before and after the degassing opening to guarantee, that only volatile components are sucked off by the vacuum. Between the degassing openings, high angled elements are used and driven partially filled to decompress and give a large surface. In the discharging zone respectively pressure build-up zone, pressure is build up by single elements, due to their good pressure build-up capacity and double-flighted elements, due to the more constant flow. However it is recommended to use a melt pump, because the flow through single- and double flighted elements are likely to pulsate, so the throughput can fluctuate without forced conveyance [1, 24, 45].

Regarding the residence time of a compounder it is to mention, that there are two important factors, the minimum residence time and the distribution. The first stands for the dispersive mixing capacity while the second gives information about the longitudinal mixing behavior. Three parameters primarily influence the average residence time, the screw speed and the pitch in starved sections and the throughput in fully filled regions. Due to the characteristics of the compounder described above, its residence time is higher than those of the single screw or the counter-rotating TSEs (see Fig. 17) [19, 20, 24, 27].

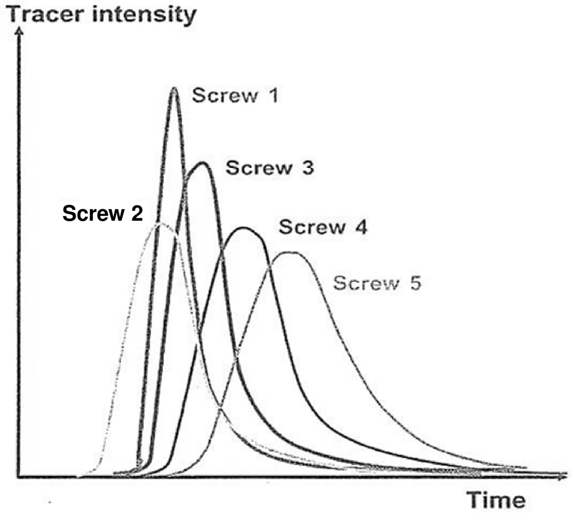


Figure 17: Residence time distribution for different screw geometries; from screw 1 consisting only of right-handed single flighted elements, to screw 5 containing the most kneading and mixing elements [24].

Today the throughput is conventionally programmed by the input and ranges from 10 kg/h to 5000 kg/h and more. As a consequence to the higher possible screw speed of the compounder, the throughputs of this machine lies significantly over those of single screw and counter-rotating TSEs. Common applications for compounder are in the compounding industry and if high outputs are demanded [4, 24].

2.4 Heating-cooling mixer

The heating-cooling mixer (shown in Fig. 18) is the only discontinuous technology discussed within this work.

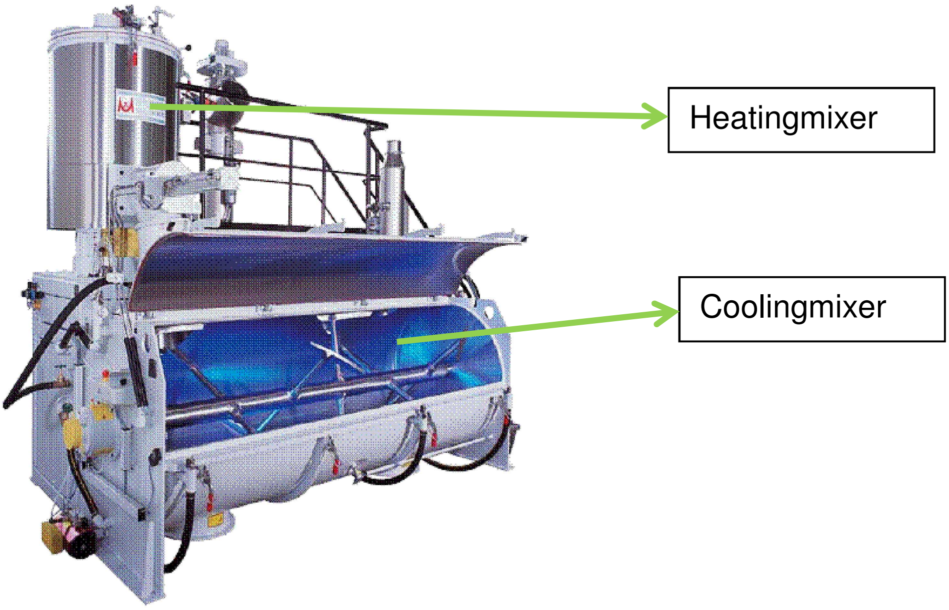


Figure 18: Heating- cooling mixer in a vertical-horizontal order [44].

The material is heated and mixed or agglomerated in the first step and cooled respectively shredded in the second step after the scheme shown in Fig. 19. The temperatures needed depend on the material. It is not desired, that PVC is fully melt, because it would not be further processable by the cooling mixer. Therefore only temperatures around 120-125℃ are applied, so that PVC is mixed and slightly fused with the wood fibers, however the end-product has the form of a powder. When agglomerating PP, the polymer is fully melted so temperatures from 175-180℃ are common.

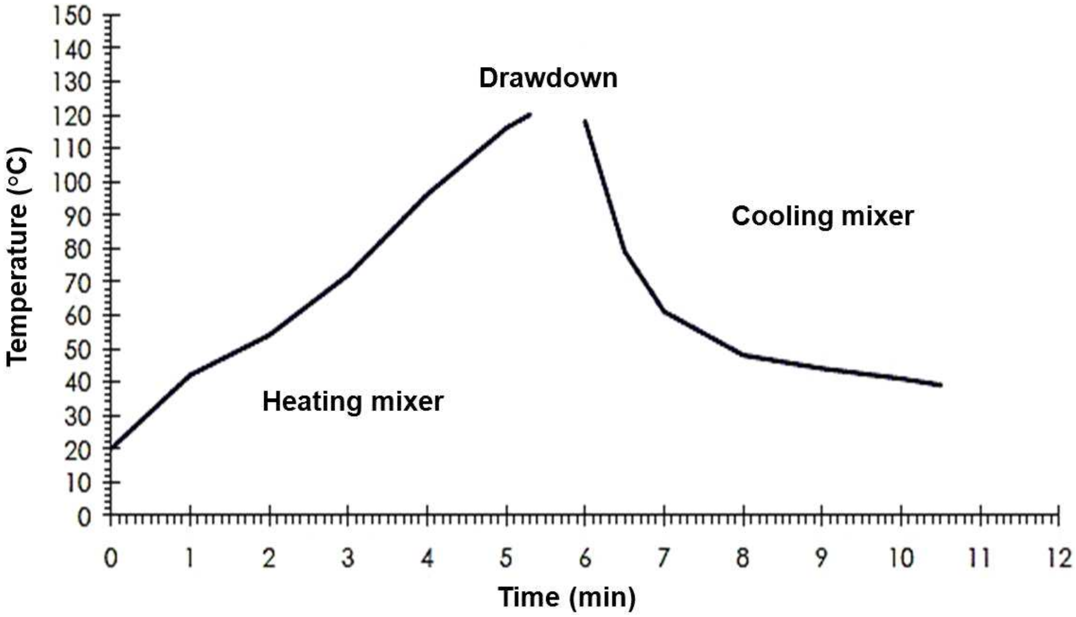


Figure 19: Time-scheme of a heating-cooling mixer process shown on the example of PVC [30].

Actually this machine is more known for its application in the PVC-dryblend production, but nowadays also commonly used for agglomerating WPC. The aim of this process is also to economically distribute and agglomerate modifiers and fillers with polymer components. The mechanism used by the heating-cooling mixer is similar to the extrusion even though the execution is different. It also dissipates the mechanical drive power to generate frictional heat and afterwards uses heat conduction to cool the agglomerated material. As the term heating-cooling mixer predicts, the machine consists of two separated mixers, one for heating and one for cooling, which should be explained in the following paragraphs [14, 41, 44].

The heating mixer is equipped with an insulating jacket to reduce the heat loss through radiation. The common mixer volumes lie between 200 l and 3000 l, the tooling speed varies from 20-50 m/s. Tools used for this application vary in shape, speed and geometry parameters. They are adjusted to the mixer size and individual process demands (common versions are 3-5 single blades). The tools are, similar to an extruder's operating unit, the heart of the device and responsible for the heating characteristics initiated by the contact between product and the tool's projected and in rotation direction "active" area. There are three mechanisms responsible for the heat, the friction between the tool and the product, the friction between the product and the mixer wall and the friction between the material particles themselves. The energy generated by these mechanisms is high enough, so that no additional thermal heating is required. The tool consists of multiple blades (see Fig. 20 right), the so-called base-scraper, which avoids stagnating zones on the bottom of the mixer, the two fluidization blades to develop a material flow and the hook, to create a second material flow and superpose it with the first. This construction can also be executed as a sickle tool (shown in Fig. 20 left), when additional grinding of particles is demanded. To work economically, the heating mixer has to be 100% filled to achieve the recommended load level. If the mixer is not fully filled, the characteristic motion pattern cannot develop, which leads to a long mixing time and a loss of the generally existing self-cleaning effect [4, 14].

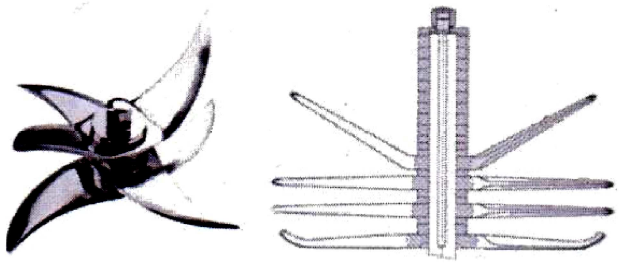


Figure 20: sickle tool (left), multiple blade tool (right) [41].

The cooling mixer is equipped with a double jacket made of mild steel including guide plates for the water flow, to ensure that the water is circulating. The cooling mixer's tooling is similar to the heating mixer, but does operate with low speed in order to minimalize the energy input through friction. The temperature recommendation for the used cooling water is about 15-20℃. When on the one hand hotter water is used, the desired cooling effect is not given and the cycle time gets too long, on the other hand colder water temperatures can cause condensation on the inside of the mixer wall and therefore undesired material deposits. To ensure a long lifetime it is recommended to use a recooling-system of circulating water [14, 46].

To give an overview of the process, the single operating steps are described here. At first, all components are fed into the mixer (polymer, additives, fillers coupling agents etc.) Then the material is heated through friction until the melting point of the polymer is reached (speed ~40 m/s). At this point the polymer covers the filler and builds up a coating. When reaching the nominal current, the speed is reduced to 20 m/s to empty the heating mixer. The material is transported, via a vacuum pump, into the cooling mixer at a temperature of 130-180℃, depending on the polymer. In the cooling mixer the material is cooled to ~40℃ and afterwards released. In a perfect working "quasi-continuous" process, the cooling time is a bit shorter than the heating time, to totally overlap the processes and continuously producing compound. As the cooling time is crucial for the cycle time, therefore the cooling mixers are 3-4 times larger than the heating mixers to provide a maximum of cooling surface [14, 44, 46].

Another decisive parameter for the cycle time is the way the particles are pressed to the wall, the motion pattern. This pattern is defined by the Froud-number, a coefficient opposing the towing powers and the inert forces inside the system.

$$Fr = r * \omega^2 / g \quad (-) \tag{2}$$

If the mixer operates with $Fr \leq 1$, the material is shifted, but does not reach the zenith of the mixer (see Fig. 21).

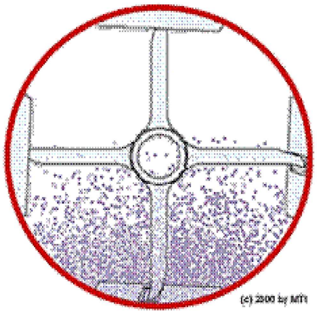


Figure 21: Mixer operating with low Froud number, particles are only shifted. [44]

If the mixer operates with Fr ≥ 1, the material is shifted and partially reaching the zenith, but the motion pattern stays generally undeveloped. The motion is defined by single pitch paths (see Fig. 22).

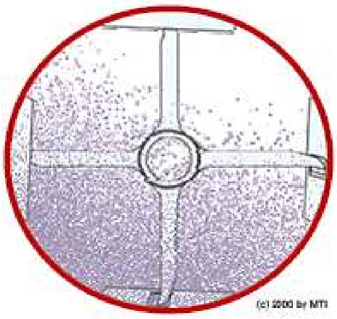


Figure 22: Mixer operating with middle Froud number, particles partially reach the zenith [44].

If the mixer operates at Fr>> 1, the whole material is lifted and a fully developed motion pattern is built up, the so-called *trombe (see Fig. 23 (right))*.

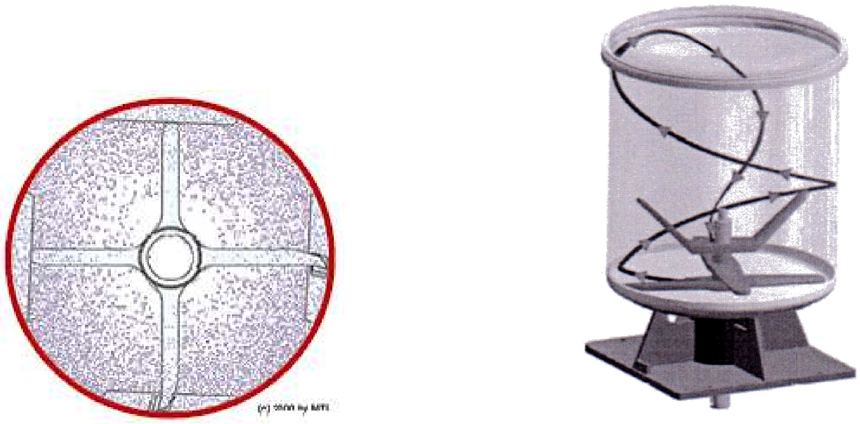


Figure 23: Mixer operating at high Froud number, trombe is fully developed (left), particle path in a fully developed trombe motion (right) [41, 44].

Since vertical mixers are only economic up to a volume of 1500 l, different constructions and combinations are available on the market. Devices of different brand differ in tooling and operating speed. The most important mixer versions are described below [41, 44].

Vertical system operating at middle Fr-number:

A triple bladed mixing tool is rotating near the bottom to avoid stagnating zones. Blade form and speed are coordinated in a manner, that the material is sensitively driven to form a trombe-like circulating pattern. Particles move on a path around horizontal and vertical planes. If necessary, a separately driven knife tool can be applied to support the mixing effect.

Horizontal working system operating at middle Fr-number:

The tools are rotating on a horizontally constraint shaft, the order of shovels varies from brand to brand. Size, number, positioning, geometry and speed of the mixing tool are optimized to achieve a 3-D motion pattern, which partially contacts the wall. Stagnating zones are avoided through the high turbulence and a partial ring-layer movement is developed through centrifugal forces. Predominantly this process is applied for fragile or thermal and/or rheological problematic materials.

Vertical operating system at high Fr-number:

For this application, the mixer has to be large and high enough. The tool shape, its speed and positioning are coordinated to achieve high energy input through strong friction. The blade at the bottom, the shovel-plat-tool, is fully covering the surface and develops a trombe motion. Above the shovel-plate-tool is the pegtop-suction-tool, supporting the mixing effect by forming a second inner trombe, which superposes with the outer trombe and accelerates the material flow. It is a quick, gentle method of heating with the prevention of temperature peaks and is specially applied for fiber-like products like WPC.

Regarding the cooling mixer, the only difference is, that the speed of the tool is much lower, to avoid a heat effect through friction. It is important, that the whole cooling surface is used and the material flow enables all particles to contact the cooling wall [14, 41, 44].

The advantages of heating-cooling mixers are the high filler content achievable with this technology, the low-cost and simple change of material makes the user independent of the supplier. The machine needs little maintenance and the change of tools is quick and simple. On the other hand the agglomerate has a broad particle size distribution and dust content, which causes problems when it comes to gravimetric dosing, where the bulk density fluctuation causes dosing fluctuation and directly affects the further process. The output rate of commonly used heating-cooling mixers is up to 1000 kg/h and more [14, 44, 46].

2.5 Specific energy consumption / energy balance

Since electricity costs constantly increased over the last decades cost- and eco-efficiency gained attention. In plastic processing the energy costs are up to 5% of the total production costs. Therefore energy efficiency inhibits a high potential for cost saving. To visualize the specific energy consumption the total current consumption is related to the processed product per time unit as shown in equation 3 [2].

$$e_{spec} = P_{wirk} / (m/h) \quad \text{(kWh/kg)} \qquad (3)$$

The theoretical energy need of polymers to plasticize is described by its melt enthalpy, measurable with the differential scanning calorimetry (DSC). The plasticizing energy is the minimum energy needed and can therefore be considered as the basis to calculate the degree of effectiveness which is defined by the plasticizing energy divided by process´ total energy consumption. The relatively mediocre degree of effectiveness of industrial applied machines can be explained by the high loss of performance which constitutes by several factors. Energy consumer and loss-performance producer within e.g. an extruder machine are the drive represented by the electronic frequency converter, the electrical machine, the gear box and the bearing, the extruder-control and the operating unit containing electrical heating. The energy input is in general provided by electrical energy which is, over the motor and the gear box transformed into mechanical energy to move the screws. Every transformation of energy causes energy loss. Losses occur at every device, the motor, the gear box, the heating or the loss due to heat radiation and convection over the barrel. To visualize the loss factors a flow chart is used and shown in figure 24. It illustrates all performance losses of the single components [30, 31].

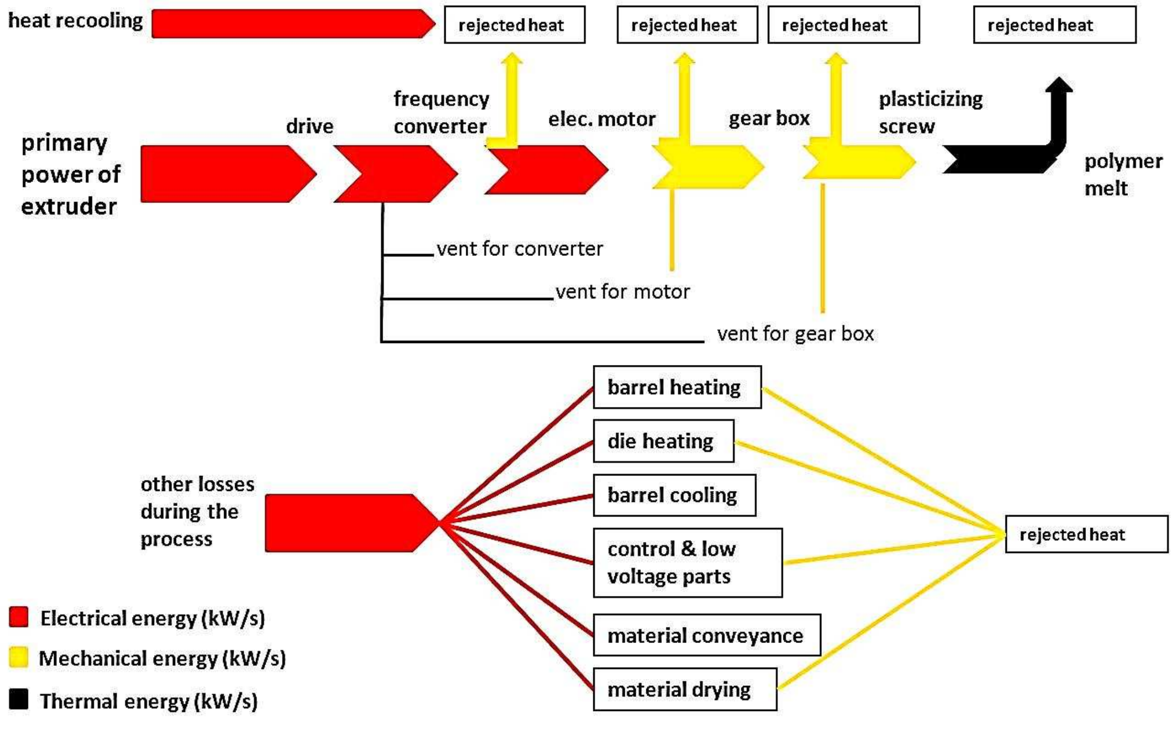


Figure 24: Energy flow of the extrusion process.

