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Citation for published version (APA):

Ingen Housz, J. F., & Meijer, H. E. H. (1981). The melting performance of single screw extruders. II. *Polymer Engineering and Science*, 21(17), 1156-1161. <https://doi.org/10.1002/pen.760211707>

DOI:

[10.1002/pen.760211707](https://doi.org/10.1002/pen.760211707)

Document status and date:

Published: 01/01/1981

Document Version:

Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

- A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
- The final author version and the galley proof are versions of the publication after peer review.
- The final published version features the final layout of the paper including the volume, issue and page numbers.

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The Melting Performance of Single Screw Extruders. II

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In the previous paper (1) the melting performance of a number of recent screw designs was analyzed, using a rather simple theory. A new screw design was proposed. Here the results of more elaborate calculations are given in which the influence of the flight clearance and of a shear-thinning temperature dependent viscosity are investigated. The former conclusions are not altered in essence by these effects. Experimental results with a prototype screw are presented, showing that melting capacity is increased. Up to 100 percent increase in throughput is possible in the high RPM range (in comparison with a much longer traditional compression screw), provided that the feed capacity is sufficient. This usually requires the use of a grooved, well-cooled, feed section; the capacity of such a feed section depends, for a given screw geometry, on channel depth and granule dimensions. The melt leaves the melting section at a relatively low temperature. The melting section only melts the material and does not raise its temperature unnecessarily. A further step towards separating distinct tasks of the extruder by functional screw design has been made.

INTRODUCTION

The main elements which affect the melting performance of recent screw designs (1) have been known for years already.

1. The effect of taper causes a larger part of the available surface area to be used for heat transport to the solids.

2. By use of a melt separation flight the solids can be made to occupy a defined part of the screw channel. Moreover solid bed breakage is avoided and no bulk of unmolten material can pass these flights and enter a metering section or the die, therefore melt quality is improved. Screws by Barr, Dray and Lawrence, and Kim combine the melt separation flight with the maximally practical effect of taper.

3. A multichannel design decreases the average thickness of the melt film between barrel wall and solids and thereby increases the heat flux to the solids. However the channel may easily become prohibitively narrow in such a multichannel screw.

In the new screw design proposed in our previous paper (1) this channel width problem has been solved by drastically increasing the screw pitch, which by itself hardly influences the melting capacity (depending on the Brinkman number) but which increases the totally available channel width considerably and allows for a combination of the two major effects (1 and 3 above).

A reason that this last step was not taken earlier may well be, apart from pure tradition, a fear of losing

pressure generating capacity in the melting zone. However, the development of very effective entry zones for plasticating extruders, has led to a concept of feed controlled design. In this concept the feed section is relatively short, usually not over 4D long, over which length the barrel has axial or helical grooves and is very well cooled in order to prevent early melt formation due to friction. This zone is capable of building up such high pressures that the rest of the machine may be laid out in pressure consuming sections. As a result the traditional pumping zone has become superfluous. Its place is now taken by, preferably short, special mixing or shearing elements. It also means that the melting zone need no longer contribute to the pressure generation.

One limitation of the theoretical analyses in Ref. (1) is the explicit assumption of the validity of a melting model according to Tadmor (2), in which the melt film thickness is a function of the cross channel coordinate. Only in this case can the average melt film thickness be decreased by a multichannel design. In a model according to Lindt (3), for instance, melt film thickness is a function of down channel coordinate only. Here a multiple thread has no other influence on the melting process than occupying some space. In Edmondson and Fenner's model (4) the melt film thickness is basically a function of both coordinates but in working out their theory only the down channel thickness variation is maintained. If any one of these two models should occur in practice, then no improvement over the results already reached by Barr, etc., can be achieved, except

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for a small increase in dissipative heat generation. The validity of these models over the whole melting zone is questionable however. Moreover, especially when the screw pitch is increased, Tadmor's model is more or less imposed because of the increased importance and magnitude of the drag component in cross channel direction, and the relative motion between barrel and solids.