In the past DC motors, with an efficiency approximately from 75 %–80 % were applied for extruders due to their good start-up behavior and controllability. The coal brushes used as sliding contacts are consumables hence the maintenance is very high and leads to production loss. Therefore, due to their better degree of efficiency (7-15%), AC motors are applied nowadays. To control the AC an electronic frequency converter must be used to transform the 50 Hz signal. This electronic frequency converter is a high performance electronic device which though leads to losses. At nominal load the converter has a degree of efficiency of about 96 %-98 %. At higher frequency, the degree of efficiency is lower due to the higher switching loss. If the load is much lower than the nominal, the losses are tremendously higher.

The next device, which is marked with losses is the gear box, today 2-3 step helical gear boxes are applied. They generally have a loss of performance of 1-1,5% per ratio step and additional 0,5% for the axial bearings. The resulting degree of efficiency lies between 95-97%. Another point to consider when speaking of performance losses is the idle power which additionally increases the transmission losses due to the higher load. The energy efficiency of the three processes is investigated and compared. The losses are split and the degree of efficiency as well as the specific energy consumption is illustrated in diagrams in chapter 3 [28, 30, 31].

Figure 25 schematically shows the energy balance of an extruder machine. Energy is put into the material through heat (heat conduction from heating bands to the material) and dissipation (drive power). The energy stored in the product is a result of the mass flow multiplied with the temperature difference of the entrant and emergent material, as well as the compression work performed on the material. A loss of energy is due to the heat radiation and convection, the loss of drive, the optional cooling sequences and the vacuum pump.

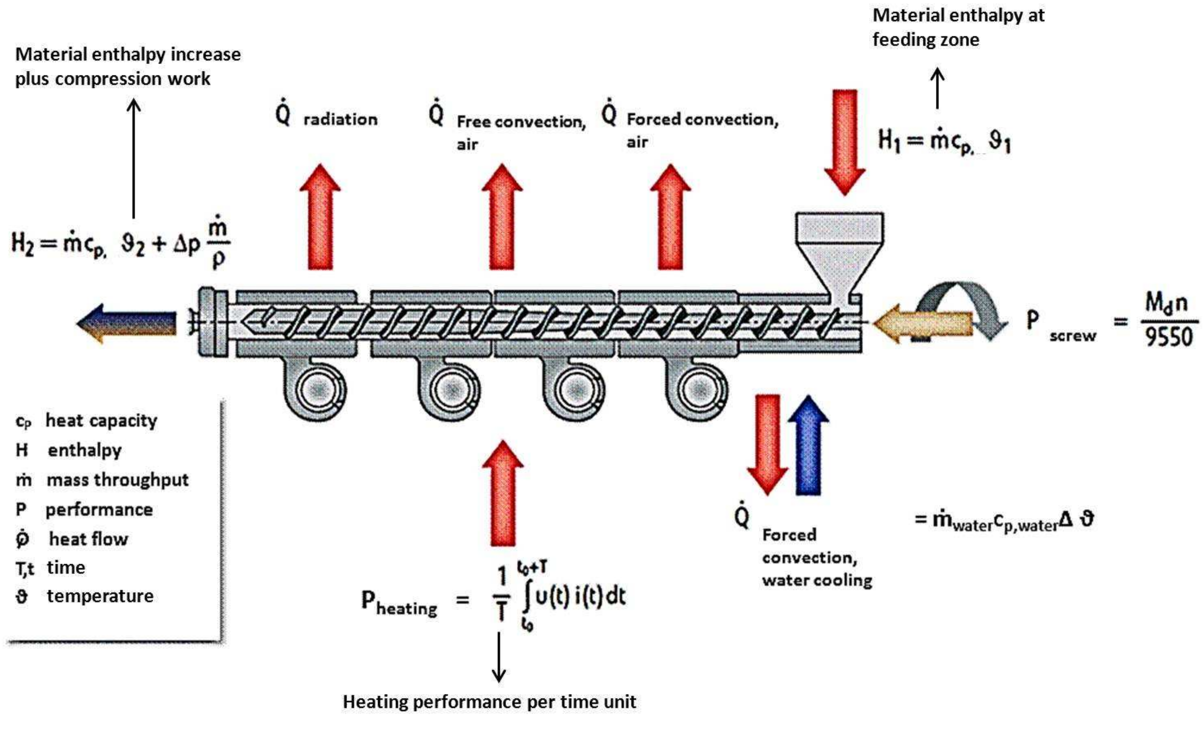


Figure 25: Extruder energy balance [31].

Concerning the heating mixer, the energy is put into the material through heat and friction in the first stage and is removed with the help of the cooling mixer in the second stage. In this case energy gets also lost through radiation and loss of drive [28, 30, 31].

2.6 Qualitative evaluation of the compound

To ensure the comparability of the investigated procedures, quality standards have to be defined. On the basis of these standards the products of every process shall be compared. The two basic and commonly used indicators in the plastic industry are the flowability and the bulk density. Since there is no industrial standard for these measurements concerning WPC materials, a method based on the standard EN ISO 60 („Plastics – Determination of apparent density of material that can be poured from a specific funnel“) is used. Furthermore, additional characterization regarding the moisture content and the homogeneity should be realized and is examined using a mobile Sartorius moisture measurement device, which measures the weight loss after heating. The homogeneity was investigated with a SEM-microscope. The moisture content should not exceed 2%.

3 EXPERIMENTAL

The following chapter will give an overview how the measurements were done, which machines and materials were used, which parameters set and how the data was evaluated and analyzed. The focus will lie on the material and the measurement device for the energy measurements

3.1 Materials

The processed materials are two state-of-the-art formulations often used in the industry and therefore representative. The polymer component is Polypropylene (PP) and PVC (Polyvinylchloride), whereas the wood component stays the same within the formulations. With the exception of the PVC-Dryblend, all materials were provided by Battenfeld-Cincinnati GmbH.

3.1.1 Wood component

In both mixtures the same wood component Lignocel type BK 40-90 purchased by J.Rettenmaier&Söhne GmbH was used. It is a combination of several coniferous soft wood types, defined by the oven-dry density of below 0,55 g/cm^3. The material has a particle size of 300µm – 500µm, the color is yellow and the structure cubic, which is important when looking at the produced WPC pellets in the result part of this work. The bulk density and the moisture content are listed in table 1.

3.1.2 PP

The tested PP component is a homopolymer sold by Borealis under the product name HC 205 TF. When processing PP-based WPC, it is recommended to use coupling agents to ensure ideal bondage and mechanical properties. This coupling agent is a maleic acid carboxylated PP marketed by Kometra AG named Scona TPPP 8112 FA. The processed mixture was 60 wt% wood, 38 wt% PP and 2 wt% coupling agent. The bulk density and the moisture content of the raw materials are shown in table 1.

3.1.3 PVC

Since PVC cannot be highly filled, the used mixture was a 50/50 wt% ratio of PVC and the wood component BK 40-90. The PVC material was provided by the WoodK+ GmbH, an associate of Battenfeld-Cincinnati GmbH. Originally the PVC component was mixed as a dryblend by WoodK+ GmbH for a customer and therefore all further data has to be confidential at this point. For the bulk density and the moisture content see table 1.

Table 1: Values of moisture content and bulk density for the raw materials.

Material	**Bulk density (g/l)**	**Moisture content (%)**
BK 40-90	215 ± 2	7,42 ± 0,4
PVC Dryblend	569 ± 4	-
PP - HC 205 TF	543 ± 5	-
SconaTPPP 8112 FA	585 ± 3	-

3.2 Measurement setup

The measurements were done locally at the companies. Therefore it was important, that the devices were mobile and easy to transport. The installation of all needed devices and the establishment of the network connection had to be considered in the time management, since every company uses its individual control cabinet and wiring system and consequently, the installing situation is new at every machine. It had to be cleared with every company in advance, that the right main supply, the right connection and enough space for the converters was locally available. To proof that the results are meaningful, it was decided, that the minimal measuring time should be 30 minutes or 12 data points. To ensure the imaging of representative industrial processes, the machines were first run-in, guaranteeing a stationary process.

Table 2: Overview of the measurement time table.

	Machine	**Material**	**Outputs (kg/h)**		**Company**
1	Counter-rotating TSE	PP	120	150	**WoodK+ GmbH**
		PVC	120	150	
2	Heating-cooling mixer	PP	639		**Plasmec s.r.l.**
		PVC	410		
3	Compounder	PP	150	300	**Reimelt-Henschel GmbH**

The final result was the comparison of the specific energy consumption (kWh/kg) for two conventionally used recipes processed on the three categories of machines discussed in chapter 2. In the following, an energy balance is drawn, in which all inputs, outputs and losses are shown separately. Due to the fact that the heat radiation, lost on the environment can be neglected, the equation of the energy balance is composed of:

$$\underbrace{\int dP}_{1} \pm \underbrace{\int dH}_{2} = \underbrace{\dot{m}\int c_p \cdot d\vartheta_M}_{3} + \underbrace{\int \dot{V} \cdot dp}_{4} \qquad (4)$$

1…drive power

2…heat performance

3…increase of enthalpy

4…pump performance

The drive power and heating power were detected by measuring the specific energy consumption; the other terms had to be calculated through the temperature and pressure difference between the dosing zone and the screw tip. The pressure difference results of the atmospheric pressure and the pressure on the screw tip, which is shown by the extruder itself, as is the temperature [30, 45].

3.2.1 Ducati measurement device

All energy measurements were done with a so-called Ducati measurement device produced by Ducati energia s.p.A. (see Fig. 26). The particular product description of this device is Smart 96 Piú, an analyzer with measurement accuracy class 0.5.

The device can directly measure the following factors:

- Phase-to-neutral voltage
- Phase currents
- Frequency
- Phase active powers

Based on these factors, the device can calculate the following parameters:

- Three-phase active powers (instantaneous, mean and maximum powers)
- Three-phase reactive power
- Phase and three-phase system power factors
- Phase and three-phase equivalent active and reactive energy

- Voltage and current ThdF's (Transforming Harmonic Derating Factor) (calculated on phase L1)
- Voltage between phases

The Smart 96 Piú has a default attachment of a three-phase system, but can also be used for measurements on single-phase systems. The device and the equipment (wires etc.) was provided by Battenfeld-Cincinnati GmbH, in form of a measuring kit, containing ten Ducati devices (see Fig.26) of which every single one can independently measure a consumer load.

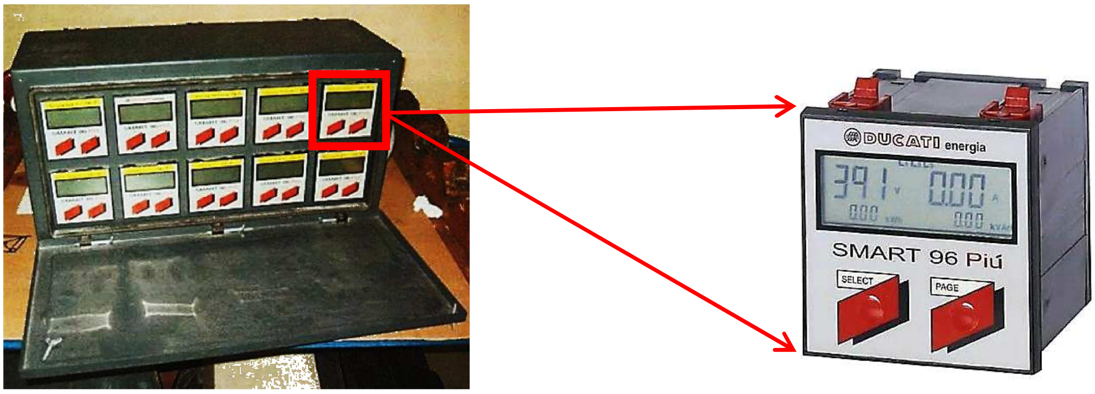


Figure 26: Measuring kit (left), single Ducati SMART 96 Piú (right) [10].

The current supply of the measuring kit was made by a 32A euro-connector, which has to be fed by the same main supply as the measured consumer load. The device is installed between the supply and the consumer load and takes two measuring points per second. These measurements were averaged over two and a half minutes and send over the LAN-connection to the Laptop, where it is saved by the WarpNet Software.

3.2.2 Choice and installation of converters

The Ducati device needs converters to transform the current in an area measurable for the voltmeter and the ampere meter. They are therefore an inherent part for the measurement. The right choice of the converter size is fundamental for accurate and reasonable results. The converter size (given in transduce ratios e.g. 200/5A or 500/5A) should not excess the nominal current of the load and should not be highly oversized. E.g. if a load has a current absorption of 550A, a 1000/5A converter has to be used, but if the machine is run-in and heating devices are switched down, a 500/5A converter should suffice, so the nominal current of the load is approximately the same as the converter size. For this work two converter constructions were used, the flap- and the ring converter (see Fig. 27).

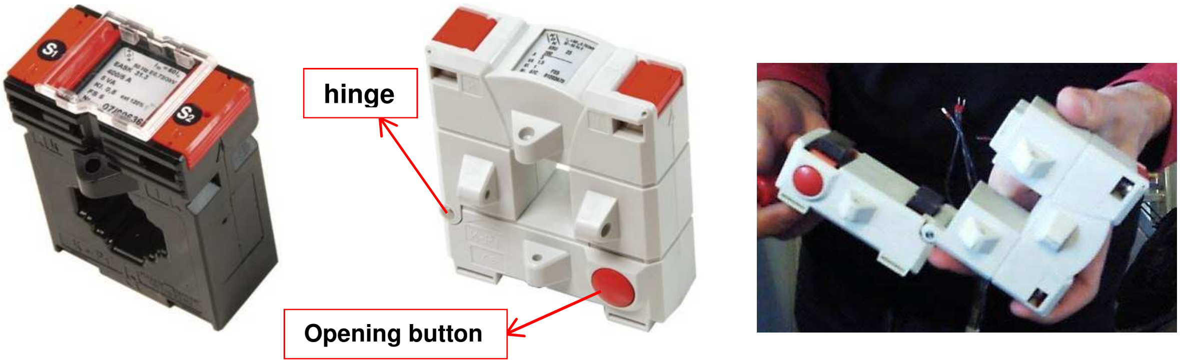


Figure 27: Ring converter (left), flap converter (middle), flap converter opened (right).

The flap converters size from 200A to 1000A, while the ring converter was applied for loads up to 50A.

After choosing the right size the right converter installation had to be carried out. The installation was the same for every converter construction and was eased by the imprinted terms at the bottom of a converter, which is k-P1 (for the current supply side) and L-P2 (for the load side). So the current flow went from the main supply to the measured load and had to be maintained separately for every converter. Apart from the nominal current, the two converter constructions differed in the way they had to be installed. While the flap converter could be opened on one end and easily be installed by flapping over the phase-cable, the ring converter could not be opened. When using the ring converter construction, the phase-cable has to be disconnected, dragged through the converter and then reconnected. The converters have to be wired by three-phase cables (see Fig. 28).

If a three-phase system is used, three converters are required for one Ducati device. Regarding a single phase system only one converter is necessary.

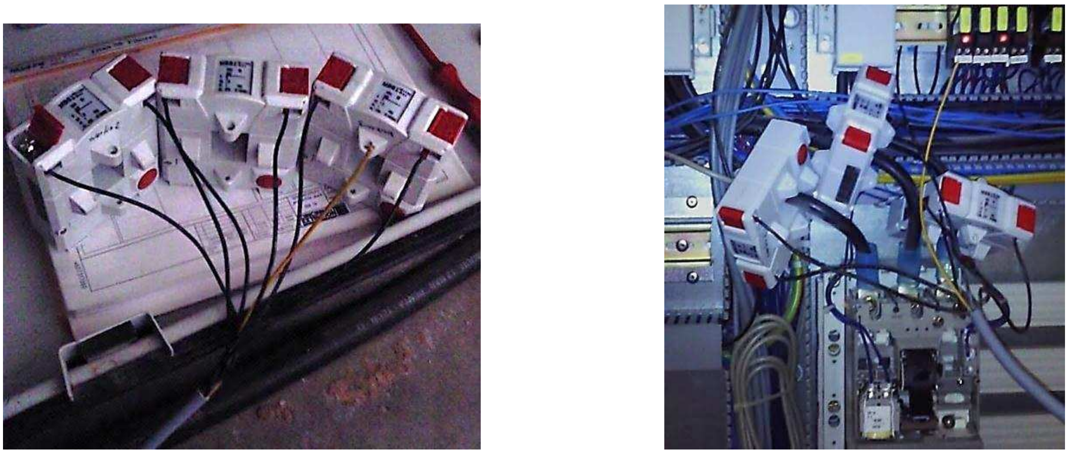


Figure 28: Wired converters – 3-phase cable (left), installed converters flapped over the main supply.

3.2.3 WarpNet

The data communication between measuring kit and notebook was realized by a network (LAN-) connection and the software WarpNet (Version 2.6.70) from Neptune India Limited. The software gathers and saves the data sent by the Ducati device. Once the measuring kit is connected to the software, all parameters and settings can be programmed over the laptop. The software communicates separately with every single Ducati device, therefore it is possible to name the different devices after the consumer loads they measure. The selection of the factors to be measured is also done with the Software and can be chosen individually for every device. To ensure reasonable results, it is crucial to set the right converter ratios, e.g. if a converter 500/5A is used, the ratio would be 100.

3.3 Quality measurements

To ensure the comparability of the energy measurements, quality properties of the end product have to be considered. Since WPC is a very young group of material, there are no compulsory standards how to test the compound. The standards defined in this work are the bulk density, the flowability, the moisture content and the compound homogeneity. Depending on the further processing procedure and the associated requirements on the compound, quality demands highly vary between the customers.

3.3.1 Bulk density and flowability measurement

There is no exact standard for WPC regarding the bulk density measurements. Therefore the tests are performed according to EN ISO 60 for conventional polymers. The polymer (500 ml) is poured in the funnel, then the damper is opened and the polymer flows in the breaker. The breaker is weighed before filling with polymer to tare the weighing machine after the breaker. Then the filled breaker is weighed and the result is multiplied with the factor 2, so that the end result is the density in g/l.

The measurement of the flowability of WPC compounds demands a modification of the industrial standards and is performed in this work on the funnel construction of EN ISO 60 (see Fig. 29), which is normally defined for PVC dryblends. The material meets the definition of free flowing if it is running continuously and without interruption through the standardized funnel without any external force (e.g. additional cramming of material or shaking of the funnel). These tests were done locally, at the companies, where the machine was tested. The evaluation in the result part of this work works with signs from “++” to “--“ standing for the degree of flowability. The sign “++” defines a compound, which flows without any help through the funnel, just after the gap is opened. The single “+” stands for a compound, which flows through the funnel after an impuls e.g., pushing or bumping the funnel for one time. Here no residues are left in the funnel, various a compound signed with “-“ leaves residues behind and does not flow continuously through the funnel, without multiple pushing. The sign “--“ stands for a compound, which flows not at all through the funnel and constrains itself from slipping through the gap.

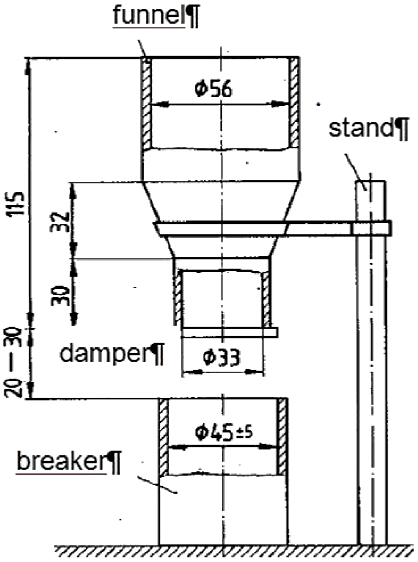


Figure 29: Funnel construction acc. to EN ISO 60 [12].

For every material, output rate and machine, three measurements were done and the results were averaged. If the single results differed more than 10 g/l for the bulk density, 5 measurements were averaged in order to achieve a more precise result.

3.3.2 Measurement of moisture content

The wood component has a moisture content of about 7-8 % r.h., which complicates the compounding process. The aim is to remove as much moisture as possible over the degassing section. Therefore the moisture content of a compound is an important indicator of how good the compounding process is handled. This measurement is also done in-field, after producing the compound. A portable Sartorius moisture analyzer of the type MA 30 (see Fig. 30) was applied for these measurements. The moisture content is measured with the principle of weight loss after heating the sample due to the water content that evaporates as steam. The raw materials and the compounds are put on the weighing machine, the weight is measured and after closing the flap gate, the sample room is heated until there is no more weight loss detectable.

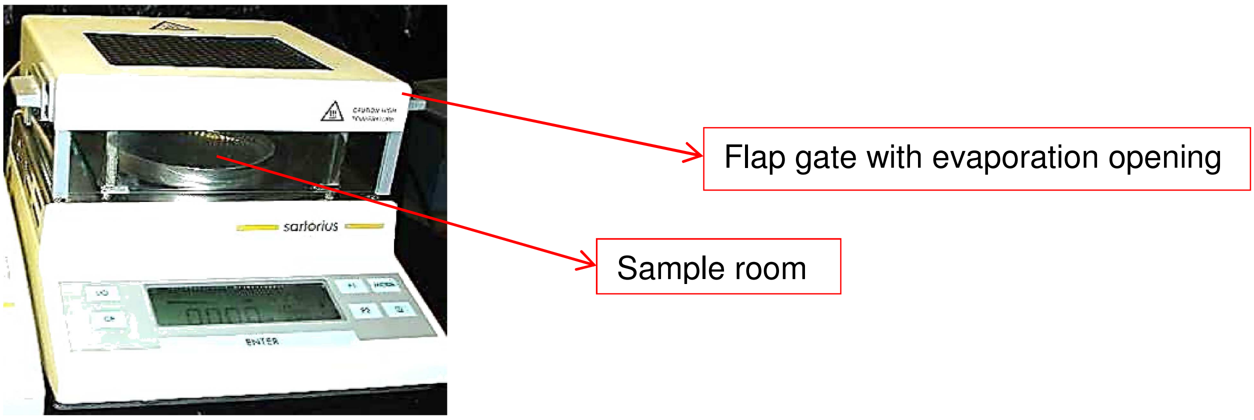


Figure 30: The applied Sartorius moisture analyzer MA 30.

To ensure the reproducibility of the results, it is recommended to take approximately the same weight for every measurement. In this work the initial weight was 2 g ± 0,3 g. For every compound produced, three samples were measured and their results were averaged. If significant differences between the single measurements were detected, 5 samples were measured, to achieve a more representative result.

3.3.3 Compound / agglomerate homogeneity

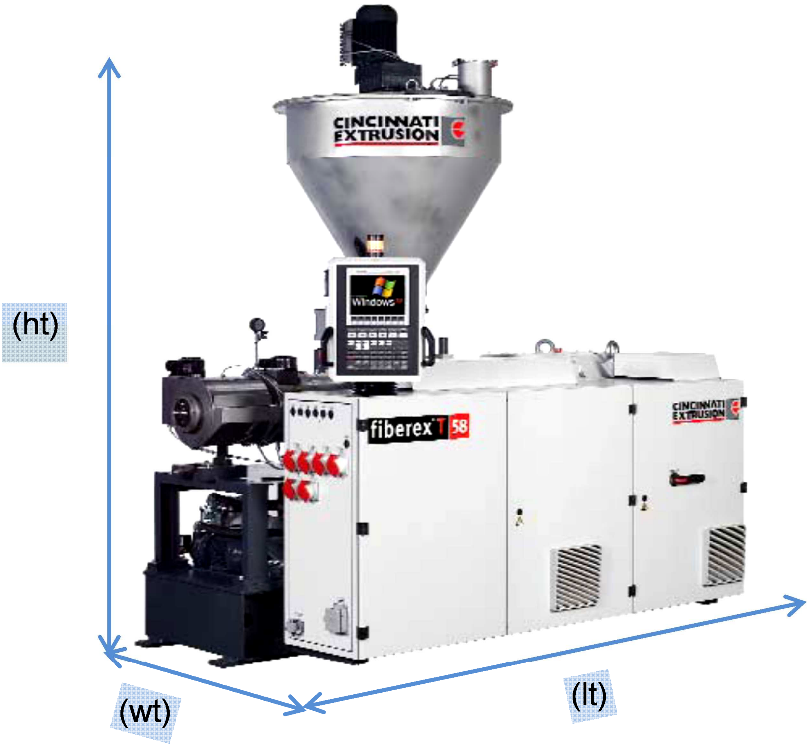
In this work the homogeneity of the compounds were tested with a Scanning Electron Microscope of the type Hitachi S-4000 SEM, provided by Lenzing AG. Three samples for every material and every output rate of the three machines were prepared and sputtered with gold particles. These samples were examined with 30-, 50- and 100-fold magnification. To achieve a representative cross-section, the agglomerates of the heating-cooling mixer were used un-manipulated, while the compounds of the extruders were cracked in the middle with the help of a razor blade. It was important that the razor blade did not cut through the whole compound, because that would have smeared over the cross-section, consequently the razor blade was used to cut approximately 0,5mm in the compound and then it was twisted, until the compound fell apart and a representative cross-section was visible.

3.3.4 DSC-measurements

For the calculation of the energy saved in the material during the process, DSC curves were taken of both, the PP- and the PVC mixture (see appendix). The used device was a DSC1 of Mettler Toledo GmbH, which was operating with a heating- and cooling rate of 10 K/min. The temperature range was chosen to be 25°C (room temperature) to 200°C. The integral was taken from the minimum (25°C) to the maximum temperature for all processes (see appendix). When neglecting the water cooling of the underwater granulation and the internal screw cooling, one can say that the extrusion processes only use energy to heat or melt the material, not to cool it (passive cooling). As a consequence, only the heating curve is needed to characterize the enthalpy increase due to the extrusion process. Regarding the heating-cooling mixer, the heating and the cooling curve is necessary to calculate the enthalpy difference achieved by the process, because in this case the cooling part is connected with energy input (active cooling).

3.4 Measurements on the counter-rotating TSE

At WoodK+ tests were done on a conical counter-rotating TSE type fiberex T58 from Battenfeld-Cincinnati GmbH (see Fig. 31).



Height (ht): 2352 mm

Length (lt): 2735 mm

Width (wt): 1361 mm

Figure 31: Fiberex T58 with forced feeding unit [7].

The diameter at the back of the screw is 125 mm and decreases constantly over the length to the front diameter of 58 mm. This machine is specially built for fiber extrusion using forced feeding for low bulk densities and materials with low flowability. Regarding compounding, the focus lies on material mixtures with more than 50 % wood. The maximum output range for this extruder type, depending on material mixture and process, ranges from 50 kg/h to 200 kg/h. The drive contains a motor with 39 kW nominal performance and a speed of 2000 min^{-1} resulting in a maximum screw speed of 120 rpm. The maximum melt pressure is 450 bar. It has four heating/cooling zones and an additional adapter zone with a maximum heating power of 135 kW including adapter heating and maximum die heating. The vacuum pump's performance is limited to 1,10 kW. The machine is combined with a hot-cut and an air cooling system. The screw geometry is especially developed for fiber-filled materials and has the company internal name T750.3N9K/19 (see Fig. 32) with the last three kneading grooves linear decreasing from full depth to zero. The applied screw comes with an internal oil cooling unit.

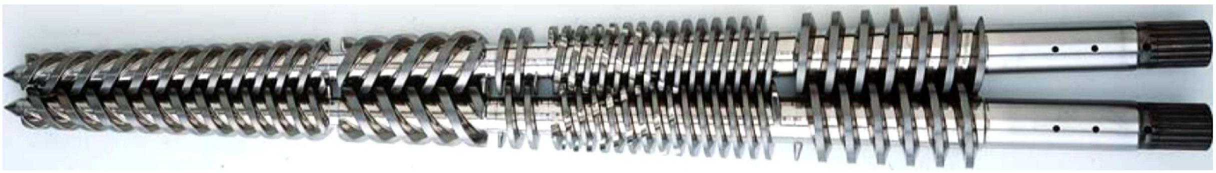


Figure 32: Special operating unit used for the measurements at WoodK+ in Wels.

The machine was first run-in for half an hour before the measurements started, to ensure that the temperature profile and stationary conditions were fully established, the moment the data collection started. The process was very stable and reproducible, therefore the measurement was stopped after half an hour and extrapolated to one hour. The process setting and control are listed in the test protocol shown in Table 3.

The trial was performed without complications and the measuring conditions stayed stable throughout the whole trial. There were no side feeders, all the material components were fed over the hopper, whereat the wood component was dosed over a gravimetric dosing unit and all other components like polymer and coupling agent or dryblend were fed by a volumetric dosing unit. Inside the hopper there was a crammer unit, which supports the constant feeding. Since the machine is built for about 175 – 200 kg/h output, one of the two measured outputs was determined to be in an industrial relevant size, the other was measured for comparison. Ten minutes after the output rate was raised from 120 kg/h to 150 kg/h, the energy measurements for the new setting were started.

The most important values of the test protocol of the trial with the counter-rotating TSE are shown in Table 3, for further and more detailed information, the total test protocol is shown in the appendix, where all process parameters are recorded.

Table 3: Test protocol of the trials done on the counter-rotating TSE.

		PP – wood		PVC – wood	
		120 kg/h	150 kg/h	120 kg/h	150 kg/h
Melt pressure	(bar)	150-180	165-185	223-232	227-235
Melt temperature	(℃)	180,4	180,3	187,4	189,9

After the measurements, all recorded measuring points were exported to Excel and the terms of the energy balance were calculated. For the calculation of the enthalpy term (see chapter 4.1.2) in the energy balance only the DSC-heating curves of both materials were used (see appendix), since the energy used in the screw cooling was neglected. The compression work was evaluated over the pressure difference between the feeding zone and the screw tip and is shown in chapter 4.1.5.

3.5 Measurements on the compounder system

At Reimelt-Henschel tests were done on a co-rotating TSE, a compounder. The specialty and uniqueness of this machine is that within this concept the melt pump, which is often needed for the co-rotating machine concept to overcome the die pressure, is replaced by a single screw extruder respectively a melt extruder (see Fig. 33). Since a melt pump is a wear part and highly stressed when processing fiber-filled materials, the single screw is a long-term solution.

The tested compounder was a test machine with the company name R.H.C 55 with 48D in length and has a total drive power of 132 kW. The heating power lies at 144 kW and the two side feeders, for feeding the wood flour have a power of 1,1 kW each. The flanged single-screw is driven separately with a drive power of 45 kW and a heating power of 19,2 kW. Contrary to the counter-rotating Fiberex T58, this process uses an under-water-granulation system (EP 200) combined with a drying system (EVS 1500) both delivered by Econ GmbH (see Fig. 34).

The first trial failed due to problems with the venting unit, the screw configuration and the instabilities of the process. After adapting the machine, the second trial was successfully conducted for the PP-wood material.

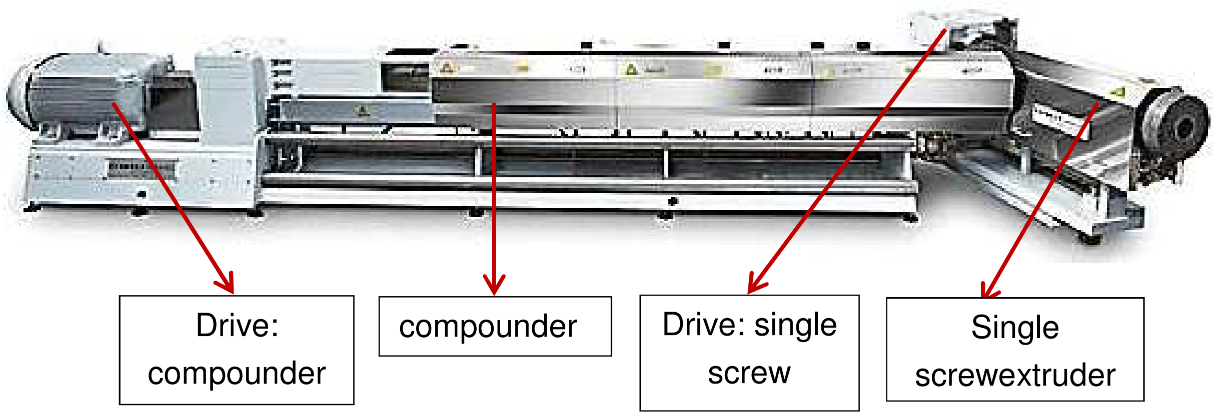


Figure 33: The machine concept for the compounding system with the flange connected single screw extruder [33].

Figure 34: EVS 1500 – drying unit (left) and Econ EUP 200 – under-water-granulation unit (right) [33].

Two trials with different output rates (150 kg/h / 300 kg/h) were done with the formulation of 60 wt% wood fibers, 38 wt% PP and 2 wt% coupling agent. Since the machine is built for about 400 kg/h output, one of the two measured outputs was determined to be in an industrial relevant size, the other was measured for comparison. For both trials the process control and parameters were unchanged to guarantee the comparability of the measurements. Due to a lack of material it was decided that the energy measurements were run for 20 min. instead of the planned 30 min. to ensure the performance of the two trials, which compromises the results due to the few measure point available.

Regarding the process control, 55 % of the wood particles and the PP were fed into the main feeding zone of the compounder. The first side feeder was used for dosing the coupling agent, while the second side feeder was used for dosing the remaining 5% of wood particles. Degassing performance was realized via two degassing side feeders, the first immediately after the compounder's main feeding zone and the second just after side feeder, where the additional wood particles were fed in. The tool plate was heated at 250 °C and the underwater granulating unit was fed with 20 °C tempered water, which had 40-45 °C at the emersion point.

The measurements were not taken under constant process parameters and therefore are compromised due to difficulties at the venting unit. The most important process parameters for this trial are shown below in Table 4. Detailed information about the temperature settings and other process parameters are shown in the appendix, where the test protocols are attached.

Ten minutes after the output rate was raised to 300 kg/h, the energy measurements for this setting were started. The trend preview of the extruder showed slight fluctuations in the drive load, but basically the process control was stable during the 20 min recorded.

Table 4: Melt pressure and melt temperature of the compounder trial.

			Output (kg)	**Material: PP - wood**
Melt pressure	(bar)	Compounder	150	2
			300	4
		Single srew	150	67
			300	155
Melt temperature	(°C)	Compounder	150	147
			300	59
		Single screw	150	200
			300	201

3.6 Measurements on the heating-cooling mixer

Measurements were carried out on a conventional heating-cooling mixer for mixing PVC and wood and for the PP measurements a cooling bed was used instead of the cooling mixer. The latter is especially made for the agglomeration of WPC, based on polyolefins. These two configurations will be treated as one machine concept and be referred to as the heating-cooling mixer. This simplification is made to maintain the comparability of the three different machine concepts counter-rotating, compounder and heating-cooling mixer.

The tested heating-cooling mixer for processing PVC (see Fig. 35) is named type COMBIMIX-HC 400/1000/FV with a heating mixer of the type TRM-400/FV and is a fabricate of Plasmec s.r.l.

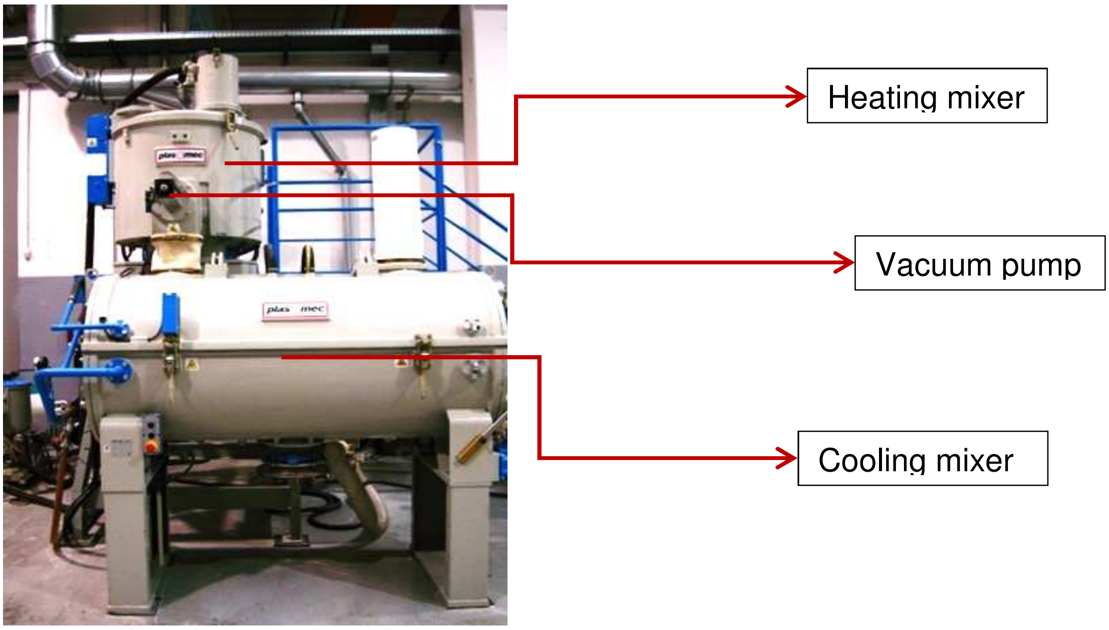


Figure 35: Heating-cooling mixer for processing PVC [31].

The heating mixer's volume is 400 liters, whereof 340 liters are the useful capacity. The drive has a power of 90 kW and is driven with alternating current. This heating vessel uses a 4 stage mixing tool. The cooling mixer is a the type HEC-1000 and is a horizontal operating mixer. It has a volume of 1000 l, whereof 680 l are useful capacity. The water put in the cooling mixers jacket has a maximum temperature of 12 °C, a minimal flow rate of 7,5 m^3/h and a maximum pressure of 0,5 bar. The drive power of this mixer type lies at 7,5 kW. The vacuum pump for the material transfer from the heating to the cooling mixer has a power of 5,5 kW. First the mixer was run-in to guarantee stationary conditions. The material components were fed by hand into the mixer. Since no automatic dosing and weighing could be applied, the weight of the single components had to be calculated through the volume before the material blend could be fed to the machine. For this purpose, the bulk density in combination with the fillable volume (75%-80% of the mixer volume) was used. To achieve a filling degree of 75%, 82 kg (41 kg wood fibers and 41 kg PVC) material was fed at every cycle.

The general test setup was:

1. After feeding the heating mixer the drive is activated with full speed
2. 850 rpm (40 m/s) held for 415 s until 120 °C were reached

3. Decrease of speed to 380 rpm (18 m/s) to hold the 120 °C and apply the vacuum
4. Reduction of speed so that the material transfer via vacuum pump into the cooling mixer can be completed
5. Cooling mixer is run with a fix number of revolutions per minute (rpm)
6. After the material is cooled to 35-40 °C (~ after 2 minutes) it is discharged to big bags
7. The circulating water is warmed to 16 °C

The mixing times lied between 12 and 16 minutes, for the estimation of the output per hour, the shortest trial was taken, because in industrial optimized processes, the working steps are very good synchronized and the heating and cooling process work simultaneously as a quasi-continuous process. Consequently the 12 minute-process is a realistic representation of an industrial process.

The heating mixer with the attached cooling bed (see Fig.36) for agglomerating WPC based on PP has the company internal name type TRM-600/FV/WPC and has a total capacity of 600 l, whereof 510 l are usable capacity. The drive power of the mixer is 200 kW and the maximum mixing speed lies at 50 m/s. This machine uses a 4-stage mixing tool coated with ceramic. The cooling bed was equipped with four cooling ventilators or blowers with each 1,5 kW placed underneath the grid (perforated stainless steel surface).The material is directly forced out of the heating mixer over a vacuum pump, which has a power of 5,5 kW, onto the cooling bed, which has an adjustable pitch, to realize the further transportation of the material. During the cooling phase, the cooling bed was vibrating as one piece, to avoid agglomeration and enhance the transport of the PP fractions. At the end of the cooling bed a granulator or roll breaker with 7,5 kW nominal power was attached to reduce the agglomerate particle size.