RESULTS OF IMPROVED CALCULATIONS

First, some limiting assumptions of the calculations in Part I (1) will be abandoned. The effects on calculated melting lengths of the leakage flow and of a non-constant viscosity will be shown. In this context only a global description and a presentation of the final results will be given.

Influence of Flight Clearance

The influence of the leakage flow through the gap between screw flight and barrel wall decreases the melting rate because it causes an increase of the thickness of the melt layer between solid bed and wall. In some of the eight treated screws this effect can very easily be taken into account, in other screws a (simple) numerical approach is required. In the program that is written also earlier restrictions, like the neglect of the influence of $\cos \phi$ in ξ , are removed. The results are found in Fig. 1, which shows a kind of aging process for

Fig. 1. Newtonian solution of calculated melting lengths as a function of flight clearance δ , relative to that of the standard screw with $\delta = 0$. $D = 60$ mm. 1. Standard, 2. Compression, 3. Multichannel, 4. Maillefer, 5. Barr, 6. Dray & Lawrence, 7. Kim, 8. New concept.

extruder screws: the influence of an increased leakage gap (by wear for instance) on the required melting length for a 60 mm diameter extruder. Melting lengths are given, relative to that of the standard screw with $\delta = 0$, for the screws turning at 80 RPM giving 80 kg/h LDPE, resulting in a Brinkman number of 0.47 and a feed coefficient $K = V_{sz}/V = 0.27$.

It is shown (Fig. 1) that melting lengths increase considerably for all screws when the clearance increases.* For all screws where only the taper effect is used, the leakage flow influence is relatively less than for the standard screw. For the two screws where (also) the multichannel effect is used (Fig. 1, curves 3 and 8), the influence is relatively larger. This is obvious, because the improvement caused by more channels is a result of a decrease in melt film thickness and it is exactly this melt film thickness which is now increased again by the leakage flow. Overall the new screw concept remains promising. For higher values of the flight clearance δ the differences between this screw and the others become somewhat smaller.

Influence of Shear Thinning

So far, all considerations have been based on a simple Newtonian approximation. The shear thinning, temperature dependent viscosity has an important influence on the melting process and therefore also on calculated melting lengths. The use of a non constant viscosity requires a numerical treatment because the equations of motion and energy are coupled in this case.

As in Part I the most direct model is used, neglecting the secondary melting processes on the screw and the flights, only comparing the screws based on differences in the melting performance of the more important upper melt film. The solid bed is considered as being semi-infinite. The solid bed velocity in channel direction is assumed to be constant. Barrel and screw temperatures are taken constant. With these assumptions the melting rate over a given width of the solid bed is independent of the down channel coordinate. The Maillefer screw (changing V_{sz}) and the Kim screw (changing pitch) are not considered any more. From the big number of possible compression screws the lower limit of the extreme tapered screw (no room for melt discharge) is chosen.

Convection terms in the melt film are taken into account. A coordinate transformation is used as suggested by Pearson (5). The energy equation becomes somewhat more complicated but the boundary conditions at the important solid-melt interface now can be brought in correctly. More details and a discussion of the important assumptions mentioned above are given in Ref. (6). The results are presented in Fig. 2, in which also the results of the Newtonian calculations are given for comparison.

The numerical solutions give melting lengths which are larger by 20 to 30 percent in comparison with the (Newtonian) analytic results. The effect is not the same for all screws. The relative differences change some-

* In the standard (curve 1) and multichannel (curve 3) screw melting length is reached, according to a definition, when still 1 percent of the material is unmolten. This lower limit is needed in these cases to prevent melting lengths being infinite.

Fig. 2. Power law solutions of calculated melting lengths as a function of flight clearance δ , relative to that of the Newtonian solution of the standard screw with $\delta = 0$. $D = 60$ mm. Dotted lines: Newtonian solutions. 1. Standard, 2. Dray & Lawrence, 3. Extreme tapered, 4. New concept.

what as does the influence of the flight clearance. The most important conclusion of these analyses is, however, that the relative melting performances of the screws remain in the same order, as that which followed from the analytical treatment.

THEORETICAL EXTRUDER CHARACTERISTICS

With the aid of numerical methods, the melting capacity (in kg/h) of a given screw can be calculated at different screw speeds. Because rather important effects as heating of the solids and melting on the screw surfaces are still neglected, an underestimation of the melting performance will be made. However, provided that those effects will be roughly of the same order for the different screws, at least the qualitative results can be useful to an evaluation of the experiments.

Three screws were analyzed: a standard constant depth screw, a compression screw and a prototype of the newly developed screw. Geometries are given in Table 1, the last two screws are shown in Fig. 3. The length of the melting section is taken as a parameter. Melting is assumed to start at $5D$ from the hopper, resulting in an available melting length of $11D$ ($3D + 8D$) or $19D$, as the melting process may continue in the metering section. In the new screw the melting process must be finished where the melt separation flight ends. Here axial lengths of $4D$, $8D$, $12D$ and $16D$

Fig. 3. Traditional compression screw (1) and a prototype of the new screw with a $7\frac{1}{2}D$ melting section (2).

are chosen. Figure 4a gives the results. The curved lines are characteristic. At low screw speeds the heat supply by dissipation is diminished but that by conduction remains, giving a large enough melting capacity. In Fig. 4b two (experimental) feed characteristics are given for a smooth and a grooved feed section. Here straight lines are characteristic as is the much higher throughput of the grooved feed section. Combination of Figs. 4a and 4b yields Fig. 4c—the overall extruder characteristics.

For the grooved feed section at low screw speeds and for the smooth barrel in the whole region, melting capacity of the screws used is generally sufficient and extruder output is determined by the feed section. Using the grooved barrel at higher screw speeds, throughput is much higher, the melting capacity forms a limitation at a point which depends on the screw used. Beyond this point throughput should be decreased.

An autogenous regulating system exists in traditional extruders: the pressure. If the melting capacity is limited then also relatively cold material reaches pumping and homogenisation sections and the die. A higher pressure is needed to force it through. The higher pressure required at the end of the feed section decreases the throughput thereof and a new working point is found. The result is a curved $Q-N$ plot. There is no guarantee that the whole throughput will be completely molten.

For the grooved feed section, however, throughput is largely independent of the required pressure over a wide range. Throughput cannot be adapted, except under conditions of very high operating pressure, close to the pressure at which the transport mechanism breaks down due to melt formation at the barrel. Unmolten material will reach the die.

Two measures can be taken to prevent a situation in which throughput of the feed section exceeds the melting capacity: a decrease of feed capacity by a decrease of

Fig. 4. Calculated melting capacity of screws with different geometry and different length of the melting section as a function of screw speed (a). Feed characteristics (b). Extruder characteristics (c).

Table 1. Screw Geometries

Screw	Description	Total length	Feed section			Melting section			Metering section	
			Length	Depth (mm)	Pitch angle	Length	Pitch angle	Number of channels	Length	Depth (mm)
0	standard	24D	8D	6	17°40'	8D	17°40'	1	8D	6
1	compression	24D	8½D	6.7	17°40'	8½D	17°40'	1	7D	2.7
2	new concept	16D	8½D	7.2	17°40'	7½D	60°	3	—	—

channel depth for instance or an increase of melting capacity by a longer melting section or improved screw design.

EXPERIMENTAL EXTRUDER CHARACTERISTICS

On a 60 mm extruder the overall melting performances of screws 1 and 2 are compared. Results are presented in the Q - N curves of Fig. 5. Three different materials are used: low density polyethylene (LDPE) Stamlyan 1510, high density polyethylene (HDPE) Lupolen 5261 Z and polypropylene (PP) Shell J 6100. The results are clear.

Smooth Feed Section

When the smooth barrel is used (lines: s) hardly any differences in throughput between the screws are found. Feed capacity is restrictive, melting capacity is sufficient in both cases. The results of HDPE are missing because of feed problems. With a former prototype with a melting length of 4D only (and pitch angle 90°) the same throughputs were already reached which shows that for a given output melting length and therefore screw length may be decreased. This result is reached despite of the poor pressure generating capacity of the smooth feed section. This raises the question whether pumping capacity of the melting section could be sacrificed in favor of melting capacity without restricting the throughput too much (HDPE!).