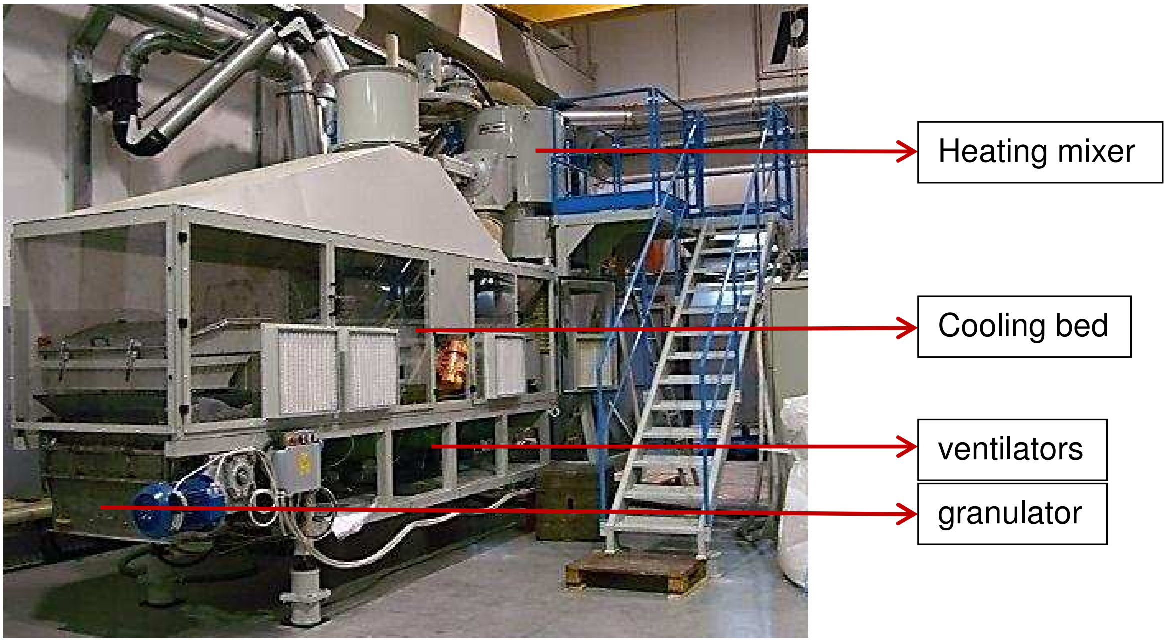


Figure 36: Heating mixer with attached cooling bed for the agglomeration of WPC based on PP.

The material components were, similar to the PVC-process, fed by hand. The cycle times varied slightly around 20 minutes, which were used as the basis for the calculation of the output per hour. Since the material was fed by hand, the weight of every component had to be calculated through the volume. For this purpose, the bulk density in combination with the fillable volume (75%-80% of the mixer volume) was used and 127,6 kg material were fed at every cycle. At this machine no continuous process could be established, because the agglomeration of the PP fractions could not be prevented and the applied granulator was too weak to break the PP hunks.

The settings for these tests were adjusted concerning the polymer's semi crystalline character and as a consequence the mixture had to be heated up to 175 °C – 185°C, to ensure full plastification of the polymer and a homogenous mixture with the wood fibers.

General test setup:

1. After feeding the heating mixer the drive is activated with full speed
2. 1500 rpm (40 m/s) held until 120 °C were reached
3. Current input increases from 70 A to 120 A
4. When 120 A are reached, the speed is reduced to 20 m/s until the current input decreases back to 70 A and the temperature stays at 165 °C
5. The current input and the temperature increase again

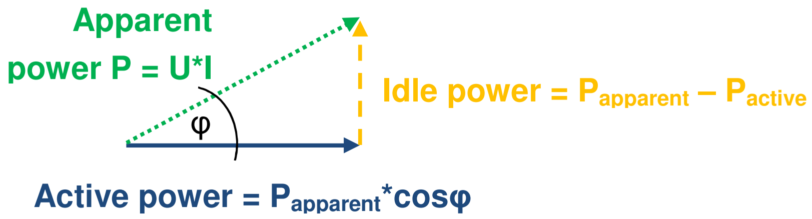
6. The material is discharged when reaching 170 °C at a current consumption of 110 A.
7. The material is transported over the cooling bed to the roll breaker, where it is hackled

After the tests, all measuring points of the recorded time were exported from WarpNet to Excel and the single measurements were extracted and evaluated. The average values of all five measurements were calculated and taken as the basis for the comparison with the other processes. For the calculation of the energy balance the c_P-value of both materials were taken from the DSC-heating curves for the melting/heating part and for the cooling part the DSC cooling curves were used as a basis (see appendix and chapter 4.1.2).

3.7 Data evaluation

For the data evaluation all measured values were transferred from WarpNet to Excel, where all calculations were done. The extracted data contains energy consumption of every component given in kW as well as cos φ, the degree of efficiency. The degree of efficiency gives information about how much of the energy put in the system is actually consumed and how much gets lost.

The total energy can be illustrated by a right-angled triangle:



Due to the fact, that the idle power is in general compensated by industrial firms and fed back into the power supply system, it has not to be paid as it is not consumed. Thereof only the active power is considered in this thesis and taken as a basis for all calculations. To illustrate the relations, the idle power and its percentage of the apparent power is calculated and shown in separate diagrams (see chapter 4.1.6).

Regarding the energy balance, the first two values (see Fig. 37), the drive power and the heating power, can be directly achieved from the measurements by multiplying the total power (apparent power) with the cos φ.

For the first term on the right side, the enthalpy difference of the material due to the process (highlighted red in Fig. 37), the mass flow, the thermal capacity and the temperature difference are needed for the calculation. The mass flow in extrusion processes is easy to calculate, because it is directly set by the extruder control and can therefore be read off the test protocol. The mass flow of the heating-cooling mixer was defined as the output per hour (kg/cycle * cycle/h = kg/h), taking the best cycle time as a basis to achieve industrial realistic values. The thermal capacity is directly detected by the DSC measurement device. If the curves are plotted over the test temperatures, the integral can be taken as the missing factor c_P $*d\vartheta_M$. It is important, that the integration limits are identical with the temperature difference of each process, going from room temperature to the maximal process temperature (see Table 10).

The fourth and last term is the compression work, performed by the process. This term is only relevant for extrusion processes, because here the material is, in contrast to the heating-cooling mixer, compressed on its way to the screw tip. The volume flow is calculated by dividing the mass flow through the density, measured on a Mettler Toledo device, working after the archimedic principal using the upwelling of solids in water. The pressure difference dp can be read directly from the extruder control, shown as the melt pressure. The difference between the left and the right side of the equation is the power loss, which is shown separately in a diagram as the fraction of the total energy input.

$$\underbrace{\int dP}_{1} \pm \underbrace{\int dH}_{2} = \underbrace{\dot{m}\int c_p \cdot d\vartheta_M}_{3} + \underbrace{\int \dot{V} \cdot dp}_{4} \quad + P_{loss} \tag{5}$$

The key result of the trials done within this work, the specific energy consumption, was calculated on basis of the total active power consumed per hour divided by the material processed per hour. The higher output was taken for each material, because the values are more representable for real industrial processes.

$$\text{spec. Energy consumption} = \frac{\frac{\sum kW}{h}}{\frac{kg}{h}} = \frac{\sum kW}{kg} \tag{6}$$

Within this work the degree of efficiency is defined as the melt enthalpy compared to the total energy input. The idea for this definition is the comparison of the minimal energy input required for melting the material and the total process energy consumed by the process itself. This factor is an indicator for how much of the total energy is put in the material and how energy consuming the rest of the process is.

$$\text{degree of efficiency} = \frac{mc_P\Delta T}{\sum kWh} \tag{7}$$

Further the total energy input is broken down to the single consumer loads, to compare the two output rates regarding the extrusion processes and the two machine concepts regarding the heating-cooling mixer. To visualize the percentage of the idle power and the active power the two values are overlaid in a diagram.

4 RESULTS AND DISCUSSION

The chapter below gives detailed information about the results from the measurements described above. The results are divided into two parts, the economic consideration and the qualitative comparison of the produced compounds.

4.1 Energy consumption of the tested machines

The following points show the energetic comparison of the tested machine concepts. The focus lies on the specific energy consumption of the different processes and the degree of efficiency. Further considerations are the energy consumption of the single consumer loads and the percentage of lost energy in the process.

4.1.1 Specific energy consumption

The key result of this thesis is the specific energy consumption for every material – machine combination. These measurements show the energy consumptions of every machine, regardless their purchase price or service costs. As you can see in figure 39 and table 5, there are significant differences not only between the tested machine concepts, but also between the two materials.

The counter-rotating TSE shows very consistent results for both materials whereat processing PP leads to slightly higher energy consumption. This process is, compared to the others, in the lower area of energy consumption, predominantly regarding PP. The specific energy of the PVC process lies a little above those of the heating-cooling mixer, but within the same range.

Due to the fact that the compounder did not work with PVC the PP process is compared and discussed here. You can see that the specific energy consumption lies significantly above the values of the counter-rotating TSE and below those of the heating-cooling mixer process. This machine, as discussed in chapter 3.6 was a test machine, never meant for sale. The process was poorly controlled and automated, which lead to the failure of the PVC measurements. The values for PP seem comprehensible regarding the extensive and complex process and the problems during the measurements.

The heating-cooling mixer shows enormous differences between the two materials whereat it should be noted, that different machine concepts were applied for the materials. The agglomeration of PP leads to a much higher specific energy consumption than the mixing of PVC. This could result of the fact that the heating mixer for agglomerating PP was a lot bigger than the one for PVC and thereof needs much more power. On the other hand, the semi-crystalline nature of PP leads to a different heat capacity curve (DSC-curve, see appendix) and needs more energy because it must be melted, whereas PVC is amorphous and not completely melted, but only surface-fused within this process. Compared to the other processes, the agglomeration of PP leads to the highest specific energies within all results, while the PVC process shows the lowest energy consumption.

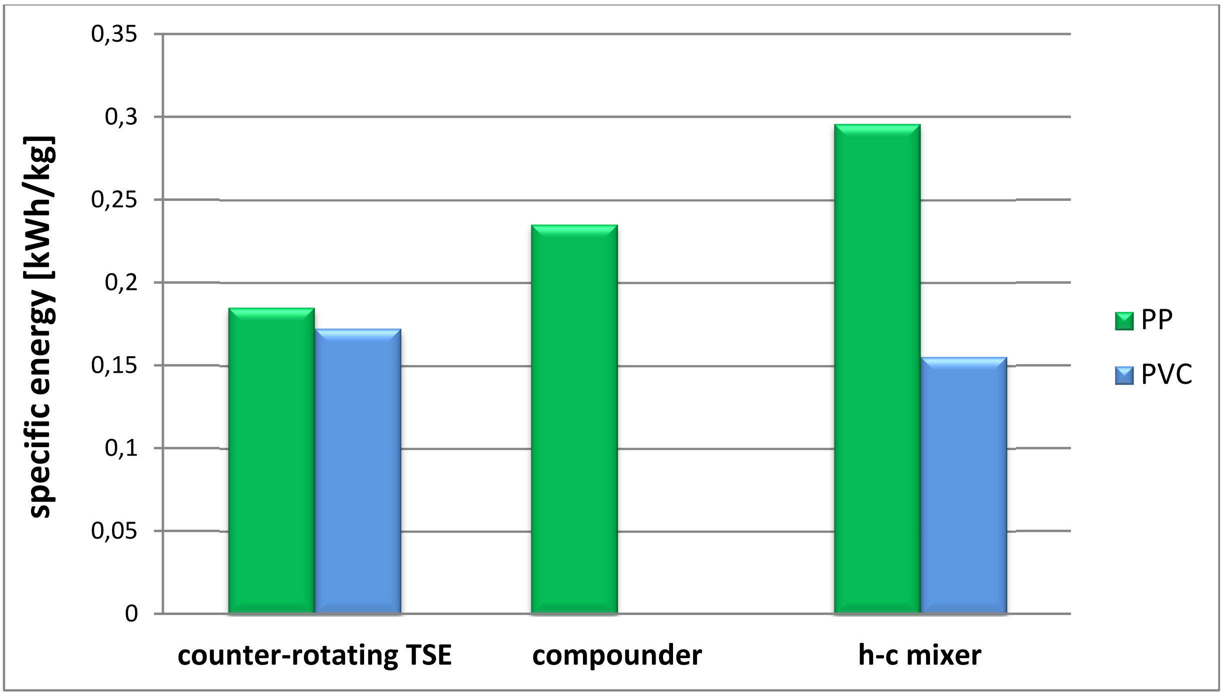


Figure 37: The specific energy consumption of all tested material-machine combinations.

Table 5: Numeric results of the specific energy consumption for the tested materialmachine combinations.

Material	**Counter-rotating TSE** (kWh/kg)	**Compounder** (kWh/kg)	**Heating-cooling mixer** (kWh/kg)
PP	0,185	0,236	0,296
PVC	0,172	---	0,156

4.1.2 Degree of efficiency

As mentioned in chapter 3.7, the degree of efficiency is defined as the melt enthalpy (the minimum amount of energy to melt the material) found from the DSC measurement (see Table 6 and appendix) compared to the total energy input in the process. In Table 6 the numeric results of the DSC measurements, representing the integral of the heat capacity over the applied temperature difference, are shown. The temperature difference is the maximum melt temperature for every process, shown in Table 3 and Table 4 for the extruders. The maximum temperature of the heating-cooling mixer was sharply controlled and is 175 °C for the PP trial and 120 °C for the PVC trial.

Table 6: Results of the DSC evaluations for the applied temperature differences and the two materials in the heating and cooling mode.

temperature range (°C)	**ΔT (°C)**	**c_P* ΔT (J/g)**	
		heating mode	**cooling mode**
		WPC (PP-Holz)	**WPC (PP-Holz)**
25-170	145	368,2	301,5
25-180	155	380,4	326,4
25-200	175	394,7	381,7
		heating mode	**cooling mode**
		WPC (PVC-Holz)	**WPC (PVC-Holz)**
25-120	95	165,7	125,3
25-189	164	244,4	233,1

The actual calculation of the melt enthalpy composes of the mass flow rate of every process multiplied with the integral found by the DSC measurements. The temperature difference signed as ΔT is shown separately in Table 7 to visualize the connection between Table 6 and Table 7. The end result, the melt enthalpy is highlighted in the framed column. This value was taken as the basis for the calculation of the degree of efficiency

Table 7: Systematic analysis of the single components of the melt enthalpy calculation.

machine	***material***	***ΔT (°C)***	***ṁ (kg/h)***	***c_P*ΔT (J/kg)***	***ΔH (kW)***
counter-rotating TSE	PP	155	120	380403	12,7
		155	150	380403	15,9
	PVC	164	120	244415	8,1
		164	150	244415	10,2
compounder	PP	175	150	397702	16,6
		175	300	397702	33,1
heating-cooling mixer	PP (heating)	145	638	368200	65,3
	PP (cooling)	145	638	301500	53,4
	PVC (heating)	95	410	165678	18,9
	PVC (cooling)	95	410	125300	14,3

The process efficiency of the counter-rotating TSE shows significant differences between the two materials. While processing PP leads to high process efficiency, PVC shows considerably lower efficiency. This result can be explained by the fact, that PP needs more energy to melt, due to its semi-crystalline nature and the resulting heat capacity curve (see appendix). PP absorbs more energy for melting because of its higher melt enthalpy. PVC has a lower melt enthalpy on the one hand and needs a higher melt pressure (see Table 3) on the other hand which leads to a significantly lower degree of efficiency. When comparing this machine with the others, the counter-rotating TSE lies in the center span of the field.

When looking at the results of the compounder, it is obvious, that this machine brings up the rear with a process efficiency distinctly under those of the other two machine concepts. The reason therefore is the amount of energy which flows into the process and is not part of the melting procedure. The process is rather extensive with the two drives for the compounder and the single screw, the many heater sleeves and the underwater granulation, which consumes a lot of energy, not to mention the increased loss of power (see chapter 4.1.5). This happens due to the bigger surface, where energy is lost via convection, radiation and the increased venting via side feeders. In addition the electric control cabinet is more complex and energy consuming than the control boxes of the other machines.

The best machine concept regarding the energy efficiency is the heating-cooling mixer and the heating mixer with the attached cooling bed. These machines show the most efficient processes for both materials, whereat the PP process leads to an outstanding result. The difference between the two materials arises besides the difference in the heat capacity from the fact, that the PP process didn't use a cooling mixer, which needs more additional energy than the cooling/vibrating bed, therefore most of the energy input flows into the material. Moreover the two machines do not use external heater sleeves, so not only the additional power, but also the loss of energy due to heat radiation and convection is eliminated which directly increases the process efficiency.

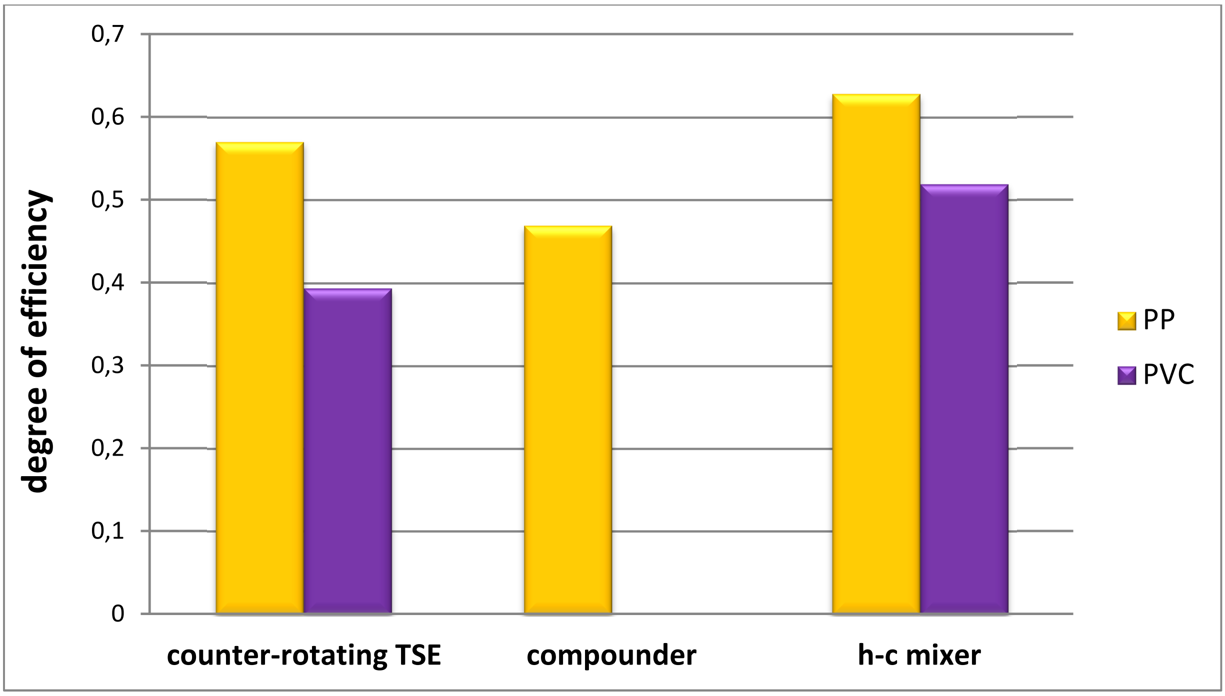


Figure 38: The degree of efficiency of all tested material-machine combinations.

Table 8: Numeric results of the specific energy consumption for the tested material-machine combinations.

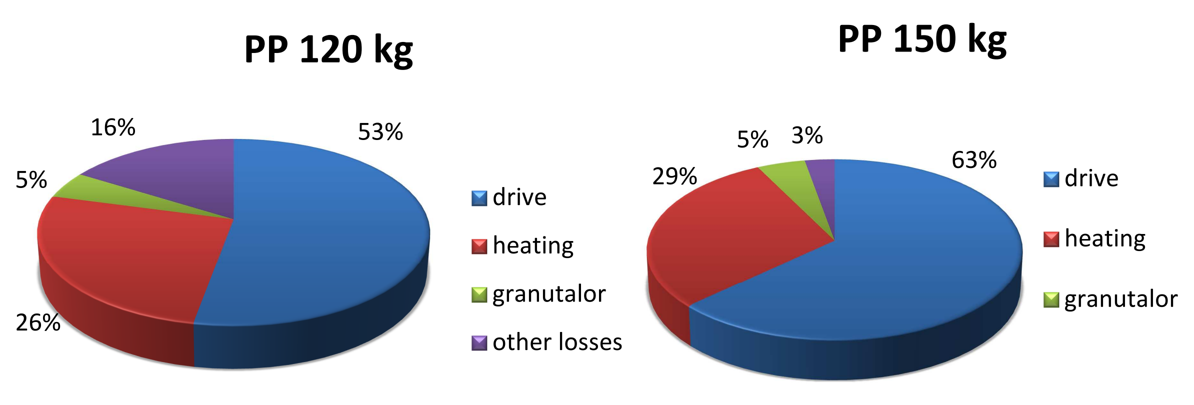
Material	**Counter-rotating TSE**	**Compounder**	**Heating-cooling mixer**
PP	0,57	0,469	0,628
PVC	0,39	---	0,519

4.1.3 Single energy components

The following sub-chapter will split up the total energy consumption in the single energy consuming components. The focus lies on the change of energy consumption for the single loads regarding higher output rates. Here the apparent power is discussed, so that process losses could be visualized.