Grooved Feed Section

The development of the new screw is based on the high throughput and capacity of pressure generation of grooved feed sections. The results are according to the expectations (lines: g in Fig. 5). Beyond screw speeds of about 50 RPM an increase of throughput is found from

25 percent (LDPE and PP) up to 100 percent (HDPE), only by using the new screw. This shows that the restriction on throughput caused by insufficient melting capacity, discussed in section 2, has been removed. According to the straight lines melting capacity is sufficient and feed capacity determines the overall throughput. This statement is confirmed by an investigation of the feed section by itself. The dotted lines in Fig. 5 represent the maximal transport capacity of the feed section for these materials having these granule shapes. The lines are obtained with a simulated characteristic backpressure and measured in the absence of a die (the material did not have to melt).

In contrast to screw 1, the new screw 2 tends to melt all material which can be transported by the feed section. Of course one can still ask why throughputs of different materials differ so much. A separate investigation of the performance of the feed section gives the explanation.

The dimensions of the granular feedstock prove to be of paramount importance. In Table 2 the dimensions are given of the three materials already used and of LDPE 1523 SX, which has replaced LDPE 1510, PP GT 6200 and HDPE Stamlyan 8109. In Fig. 6 the feed characteristics of these materials are presented. Three screw parts are used with lengths 8D and channel depths 5, 7, and 9 mm respectively. Upon the screw ends restrictions can be mounted with different diameter leaving a wider or smaller annular gap inside the barrel, to change the backpressure. An increase of backpressure up to 40 MPa has no influence on these lines. There above throughput decreases sooner or later, depending on the material (first: LDPE), channel depth (first 9 mm) and screw speed (first: $N = N_{max}$, of course). From Fig. 6 it follows that the larger granules are preferred by the feed section used and that the slopes of the lines in the Q - N plot are determined by the granular dimensions. The performance of screw 2 has been measured again using the larger granule materials. Figure 7 compares the results with those of the

Fig. 5. Measured throughput as a function of screw speed, with the grooved (g) and the smooth (s) feed section for three materials. Comparison of the performances of screws (1) and (2). Dotted lines: maximal transport capacity of the feed section for $h = 7$ mm.

Fig. 6. Measured feed characteristics for the grooved feed section. Throughput as a function of screw speed for four different materials using three screws of 5, 7 and 9 mm, respectively. 1. LDPE Stamlyan 1510, 2. PP Shell GT 6200, 3. LDPE Stamlyan 1523 SX, 4. HDPE Stamlyan 8109.

Table 2. Some Material Properties*

Material	Specification	M.I. (g/10 min)	Density ρ_s (kg/m ³)	Granule dimensions	
				d (mm)	h (mm)
LDPE	DSM Stamylen 1510	1.7	918	2.7	2.5
	DSM Stamylen 1523 SX	2.0	922	4	3
HDPE	Basf Lupolen 5261 Z	1.7-2.3	950	3.5	4
	DSM Stamylen 8109	14	953	± 3	5
PP	Shell J 6100	2.0	905	3	2
	Shell GT 6200	0.8	905	3.5	3

* The shape of the feedstock is cylindrical with diameter d and height h.

materials used before. For LDPE an increase in throughput is found indeed and throughputs now are similar to those of HDPE. For PP GT 6200 an increase is found for screw speeds up to 60 RPM. Thereabove the melting capacity is not sufficient, the required adaptation is too big, the pressure becomes too high and the feed mechanism collapses. For PP of this granule size therefore longer melting sections than the $7\frac{1}{2}D$ used in the prototype screw are required in order to allow higher operating speeds than about 60 RPM.