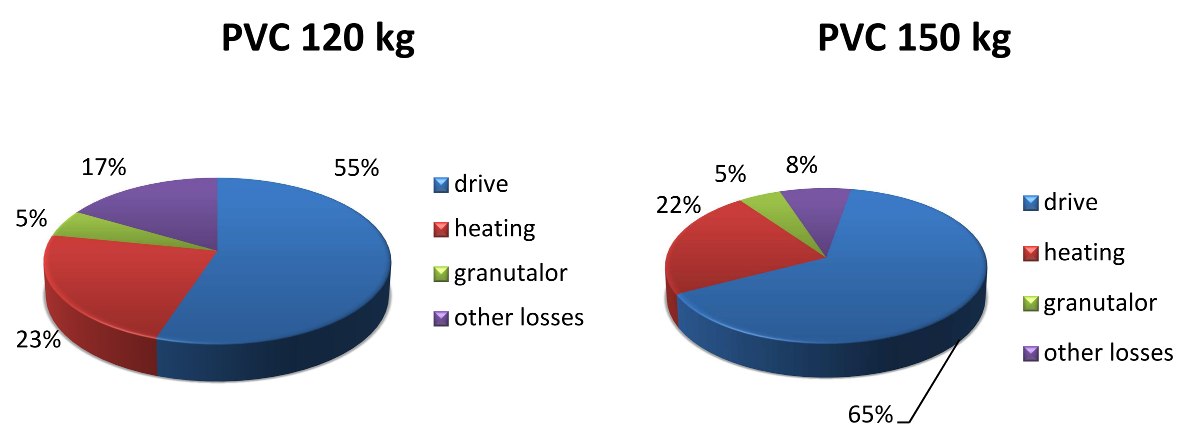
Regarding the counter-rotating TSE, more than half of the energy is consumed by the motor and put in the material via shear stress. The heating is the second biggest load followed by the losses described in chapter 4.1.5. The granulator is the smallest consumer with 5% energy consumption.

The comparison of the two output rates, 120 kg/h and 150 kg/h for both materials shows, that the higher output rate and the better workload of the machine leads to a remarkable reduction of the process losses and a better utilization of the drive. This effect is observed for both materials and proves that higher output rates are more economic and efficient as long as the drive is not overcharged.



component	power (kW)	component	power (kW)
drive	16,88	drive	23,05
heating	8,40	heating	10,80
granulator	1,49	granulator	1,68
other losses	5,16	other losses	1,03

Figure 39: Apportionment of the total energy consumption into single consumer loads for the counter-rotating TSE including the numeric results for the PP trials.

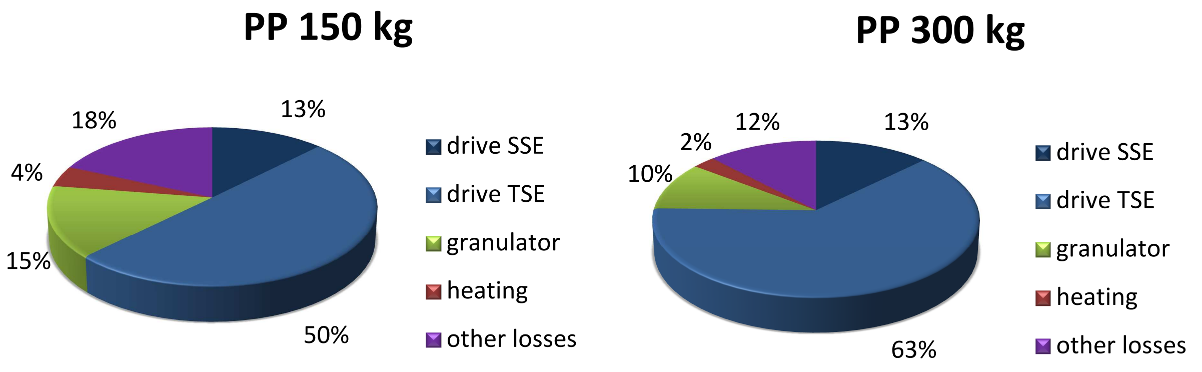


component	power (kW)	component	power (kW)
drive	17,15	drive	22,94
heating	7,16	heating	7,97
granulator	1,63	granulator	1,70
other losses	5,18	other losses	2,82

Figure 40: Apportionment of the total energy consumption into single consumer loads for the counter-rotating TSE including the numeric results for the PVC trials.

The situation regarding the compounder is similar however the process is more complex. The percentage shares of the energy consumers are shown in Fig. 41. The process is very energy consuming, considering the moderate amount of energy (50%) brought in via the twin screw. The single screw extruder or melt extruder does not participate in the melting process but is applied to replace the melt pump to convey the melt continuously. Compared to other granulation systems, the underwater granulation is much more energy consuming with 15% of the total energy input. The heating needs 4% of the total process energy which reveals that a lot of energy is brought in via shear stress and as a consequence not much heating is necessary.

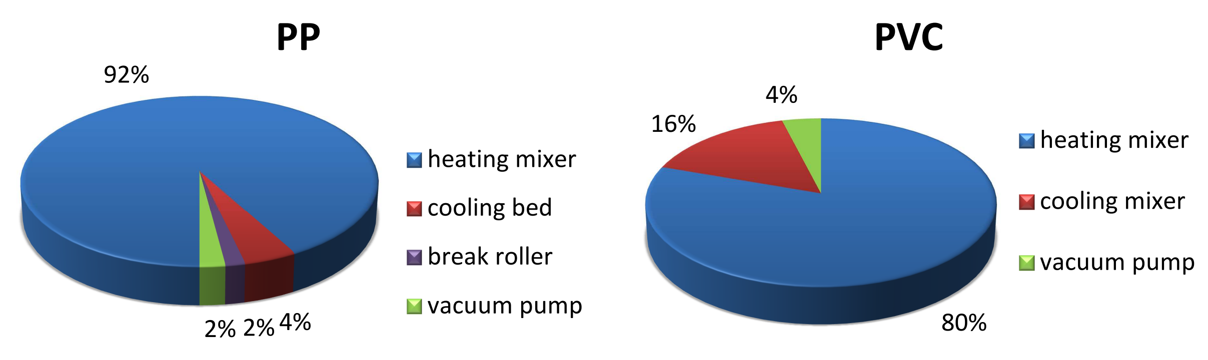
The higher output rate results in the same trend as the counter-rotating TSE process. More energy is used for the main drive whereat the shares of process losses, the heating and granulation decrease. As described in chapter 3.5, the machine is built for 400 kg/h output, therefore 300 kg/h are a good and economic workload, where not much heating is needed to bring in the necessary energy.



component	power (kW)	component	power (kW)
drive SSE	7,76	drive SSE	11,96
drive TSE	31,19	drive TSE	58,86
Granulator	9,15	Granulator	9,34
Heating	2,65	Heating	2,38
other losses	11,40	other losses	11,40

Figure 41: Apportionment of the total energy consumption into single consumer loads for the compounder including the numeric results.

The main difference between the heating-cooling mixer and the heating mixer with cooling bed is the energy consumption of the cooling devices. As shown in Fig. 42 the cooling unit of the PP process consumes a quarter of the energy needed for the cooling mixer of the PVC process (4 % resp. 16 %). The difference in the energy consumption of the two vacuum pumps results of the bigger heating mixer drive of the PP agglomerating machine and the more extensive energy need.



component	power (kW)	component	power (kW)
heating mixer	60,05	heating mixer	18,55
cooling bed	2,83	cooling mixer	3,63
break roller	1,05	vacuum pump	0,92
vacuum pump	1,35		

Figure 42: Apportionment of the total energy consumption into single consumer loads for the heating-cooling machine concepts including the numeric results.

4.1.4 Comparison of cycle-differences regarding the heating-cooling mixer

To illustrate the difficulties of the measurements performed on the heating mixer with the attached cooling bed, Figure 43 and Table 9 show the differences among the five trials. However the machine was run with four cycles before the measurement started, the first two runs showed significant higher energy consumption than the last three trials. Presumably the machine jacket was not fully heated by the four run-in cycles, so that it needed two more cycles to run in the machine. Comparing the idle power percentages, it is obvious, that the first two runs have a higher idle power. It also proves that this process was not very stable and not perfectly controlled. It was not possible to generate granules out of every charge, because the material was highly compacted by the vacuum pump and not prevented from agglomerating by the cooling bed. So in some trials the break roller could not manage to break all the agglomerates, because the fragments were too big and bonded together. For the comparison of the PP and the PVC trial the deviation of the average value of the active power of all performed trials were taken as a basis. For the PP trial, the average value is 38,6 kW and the percentage of deviation is ± 17 %.

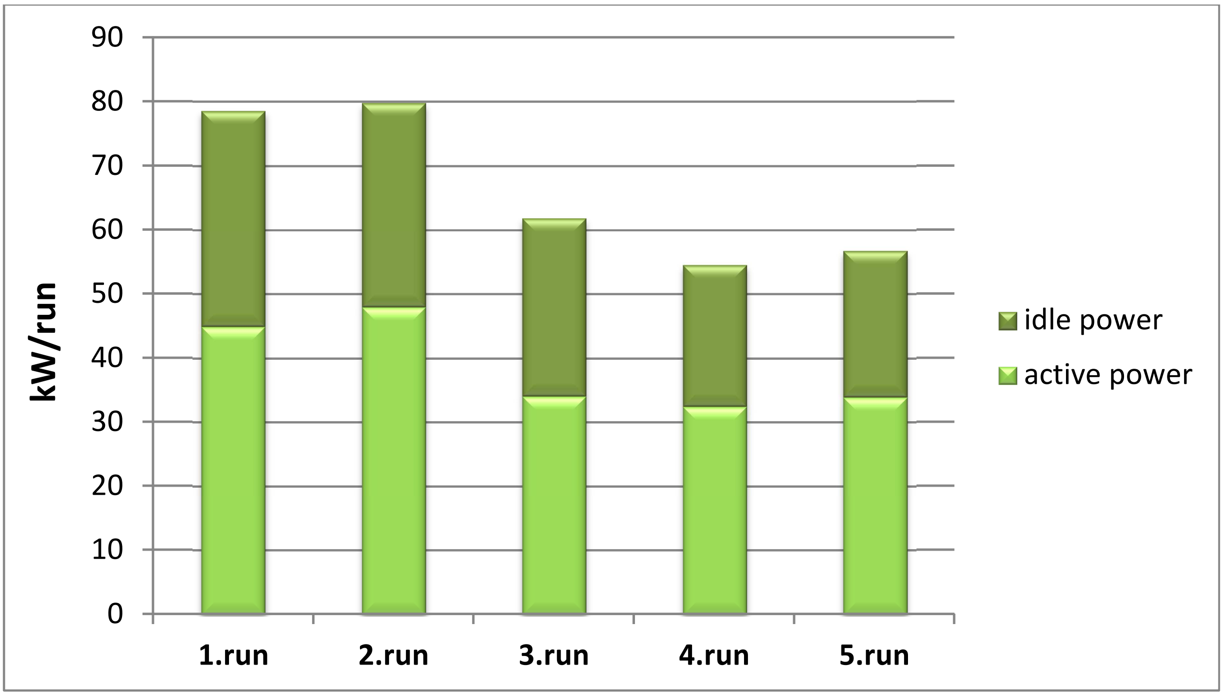


Figure 43: Differences in the energy consumption among the trials on the heating mixer with the attached cooling bed.

Table 9: Numeric results of Figure 43.

	1. run	**2. run**	**3. run**	**4. run**	**5. run**
Idle power (kW)	33,6	31,8	27,8	22,1	22,9
Active power (kW)	44,9	48,0	34,0	32,4	33,8

To compare the PP machine concept with the conventional heating-cooling mixer, Figure 44 and Table 10 show the trials of the PVC process. Not only that this process is, with an average value of 15 kW of the active power, in a lower range of energy consumption, but also the differences between the single trials are slightly lower. Here the percentage of deviation around the average value is ± 15 %.

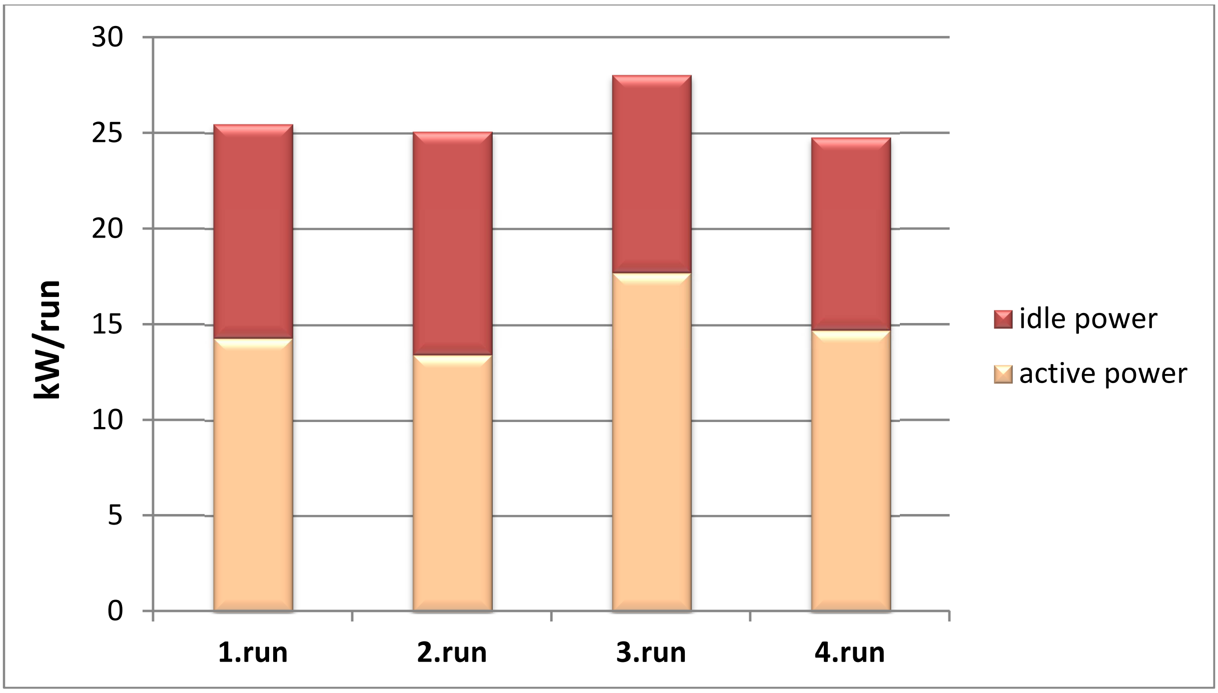


Figure 44: Differences in the energy consumption among the trials of PVC on the heating-cooling mixer.

Table 10: Numeric results of Figure 44.

	1. run	**2. run**	**3. run**	**4. run**
Idle power (kW)	11,2	11,7	10,3	10,1
Active power (kW)	14,3	13,4	17,7	14,7

4.1.5 Share of lost performance on the total process for every trial

The percentage of lost performance is the difference between the left and the right side of the energy balance (see. equation 4). In a perfect and loss-free process, the left and the right side of the energy balance would be equal. Real processes have losses due to heat radiation, convection, losses in the motor, the gear box, the control cabinet and conduction. Additionally the relatively high amount of energy absorbed by the moisture in the material, which evaporates as steam in the venting zone, is lost. There are inevitable losses and those who can be minimized by process optimization.

In chapter 4.1.2 the calculation of the melt enthalpy term is discussed in detail. The second term, the compression work is calculated with the volume flow rate and the pressure difference, shown in Table 11. Here all single components needed for the calculation of the compression work are listed and the bold framed column is the end result, the compression work. Since no volume flow was measured, the mass flow was transferred over the density to the volume flow. The pressure difference Δp is the difference of the maximum melt pressure (see Table 3 and 4) in the process and the ambient pressure of 1 bar. This term is only relevant for the extruders, since the heating-cooling mixer does not apply any pressure on the material.

Table 11: Systematic analysis of the single components of the compression work calculation.

machine	***Material***	***ρ (kg/m^3)***	***$\dot{m}$ (kg/h)***	***V‘ (m^3/h)***	***Δp (bar)***	***V‘* Δp (kW)***
counter-rotating TSE	PP	916,8	120	0,131	155	0,564
		916,8	150	0,164	175	0,795
	PVC	1253,7	120	0,096	227,5	0,605
		1253,7	150	0,120	231	0,768
compounder	PP	916,8	150	0,164	67	0,305
		916,8	300	0,327	72	0,654
heating-cooling mixer	PP (heating)	916,8	638	0,696	0	0
	PP (cooling)	916,8	638	0,696	0	0
	PVC (heating)	1253,7	410	0,327	0	0
	PVC (cooling)	1253,7	410	0,327	0	0

To identify the loss of performance, the energy balance (see equation 4) has to be set up to compare the left and the right side of the equation. Table 12 shows all terms of the energy balance, the term on the left side are highlighted blue, the terms on the right side are marked green. It is important to note, that the heating-cooling mixer has an additional enthalpy term $\Delta H_{cooling}$ coming from the cooling mixer, which cools the material actively and consumes energy. The numeric result for the loss of performance is bold framed and the basis for the calculation of the percentage of lost performance compared to the total energy in the equation.

Table 12: The single components of the energy balance equation for every machine-material combination.

Machine	Material	output (kg)	P_{drive} (kW)	$P_{heating}$ (kW)	P_{loss} (kW)	ΔH (kW)	V‘* Δp (kW)
counter-rotating TSE	PP	120	8,95	8,06	3,77	12,68	0,564
		150	14,75	10,37	8,47	15,85	0,795
	PVC	120	8,92	6,73	6,89	8,15	0,605
		150	14,45	21,94	7,49	10,18	0,768
compounder	PP	150	29,71	2,36	15,21	16,57	0,305
		300	60,34	2,09	28,64	33,14	0,655

Machine	material	output (kg)	$P_{heating}$ (kW)	$P_{cooling}$ (kW)	P_{loss} (kW)	$\Delta H_{heating}$ (kW)	$\Delta H_{cooling}$ (kW)
h-c mixer	PP	638	176,05	6,65	64,04	65,25	53,43
	PVC	410	49,3	11,65	27,79	18,87	14,27

In Figure 45 and Table 13 the percentage of lost performance compared to the total energy terms in the energy balance is illustrated and shown in numbers. The results were split up in the two output rates measured on the extruders, except for the heating-cooling mixer, where only one output per material was measured.

The first four columns show the process on the counter-rotating TSE, the first two for PVC and the second for PP. Trials with PVC lead to a higher loss of performance than the process of PP. An explanation for this effect is the big difference of the melt pressures necessary for processing these materials (see Table 3). A higher melt pressure (PVC) requires more energy hence the potential for losses is higher. For both materials the tendency that the higher output rate results in a higher loss of performance is the same, whereat this effect is more distinctive for PP.

The PP trial on the compounder shows higher losses than the PP trial on the counter-rotating TSE. It should be noted, that the higher output rate leads to a slightly lower performance loss. This effect is not very distinctly and shows reverse tendency compared to the counter-rotating TSE. This effect can be explained by the differences in the filling degree. In this case, the screws were more filled therefore more material was conveyed and melt.

For the heating-cooling mixer process, the trend is comparable to the counter-rotating TSE. The PP mixing process leads to lower performance loss, which is approximately in the same range as the PP trials on the counter-rotating TSE. PVC shows a higher performance loss which is exactly of the same size as the counter-rotating TSE process, but with three times more output capacity.

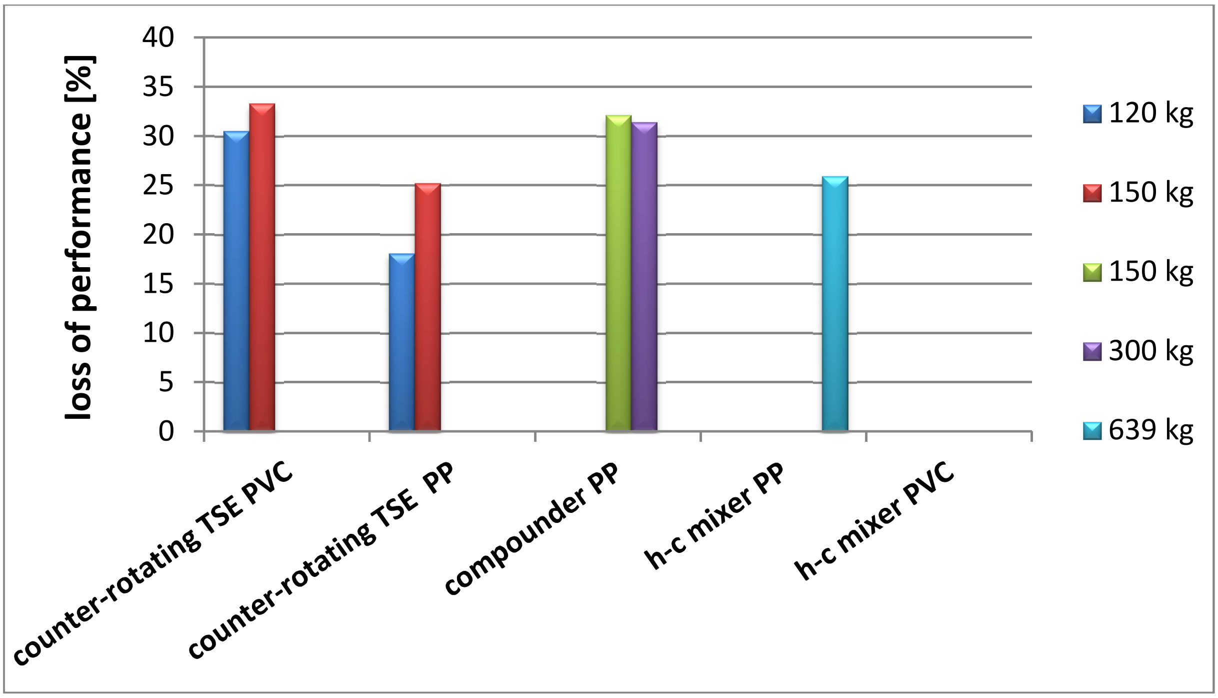


Figure 45: Comparison of lost performance for all tested machines, materials and output rates.

Table 13: Numeric data to the results shown in Fig. 45.

	Counter-rotating TSE - PVC	**Counter-rotating TSE - PP**		**Compounder PP**		**Heating-cooling mixer**
120 kg/h	30,6	18,1	150 kg/h	32,2	PP 639 kg/h	25,9
150 kg/h	33,4	25,2	300 kg/h	31,4	PVC 410 kg/h	31,3

4.1.6 Percentage of idle power

The idle power is the result of phase shifting in alternating current systems and does not contribute to the active power. In general the idle power is unwanted and often declared as impurity in the system, because it is energy that cannot be used but has to be transported. Industrial companies basically have to pay for the idle power. Nowadays the majority of companies work with compensators, who lead the idle power back in the supply system so that they do not have to pay it [1] [2].

Figure 46 shows the comparison of idle power and active power for all components of the counter-rotating TSE. It is obvious, that the idle power rises with increasing energy consumption. The effect is most distinctive for the engine, where the idle power increases due to the inductive and capacitive loads in the asynchronous machine.

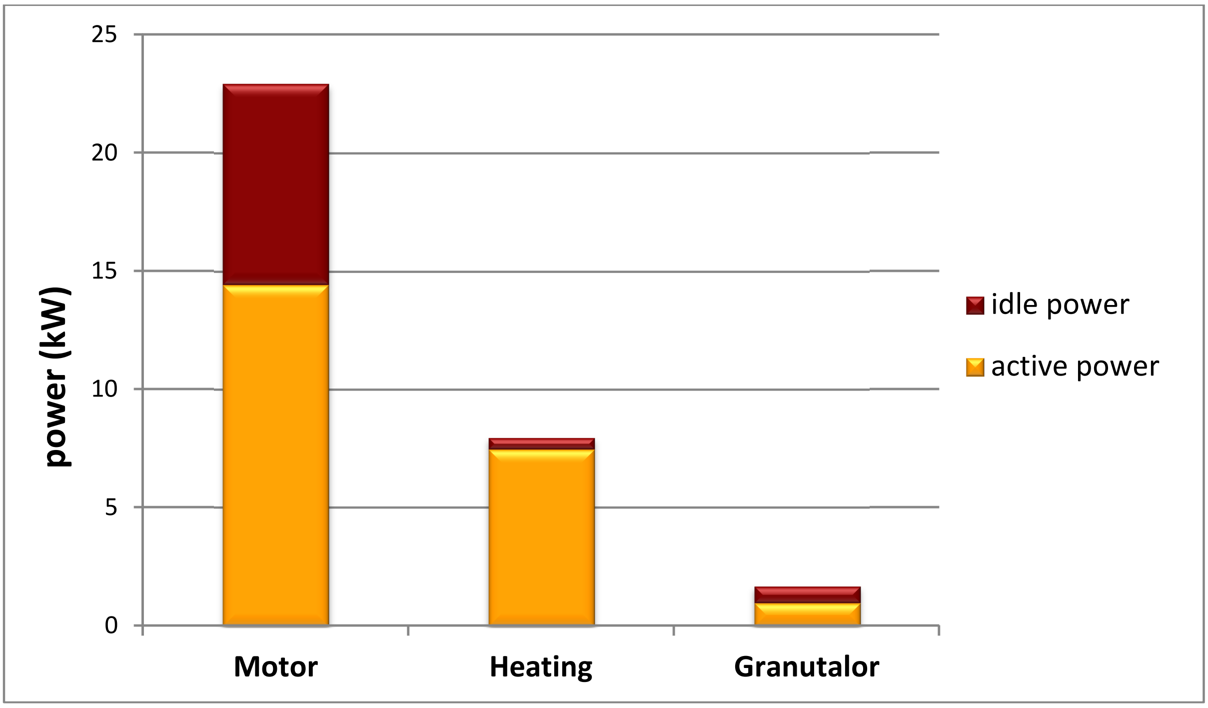


Figure 46: Illustration of the idle power to active power ratio for the counter-rotating TSE.

Table 14: Numeric data to the results shown in Fig. 46.

	Motor	Heating	Granulator
Idle power (kW)	8,3	0,43	0,71
Active power (kW)	14,7	10,4	0,97

Regarding the compounding process (see Fig. 47) on the compounder, the idle power is remarkably lower in all components compared to the counter-rotating TSE. The tendency however is the same, that the idle power is higher at the motor loads (drive for the single screw and the twin screw extruder) than at the others.

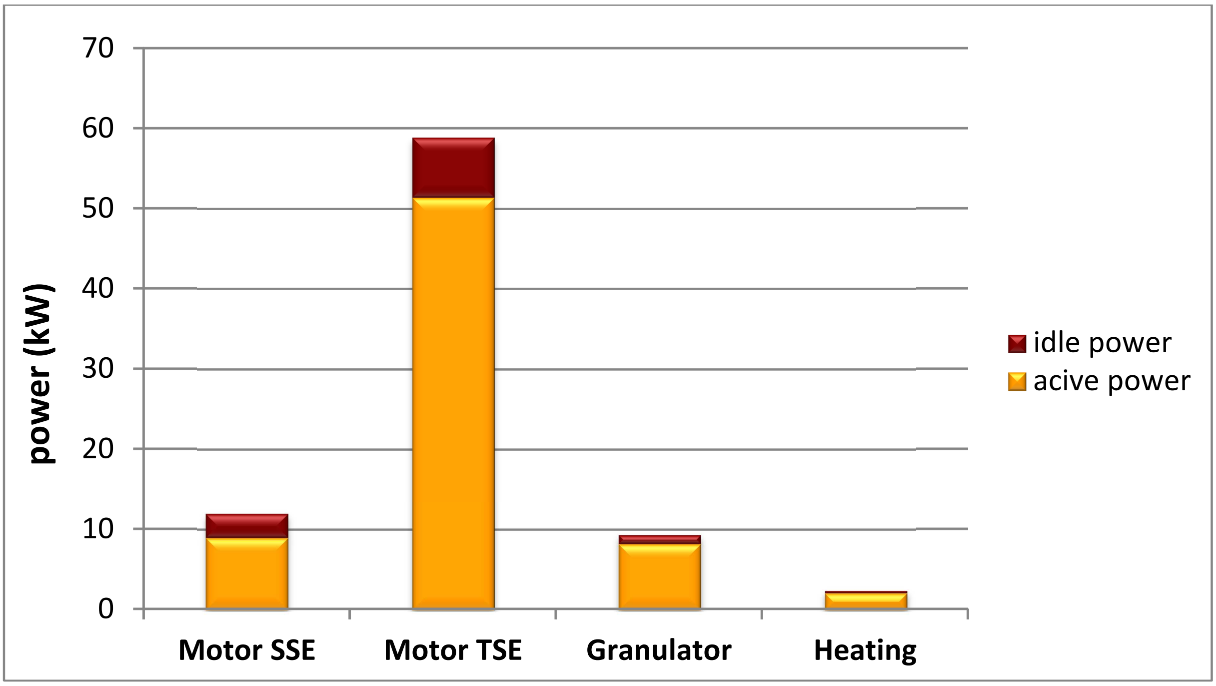


Figure 47: Illustration of the idle power to active power ratio for the counter-rotating TSE.

Table 15: Numeric data to the results shown in Fig. 47.

	Motor SSE	Motor TSE	Granulator	Heating
Idle power (kW)	2,3	6,9	1,1	0,29
Active power (kW)	5,5	24,6	8,1	2,4

The Break-down of the apparent power for the two mixing processes is discussed and shown in Fig. 43 and Fig. 44 in chapter 4.1.4. The differences between the heating-cooling mixer and the heating mixer with attached cooling bed are illustrated and shown in numbers.

The considerations of the energy consumption showed, that regarding the specific energy consumptions, the counter-rotating TSE lead to the lowest values for PP. For PVC, the heating-cooling mixer showed the lowest energy consumption. For the degree of efficiency the heating-cooling mixer lead to the highest values for both materials. The comparison of the single energy loads of every process proved, that the higher output rates lead to a decrease of lost performance. Regarding the active and idle power shares of the total power, the heating-cooling mixer showed the highest shares of idle power, after the counter-rotating TSE and the lowest shares were found for the compounder. The heating-cooling mixer also showed run-in effects, however separate run-in cycles were performed prior to the measurements. The results for the shares of lost performance showed that the counter-rotating TSE lead to higher losses at higher output rates. The reverse effect was found for the compounder. The heating-cooling mixer led for both materials similar values of the counter-rotating TSE.

4.2 Results of the quality measurements

The second part of this chapter and the following paragraphs focus on the qualitative comparison of the differently processed compounds/agglomerates. The focus within these considerations lies on the physical and optical properties of the compounds.

4.2.1 Bulk density, flowability and moisture content

To ensure the comparability of the investigated procedures, quality properties were defined within this work. On the basis of these standards the products of every process were compared. The two basic and commonly used indicators in the plastic industry are the flowability and the bulk density as well as the moisture content. The definition of the flowability had to be adjusted for WPC materials, since there is no standardization yet.

Table 16 gives an overview over the measured quality factors, comparing the tested materials, machines and output rates. Regarding the counter-rotating TSE, marked blue in the table, this process leads to a solid value for the bulk density, to acceptable flowability and to the lowest moisture content of all produced compounds. For the higher output rate, both materials show lower bulk densities and more moisture content. This can be explained by the decreased time available for degassing in the venting zone and compressing the material.

The compounds produced by the compounder lead to the highest bulk densities, due to the underwater granulation, and therefore the best flowability. The moisture content is distinctly higher. The tendency is the same as the one observed for the counter-rotating TSE, the bulk density decreases and the moisture content increases with the higher output rate.

The mixing process leads to the lowest bulk densities resulting in a poor flowability, not acceptable for gravimetric dosing in the further processing step. The moisture content is comparable with the compounder. The heating cooling mixer for PVC leads to a higher moisture level while the heating mixer with attached cooling bed shows lower moisture values.

Table 16: Results for the quality measurements for all processes, materials and output rates.

Machine	Material	output (kg/h)	Bulk density (g/l)	moisture (r.h. %)	Flowability
Counter-rotating TSE	PP	120	519 ± 4	0,81 ± 0,07	+
		150	480 ± 5	1,38 ± 0,13	+
	PVC	120	543 ± 3	0,72 ± 0,03	+
		150	519 ± 2	0,76 ± 0,18	+
Compounder	PP	150	583 ± 9	1,64 ± 0,53	++
		300	523 ± 5	2,59 ± 0,54	++
Heating-cooling mixer	PP	639	320 ± 5	1,85 ± 0,39	--
	PVC	410	377 ± 3	2,23 ± 0,72	-

4.2.2 SEM – results (scanning electron microscopy)

To complete the quality considerations SEM measurements were done on the produced granules to characterize the homogeneity due to the preparing process. The focus lied on the influence of the fibers due to the process, the material specific appearance and the effect of the higher output rate.

Figure 48 shows the PP granules produced by the counter-rotating TSE for both output rates. The compound with 120 kg/h output rate showed no influence on the fibers and a very homogenous overall impression. The polymer covers the wood component very good and literally fuses with the wood.

The PP compound produced with 150 kg/h output rate appears to be more porous and the polymer does not fully cover all wood fibers. The porosity can be explained by the shorter time span, due to the higher output rate, available for venting the material. The fibers are slightly manipulated, due to the stronger compaction.

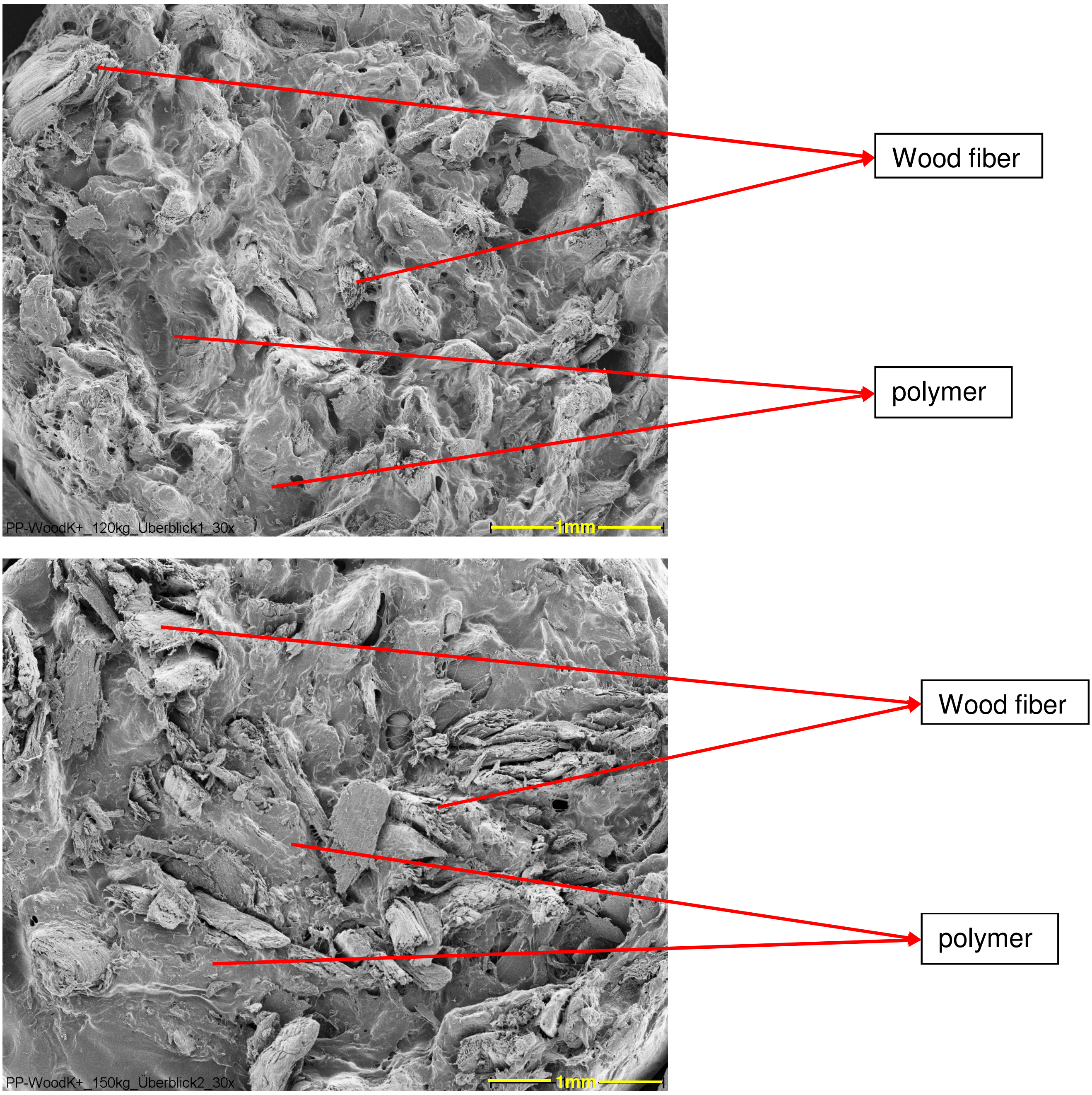


Figure 48: SEM pictures of the PP compounds produced with 120 kg/h (top) and 150 kg/h (bottom) output rate by the counter-rotating TSE.

Figure 49 shows the PVC compounds also produced by the counter-rotating TSE process. Compared to the PP compound it is obvious that the PVC material does not fuse with the wood fibers. The fibers are embedded in the PVC component, but are not covered or melted with the polymer. At 120 kg/h output rate the fibers are not manipulated or broken but only compacted. The cross section gives a homogenous impression.

The 150 kg/h output rate leads to a higher degree of fiber manipulation, but mainly through compaction. The cross section appears very homogenous and higher compacted. Regarding the porosity, the PVC compound seems to follow the reverse trend compared to PP, while the compound of 120 kg/h is relative porous, the 150 kg/h compound is very compact and dense.

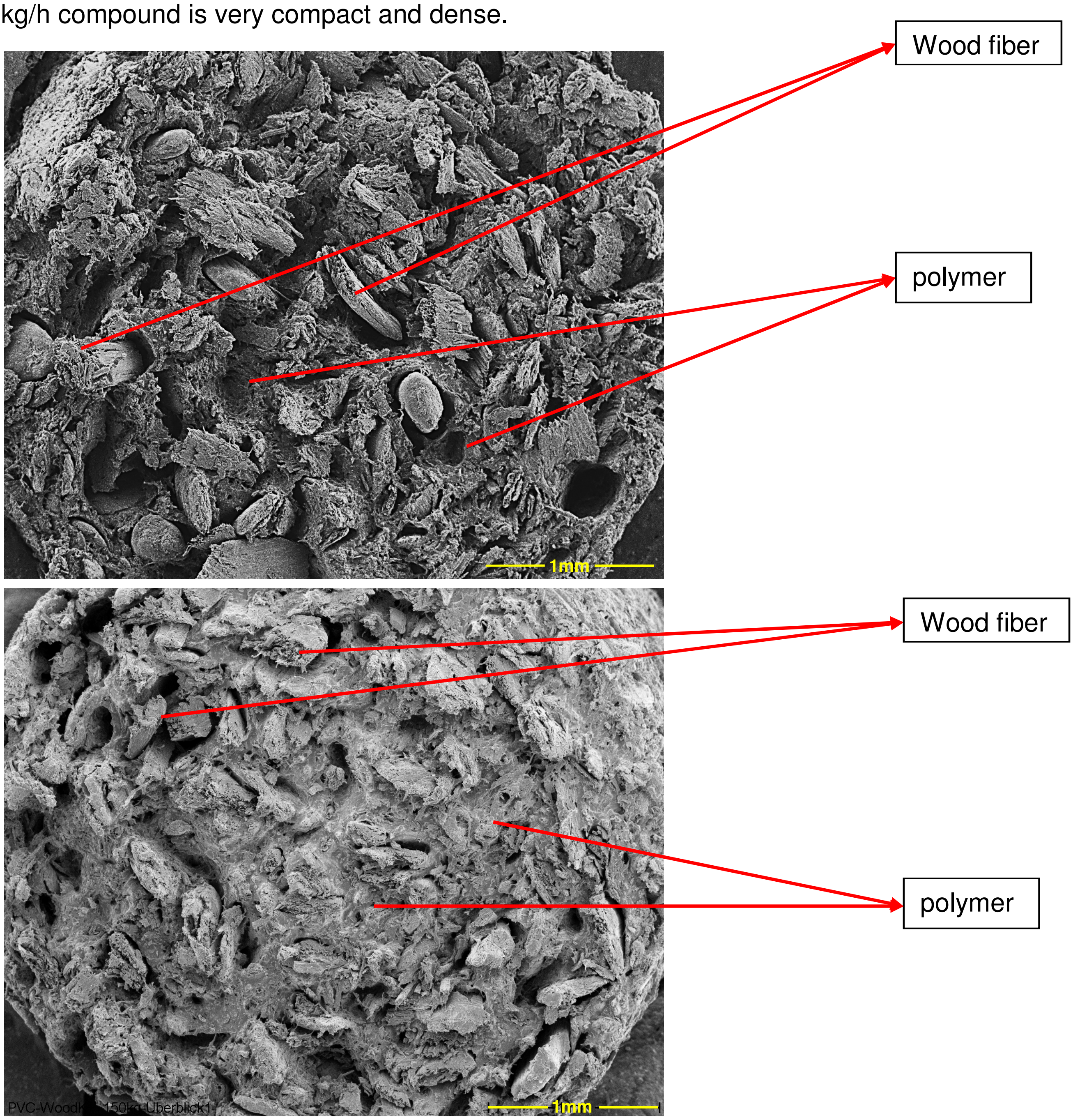


Figure 49: SEM pictures of the PVC compound produced with 120 kg/h (top) and 150 kg/h (bottom) output rate by a counter-rotating TSE.