MASS TEMPERATURES

Of course the new concept also is tested under different operating conditions. Die pressure variations from 5 up to 40 MPa show that throughput is largely independent of the required pressure at the end of the screw (a small decrease at high screw speeds only). Therefore one is rather free in die design. The mass temperatures, measured by six thermocouples inside the channel (diameter 50 mm) connecting extruder to die, are shown in Fig. 8. Although variations across the channel are found, the profiles are rather flat and, more important, the temperatures are low, especially for PP and HDPE, only 10-20°C above the melting temperature (for LDPE the wall temperature apparently was too high). This is an important result. The melting section only melts the material and does not raise its temperature unnecessarily. This may be due to the extremely short residence time of the melt in the discharge chan-

nels (at high screw speeds the average velocity there is of order 0.2 m/s).

Another possible explanation would be that unmelted material is squeezed over the separation flight. The high pressure drop over this flight, observed for HDPE and for PP, of 200 to 400 bar, appears to corroborate this suspicion. For LDPE the pressure drop, even at maximum rpm, remains below about 100 bar.

Cooling tests, followed by microscopic investigation of cross-sections from a discharge channel, do not yield any further insight in the case of LDPE or HDPE. For PP however a "cloud" of different structure is visible, entering the channel over the separation flight. In this cloud a fine spherulitic structure is observed whereas the rest of the cross section shows no structure at all. This may indicate an influx of material which is only partially melted.

The extrusion process may now be designed much more economically. If desired, the remaining temperature differences may be decreased with static or rotating mixing elements. If necessary, the temperature may be increased by an increase of wall temperature or by use of shear elements. The extra pressure needed can be generated in the feed section without restricting the throughput.

CONCLUSIONS

Theoretical extruder characteristics help to understand those found in experiments and do indicate whether the feed section or the melting section capacity is limiting the extruder throughput. Theory underestimates the melting capacity because still some important effects are neglected in the model used.

A considerable increase in throughput of the extruder for a given screw speed (up to 100 percent) can be achieved by appropriate screw design. Moreover distinct screw parts function as intended. The feed section

Fig. 7. Measured throughput of the new screw (2) as a function of screw speed using the grooved feed section. Comparing two LDPE's with different granule shape (a), PP and HDPE (b).

Fig. 8. Measured mass temperature profiles using screw (2), for different materials with the screw speed as a parameter.

feeds and generates pressure; throughput depends on channel depth and granular dimensions. The action of the melting zone is restricted to melting. The material is delivered at a temperature not much above the melting temperature and no extra heating of the melt takes place. Only melt, free of solids, passes the melt separation flights and enters the die (or mixing etc. sections, if provided). Temperature of the melt may be increased, where required, in a controlled manner by the use of appropriate shear elements which, as well as the die, may have a relatively high resistance without restricting the throughput.

A further step towards separating individual screw functions is made. This improves the possibilities of functional screw design, as each section may be designed to perform its specific function with maximal efficiency.

OUTLOOK

Current practice (especially in Germany) is to use grooved barrel feed section for nearly all extruders up to about $D = 120$ mm. For large extruders, $D \geq 150$ mm, the use of grooved barrels is less usual. This is a result of the existing experience that grooved barrels are effective only for rather shallow channels, e.g. not more than 5 mm for PP and about 6 mm for HDPE in 60 mm diameter machines and at the best very little more in larger machines (7). Based on our investigation of the grooved feed section separately, as reported above, this cannot be considered as a property of such feed sections but rather as a result of the fact that melting sections of insufficient capacity have been used.

Apparently, even the $L/D = 30$ screws which Fischer used for his investigation provided insufficient melting capacity, so that the capacity of the feed section had to be kept artificially low by using a shallow channel. With the new melting device the required melting lengths for screws with deeper feed channels are available within the normally acceptable screw length of $L = 24D$. As a result output of such machines is expected to scale with the square of the diameter of the screw, as for conventional smooth barrel machines, instead of at the low power of 1.6 reported by Fischer (7).

The higher output resulting from deeper feed channels will reduce the specific power consumption of the grooved feed section, in addition the use of a helically grooved barrel may result in a further considerable reduction of frictional heat generation according to Grünschloss (8). This high output at comparatively low screw speed, coupled with the stiff feed characteristic of the grooved feed zone should make it possible to approach some of the operating advantages of twin screw machines while retaining the much more attractive simple construction of the single screw machine.

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