The PP compound produced by the compounder with the flanged single screw has the characteristic silhouette of a granules produced by underwater granulation. Due to the high degree of compaction, the granules had to be cut to receive a representative cross section. The section highlighted in red is the cut area, smeared by the knife and not a representative cross section.

The compound produced with the lower output rate shows a very compact or better compressed microstructure with a low porosity. The fibers are strongly manipulated and broken.

Concerning the higher output rate, the granule showed higher porosity. The fibers are less manipulated, but still more than the granules of the counter-rotating TSE. This could be s result of the poor venting capacity achieved at this output rate.

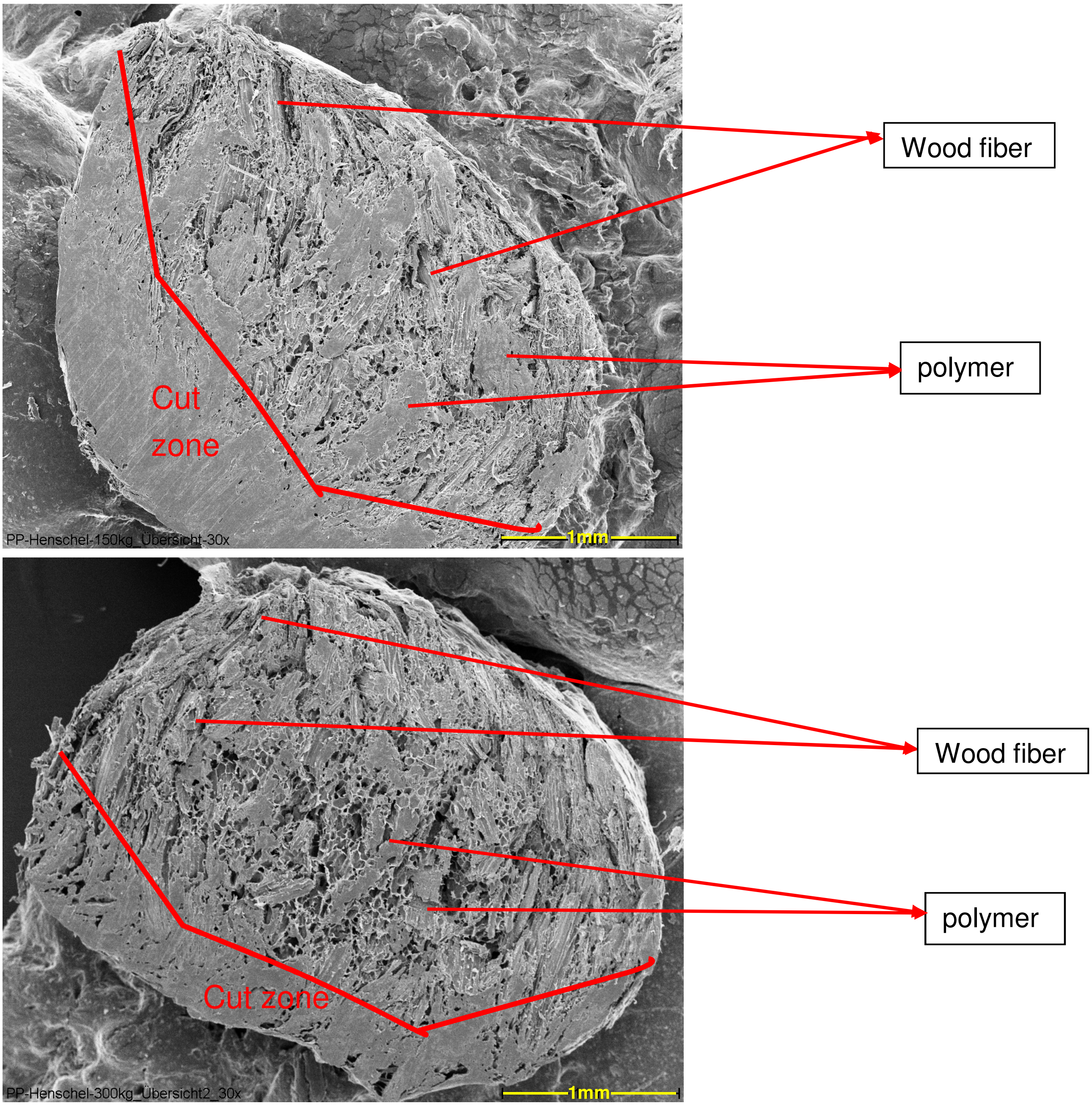


Figure 50: SEM pictures of the PP compound produced with 150 kg/h (left) and 300 kg/h (right) output rate by a compounder.

The semi-finished product produced by the heating-cooling mixer shown in Fig 51 is a loosely merged agglomerate of polymer and wood component. The fibers are not influenced by the process. The agglomerate is very homogenous.

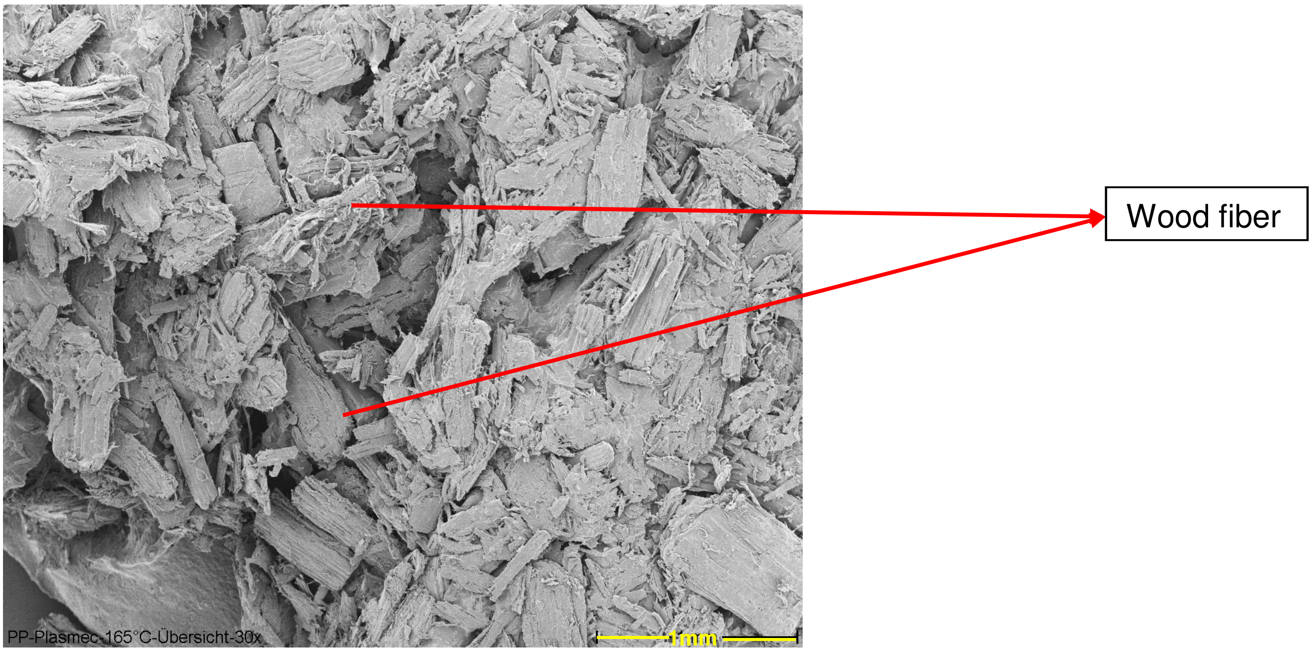


Figure 51: SEM pictures of the PP compound produced with 150 kg/h (left) and 300 kg/h (right) output rate by the heating-cooling mixer.

4.2.3 Optical influence on the material due to processing

A very important quality factor is the simple optical comparison of all compounds. The observation of all compounds shown in Fig. 52 reveals the strong influence of the different machines on the color of the compound. The compound made by the counter-rotating TSE is significantly brighter than the compound of the compounder and shows no differences between the two materials. This effect is not insignificant, especially for exterior use. This darkening of the compound is the consequence of the high and long thermal stress induced by the compounder. The color of the agglomerate produced by the heating-cooling mixer is not darkened by the process, the color is very genuine. Also the PVC dryblend is in terms of color not affected by the mixing process.

The differences in the size of the granules differ only slightly between the co-rotating and the counter-rotating TSE. Both machines produce small particles with little differences in the size. The compounder leads to slightly more uniform results. The heating-cooling mixer produced agglomerates with big differences in the particle size, which can cause problems when using gravimetric dosing in the further processing steps.

The compound of the compounder exhibits no dust content at all. The counter-rotating TSE leads to very low dust contents. Only the heating-cooling mixer produces a compound with high dust content.

Figure 52: Optical comparison of all produced compounds. Compounder compound (top left), counter-rotating TSE compound (PP and PVC) (top right), PP agglomerate (bottom left) and PVC dryblend (bottom right).

4.3 Conclusive comparison

A purchase decision is always based on more than one priority. The following figures give an overview over the strengths and the weaknesses of the single machines to make a decision based on the four priorities quality, economic efficiency, productivity and further processing behavior, which are here represented by the point “gravimetric dosing”.

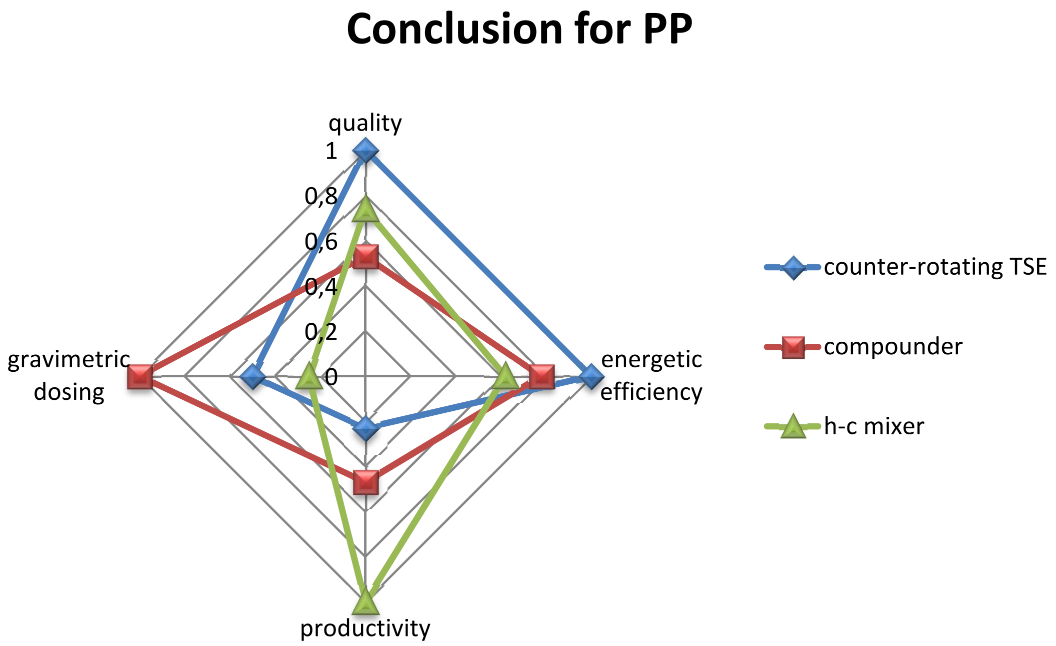


Figure 3553: Radar chart for PP

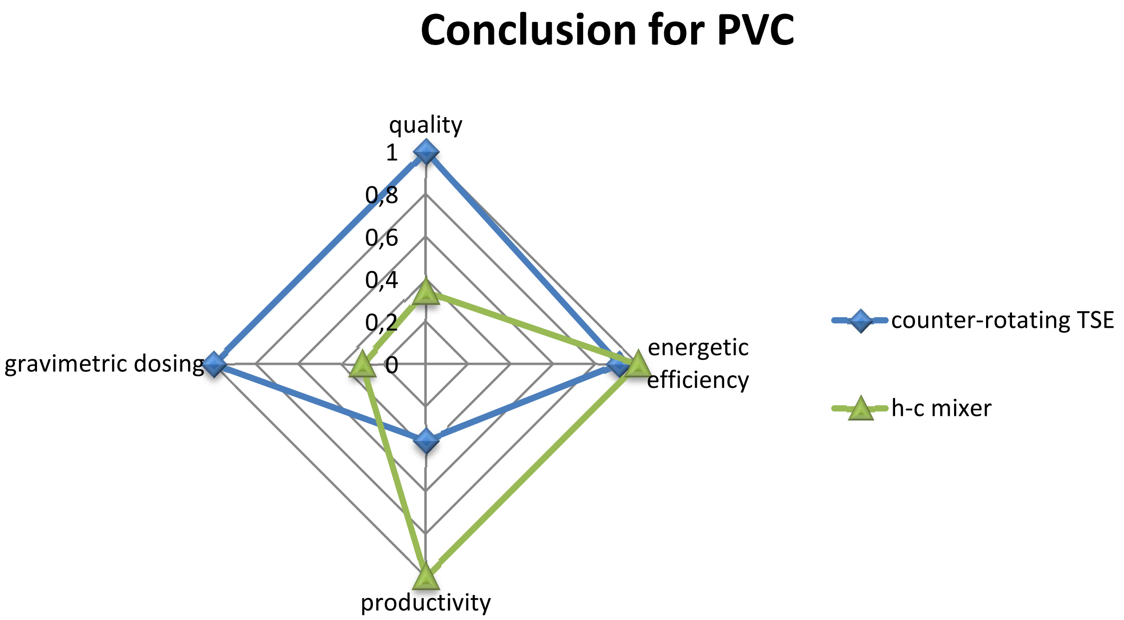


Figure 54: Radar chart for PVC

In these diagrams, all absolute values are compared to the best value for each priority. 1 stands for the highest value which is the benchmark for all other points. In this way it is possible to compare all machines simultaneously regarding the four priorities.

For PP the counter-rotating TSE shows its strengths in the economy of the process and the quality of the compound. Regarding the productivity, the heating-cooling mixer leads to the best results while the counter-rotating TSE and the compounder are the best choice when further processing of the material is done with a gravimetric dosing unit.

For PVC, the counter-rotating TSE is the choice number one regarding quality and further processing with a gravimetric dosing unit. Regarding the economy and the productivity, the heating-cooling mixer shows the best results.

Of course there are more aspects to consider when purchasing a machine like maintenance costs, investment costs or production flexibility, which are not taken under consideration within this work.

5 SUMMARY AND CONCLUSION

This work focuses on the first step of the two-step production process of WPC, the compounding process. Within this work, four machine concepts for compounding WPC were investigated, using two state of the art material formulations. The considerations of the energy consumption behavior include the specific energy consumption, the degree of efficiency and the loss of performance of every tested machine concept. The tested machines were compared focused on energetic and quality aspects. For this purpose flap and ring converters in combination with the WarpNet Software were applied. The aim of this work is to be a reference work for future customers who want to enter the WPC market.

Regarding the specific energy consumption the counter-rotating TSE shows the most constant results. For PP, the counter-rotating TSE shows the lowest results followed by the compounder system and the heating-cooling mixer. The PVC tests, which were not operable on the compounder system, showed that the heating-cooling mixer is the more energy efficient option compared to the counter rotating TSE. These results are explained due to the morphological differences between PP and PVC, showing different heat capacities and melting properties. The distinctly high value of the heating-cooling mixer’s PP agglomerate results from the large size of the machine.

The degree of efficiency is defined as the ratio between the minimal energy needed for melting the material and the total energy put in the system. Regarding PP, the highest degree of efficiency shows the heating-cooling mixer followed by the counter-rotating TSE. The compounder system shows due to the extensive process lower values. For PVC the heating-cooling mixer leads to the highest values followed by the counter-rotating TSE. Due to the fact, that the heating-cooling mixer is not heated and has no granulation it shows a higher degree of efficiency. However the end-product is a powder, which demands less energy input than generating granules.

Speaking of the loss of performance caused by thermal and mechanic losses, the counter-rotating TSE and the heating-cooling mixer show nearly identical values. PP leads generally to lower losses than PVC for the counter-rotating TSE and the heating-cooling mixer. However the compounding system shows higher losses.

To ensure the comparability of the results, the produced compounds are characterized regarding their quality. For the plastics industry conventional procedures are applied being bulk density, moisture content, flowability and optical comparison.

The highest values for bulk density and flowabilty are found for the compounding system followed by the counter-rotating TSE and far behind the heating-cooling mixer with a high dust content and abroad particle size distribution. For the moisture content the highest values were found for the compounding system followed by the heating-cooling mixer, whereas the dryest compound was produced by the counter-rotating TSE.

The SEM measurements showed that compounds produced by the counter-rotating TSE, using the PP formulation are good compacted and the polymer is fully fused with the wood component. Higher outputs lead to higher porosity due to decreased venting capacity. Regarding PVC, the fibers are embedded in the polymer matrix, but not fused. A higher output rate leads to a stronger compaction. The compound made with the compounder showed more influence on the fibers and high compaction. Higher outputs lead to a higher porosity similar to the PP-compound of the counter-rotating TSE. The agglomerate of the heating-cooling mixer gives a very homogenous overall impression. The polymer seems to be fully fused with the fibers, which show no sign of manipulation.

The optical comparison showed that the only compound influenced in terms of color is the one produced by the compounder. This is caused by extensive thermal stress which darkened the material.

It can be concluded that the measuring method is not ideal for this kind of trials and the comparison of continuous and discontinuous processes. It would be better to use a device, which records data permanently and works without averaged values. Furthermore an additional test method like a fiber length measurement should be applied in order to detect the exact influence on the fibers by the process.

Further processing of the produced compound would give information about mechanical differences due to the compounding method and would be valuable information. For representing a valid purchase decision, more information on maintenance costs and investment costs have to be provided, which was not possible within this paper, due to the lack of information.

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7 APPENDIX

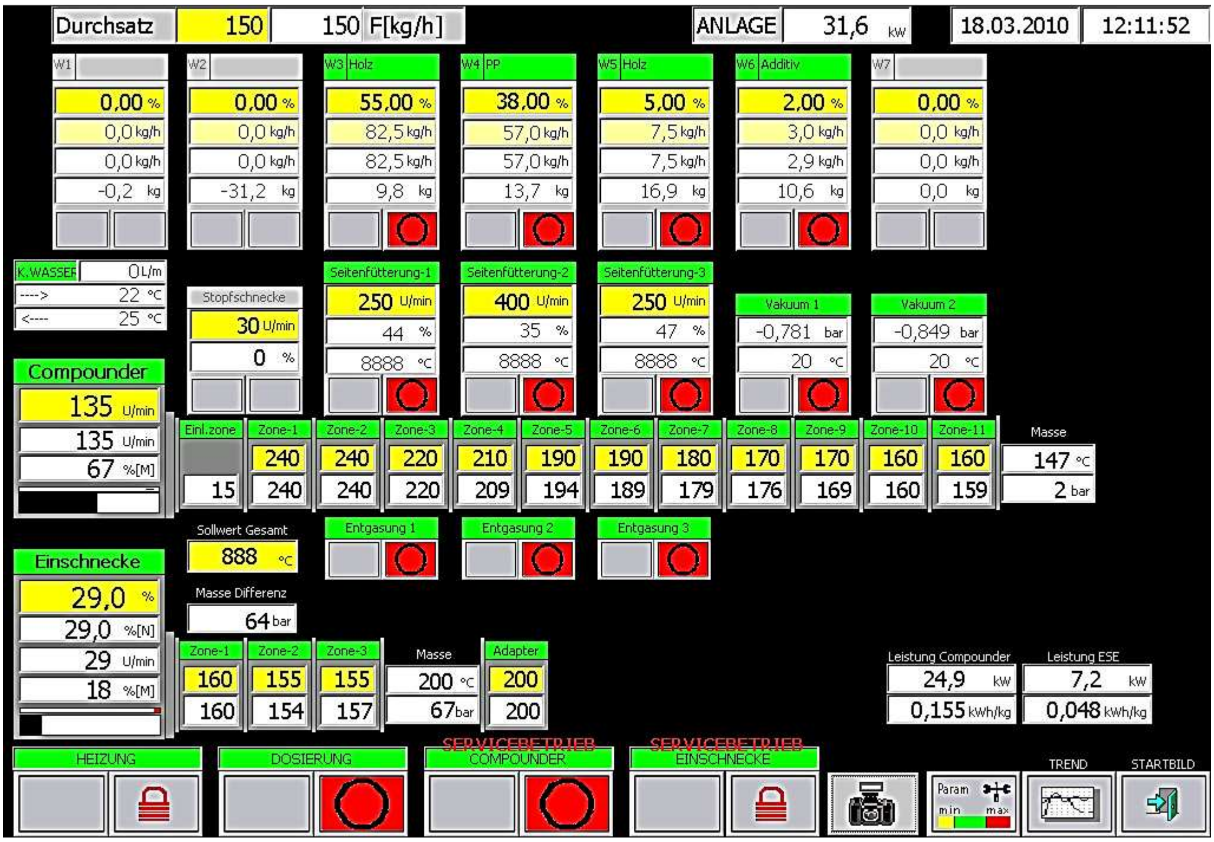
Test protocoll for the trial of the counter-rotating TSE.

Test protocol FT 58

Date	17,11,09	process engineer	Sonja Kahr	Komm. Nr.	
Extruder	T 58 fiberex	customer	WoodK+	Motor perf. (kW)	39
Mach. Number	2045259/10	column	Material	Moisture	Bulk density
Screws	T750.3N9K	1-2	HC205TF+BK40-90+Scona		
Dosing unit	TS Fiberex	3-4	PVC 6-1+BK40-90		
Granlation unit	EREMA				
Die set	Die plate8x3,5				

Column		1		2		3		4		5			6		
Time		12:15-12:41		12:45-13:12		14:54-15:20		15:25-15:51							
		set	actual	set	actual	Set	actual	set	actual			%			%
Extr.Zone 1	(°C)	195	193,5	195	194,3	195	193,6	195	194						
Zone 2	(°C)	190	190,3	190	189,9	190	190,2	190	189,9						
Zone 3	(°C)	175	175	175	174,9	175	175	175	174,8						
Zone 4	(°C)	170	170,3	170	170,2	170	170,3	170	170,3						
Adapter	(°C)	165	165	165	165	165	165	165	165,2						
Screw temp.	(°C)	130	130	130	130	130	129,7	130	130						
Granulation unit	(°C)	190	190,3	190	190,2	190	190,4	190	190,7						
Filling factor	(kg/Upmh)	4,71		4,72		4,71		4,72							
Spec.perf.	(Wh/kg)	118		125		119		125							
Screwspeed	(Upm)	25,5		31,8		25,5		31,8							
Load	(%)	61,4		65		61,5		65							
Dosing screw	(Upm)	51,1		63,6		51		63,8							
Vacuum Extr.	(-bar)	0,85		0,86		0,85		0,86							
Melt pressure	(bar)	150-180		165-185		223-232		227-235							
Melt temp 5mm	(°C)	180,4		180,3		187,4		189,9							
Deg. platification	(1-5)	1-2		2		2		2-3							
Output rate	(kg/h)	120		150		120		150							

Test protocoll for the trial of the compounder for 150 kg/h output rate (top) and 300 kg/h output rate (bottom).



Durchsatz 150 | 150 F[kg/h] | ANLAGE 31,6 kW | 18.03.2010 | 12:11:52

W1	W2	W3 Holz	W4 PP	W5 Holz	W6 Additiv	W7
0,00 %	0,00 %	55,00 %	38,00 %	5,00 %	2,00 %	0,00 %
0,0 kg/h	0,0 kg/h	82,5 kg/h	57,0 kg/h	7,5 kg/h	3,0 kg/h	0,0 kg/h
0,0 kg/h	0,0 kg/h	82,5 kg/h	57,0 kg/h	7,5 kg/h	2,9 kg/h	0,0 kg/h
-0,2 kg	-31,2 kg	9,8 kg	13,7 kg	16,9 kg	10,6 kg	0,0 kg

K.WASSER 0 L/m
----> 22 °C
<---- 25 °C

Stopfschnecke 30 U/min, 0 %

Seitenfütterung-1	Seitenfütterung-2	Seitenfütterung-3	Vakuum 1	Vakuum 2
250 U/min	400 U/min	250 U/min	-0,781 bar	-0,849 bar
44 %	35 %	47 %	20 °C	20 °C
8888 °C	8888 °C	8888 °C		

Compounder 135 U/min | 135 U/min | 67 %[M]

Einl.zone	Zone-1	Zone-2	Zone-3	Zone-4	Zone-5	Zone-6	Zone-7	Zone-8	Zone-9	Zone-10	Zone-11	Masse
	240	240	220	210	190	190	180	170	170	160	160	147 °C
15	240	240	220	209	194	189	179	176	169	160	159	2 bar

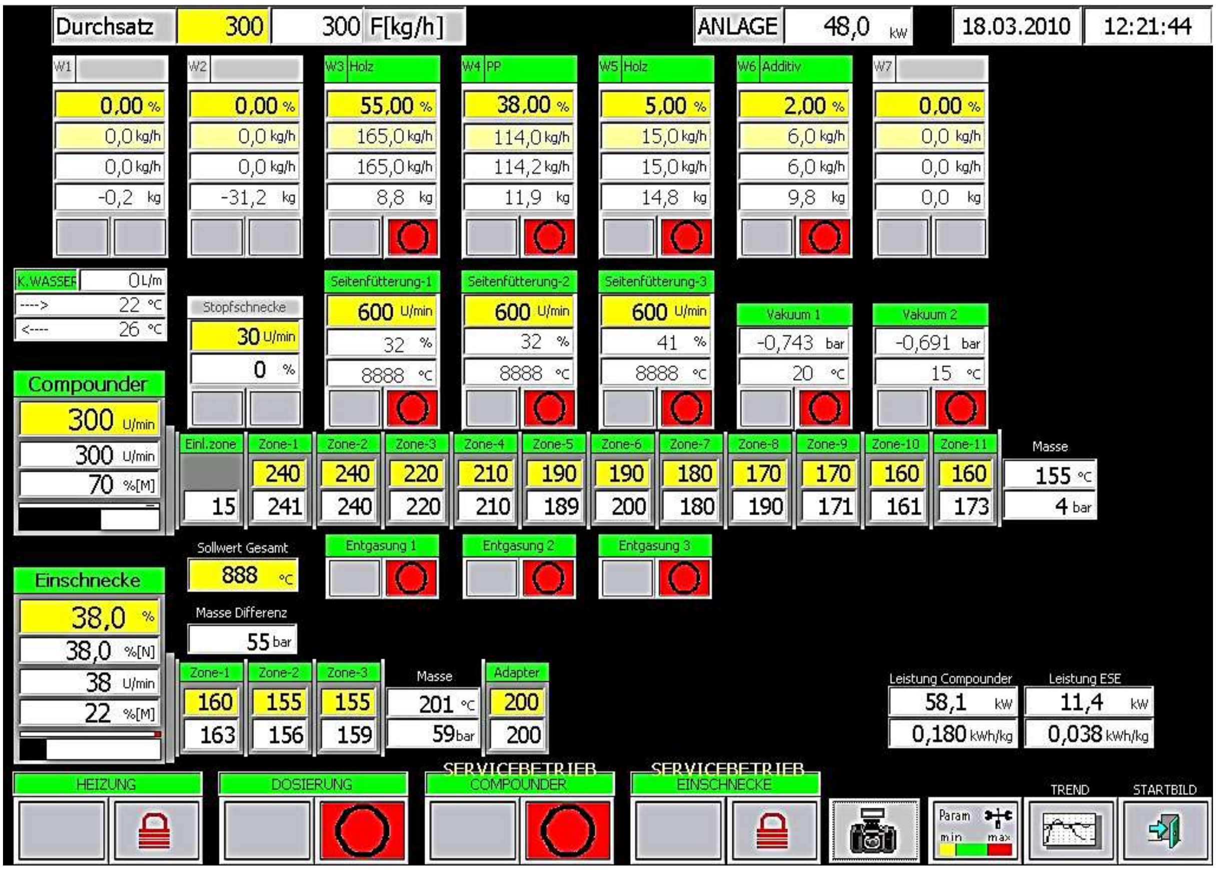
Sollwert Gesamt 888 °C

Einschnecke 29,0 % | 29,0 %[N] | 29 U/min | 18 %[M]

Masse Differenz 64 bar

Zone-1	Zone-2	Zone-3	Masse	Adapter
160	155	155	200 °C	200
160	154	157	67 bar	200

Leistung Compounder 24,9 kW | 0,155 kWh/kg
Leistung ESE 7,2 kW | 0,048 kWh/kg



Durchsatz 300 | 300 F[kg/h] | ANLAGE 48,0 kW | 18.03.2010 | 12:21:44

W1	W2	W3 Holz	W4 PP	W5 Holz	W6 Additiv	W7
0,00 %	0,00 %	55,00 %	38,00 %	5,00 %	2,00 %	0,00 %
0,0 kg/h	0,0 kg/h	165,0 kg/h	114,0 kg/h	15,0 kg/h	6,0 kg/h	0,0 kg/h
0,0 kg/h	0,0 kg/h	165,0 kg/h	114,2 kg/h	15,0 kg/h	6,0 kg/h	0,0 kg/h
-0,2 kg	-31,2 kg	8,8 kg	11,9 kg	14,8 kg	9,8 kg	0,0 kg

K.WASSER 0 L/m
----> 22 °C
<---- 26 °C

Stopfschnecke 30 U/min, 0 %

Seitenfütterung-1	Seitenfütterung-2	Seitenfütterung-3	Vakuum 1	Vakuum 2
600 U/min	600 U/min	600 U/min	-0,743 bar	-0,691 bar
32 %	32 %	41 %	20 °C	15 °C
8888 °C	8888 °C	8888 °C		

Compounder 300 U/min | 300 U/min | 70 %[M]

Einl.zone	Zone-1	Zone-2	Zone-3	Zone-4	Zone-5	Zone-6	Zone-7	Zone-8	Zone-9	Zone-10	Zone-11	Masse
	240	240	220	210	190	190	180	170	170	160	160	155 °C
15	241	240	220	210	189	200	180	190	171	161	173	4 bar

Sollwert Gesamt 888 °C

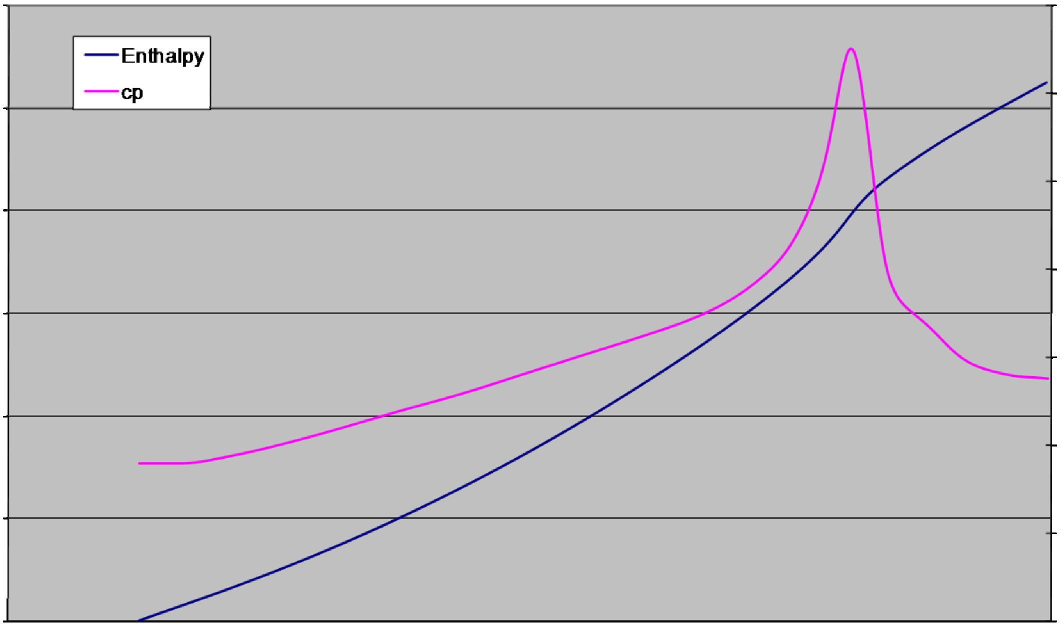
Einschnecke 38,0 % | 38,0 %[N] | 38 U/min | 22 %[M]

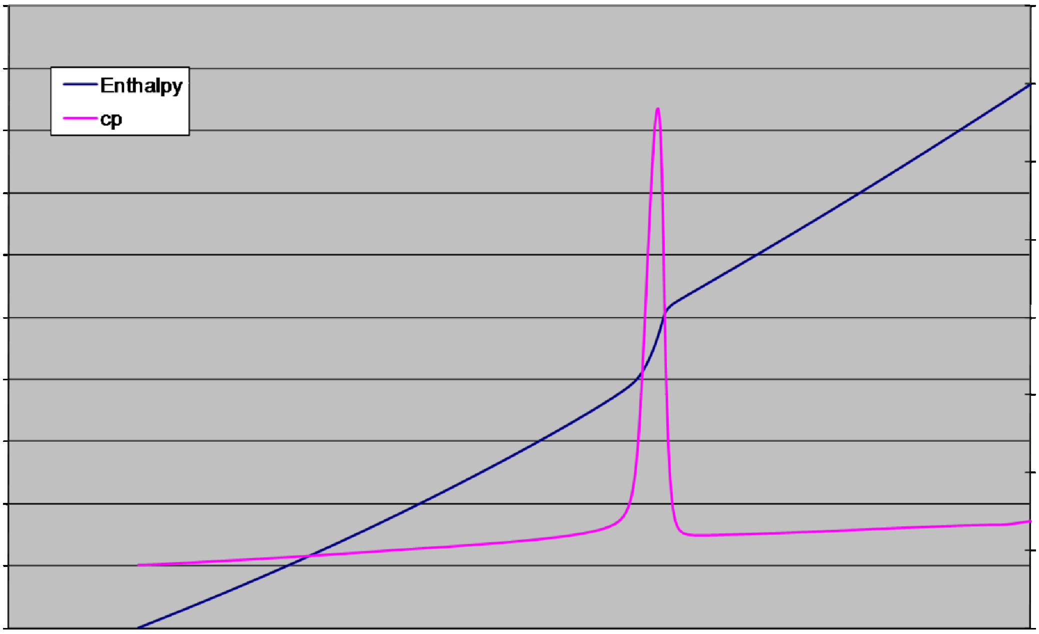
Masse Differenz 55 bar

Zone-1	Zone-2	Zone-3	Masse	Adapter
160	155	155	201 °C	200
163	156	159	59 bar	200

Leistung Compounder 58,1 kW | 0,180 kWh/kg
Leistung ESE 11,4 kW | 0,038 kWh/kg

DSC heating and cooling curves for both materials used.





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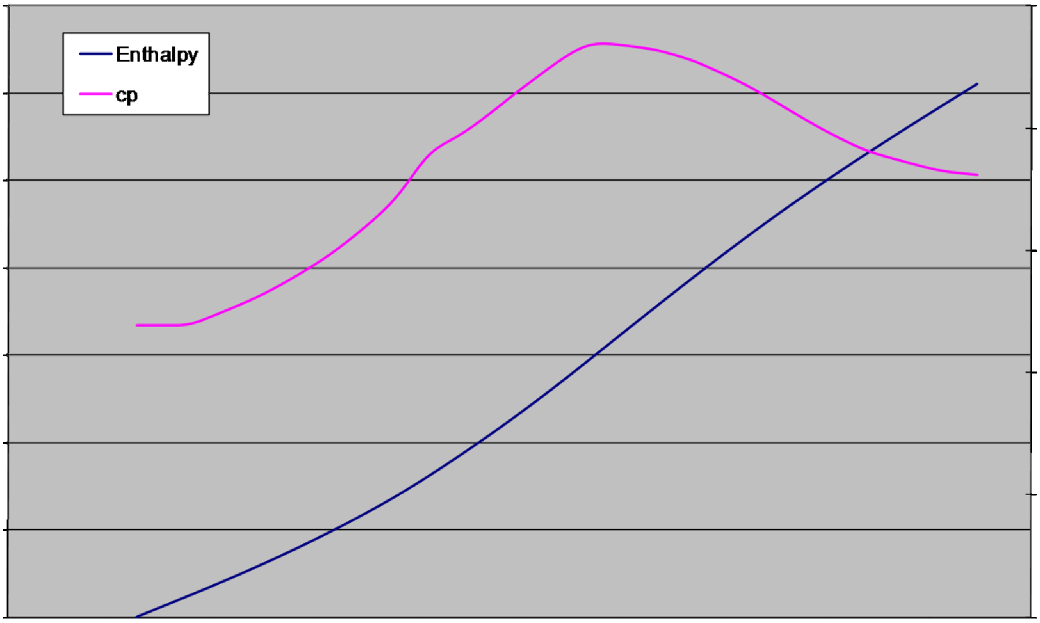
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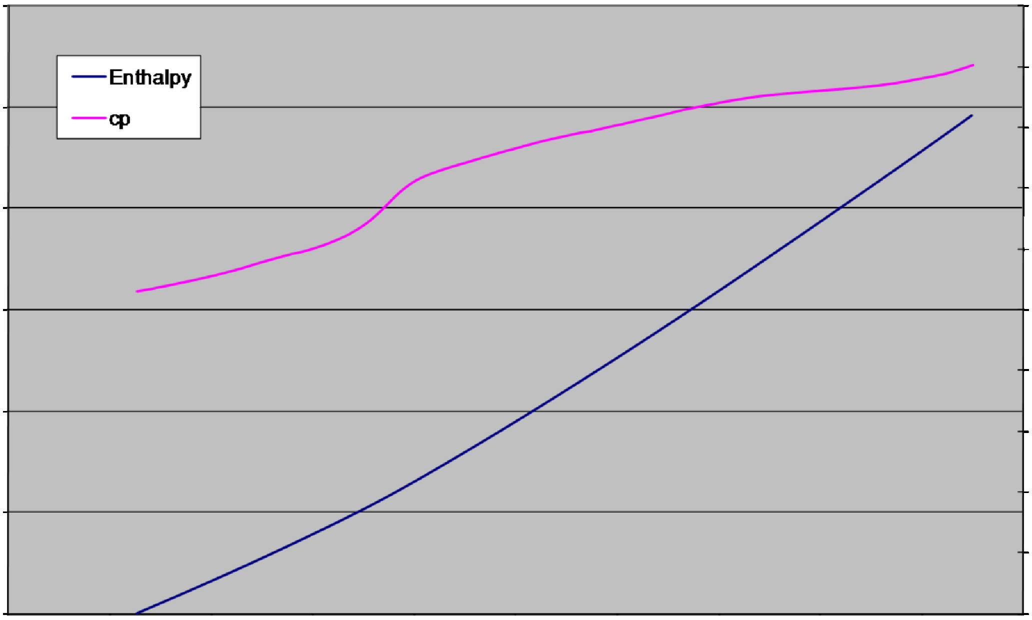
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