Screw design and melting performance in single screw extrusion

SCREW DESIGN AND MELTING PERFORMANCE IN SINGLE SCREW EXTRUDERS

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The melting performance of the more important recent screw designs is investigated. At first a comparison is made based on Tadmor's most simple newtonian theory. A classification is possible because a trend is recognized in screw development. As a result thereof a new concept is proposed. The outcomes of more elaborate calculations are given and some prototypes presented. Experimental evidence shows that a further step is made to functional screw design.

INTRODUCTION

The development of very effective entry zones for single screw plasticating extruders over the last 10-12 years, has led to a concept of feed controlled design for all but the very largest machines. In this concept the feed zone is relatively short, usually not over 4D in length, 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. This means that the traditional pumping zone has become superfluous, except for the second step in venting extruders. Its place is now taken by, preferably rather short, special mixing elements.
It also means that the melting zone need no longer contribute to the pressure generation.
Even though melting theory has been well developped since Tadmor's 1966 publication (1) and elaborate simulation programmes have been written for this zone, this work has not led to any considerable innovation in design. This is the more surprising as the main elements for the new design which we shall

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propose have been known for more than a dozen years already. These elements are the effects of taper, of multichannel design and of melt separation as first proposed by Maillefer. In order to combine these various effects it is necessary to increase the pitch angle considerably over the traditional square pitch. The reason that this step was not taken earlier may well be, apart from pure tradition and fear of losing pressure generating capacity, the fact that an increase in pitch by itself hardly effects melting performance. Only its effect on dissipative heat generation may be of some importance in the case of high Brinkman numbers.

MELTING PERFORMANCE

Using Tadmor's analyses in which of course his original assumption of constant meltfilm thickness is corrected in accordance with Vermeulen et al (2), the resulting equation is

$$\frac{d}{dz}(\rho_s V_{sz} H X) = \xi X^{\frac{1}{2}} \quad (1)$$

The change of solids mass flow equals the melting rate over a down channel distance dz. V_{sz}, H and ρ_s are assumed to be constant. The expression for ξ is

$$\xi = \left[\frac{\lambda_m (T_b - T_m) + \frac{1}{2}\mu V_b^2}{c_s (T_m - T_h) + \Lambda} \rho_m V \sin\phi\right]^{\frac{1}{2}} \quad (2)$$

$$V_b^2 = V^2 + V_{sz}^2 - 2 V V_{sz} \cos\phi \quad (3)$$

Solution of eq. (1) with the boundary condition X = W at z = 0 gives the solid bed profile

$$\frac{X}{W} = \left(1 - \frac{\psi z}{2H}\right)^2 \quad (4)$$

$$\psi = \frac{\xi}{V_{sz}\,\rho_s\,W^{\frac{1}{2}}} \quad (5)$$

With the second boundary condition X = 0 at $z = Z_{st}$, the melting length of this standard screw follows directly form eq. (4)

$$z_{st} = \frac{2H}{\psi} \quad (6)$$

Given a specific material and operating conditions, all material properties are given and barrel temperature and velocity are fixed. Also with this simple theory we can investigate the effect of geometrical changes on the melting length needed. Three measures will be treated: 1. Decreasing channel depth 2. Multiplying the number of channels and 3. Increasing the screw pitch.

1. In a compression screw a larger part of the available surface area is used for heat transfer to the solids. The effect on melting length can easily be shown. Combination of eqs. (1) and (4) learns that the melting rate in the standard screw decreases linearly in channel direction z, from $\xi W^{\frac{1}{2}}$ to 0. Keeping the melting rate constant and exactly on the maximum value which it has at the start of the melting process, only one half of the melting length is needed $Z_c = \frac{1}{2} Z_{st}$.
This could be achieved by keeping X = W, thus preventing the decrease of solid bed width X.
The molten mass now is not being replaced by a decreasing solid bed width, but by a decreasing solid bed height. A compression screw tries to reach this one half of the standard melting length but will never reach it because in this extreme the whole screw is filled with solids, there is no place available for a removal of molten material in a meltpool.
2. The effect of a multiple channel screw follows directly from a combination of eqs. (5) and (6). Neglecting the flight widths the channel width W decreases $W_n = 1/n\ W_{st}$, where n is the number of channels, and therefor $Z_n = n^{-\frac{1}{2}} Z_{st}$.
This is due to the smaller average meltfilm thicknesses.
3. An increase of screw pitch angle has a number of consequenses. As $W/W_{st} = \sin\phi/\sin\phi_{st}$, it increases channel width and, as a consequence, decreases solid bed velocity $V_{sz}/V_{sz\ st} = \sin\phi_{st}/\sin\phi$. The value of the auxiliary quantity ξ increases, see eqs. (2) and (3) as $\sin\phi$ increases and as V_b increases with decreasing $\cos\phi$ and V_{sz}. The increase in $\sin\phi$ causes an increase of the transport capacity of the drag flow across the meltfilm. The increased drag flow results in a lower meltfilm thickness, therefore in a higher rate of heat transfer to the solid-melt interface. The increase of V_b causes a higher dissipative heat generation $\frac{1}{2}\mu\ V_b^2$, also resulting in an increase of melting rate. Neglecting this effect of dissipation, $\xi/\xi_{st} = (\sin\phi/\sin\phi_{st})^{\frac{1}{2}}$. Finally, the same helical length Z now requires a greater axial length L as $L = Z \sin\phi$. Substituting these various effects in eqs. (2), (5) and (6) yields the interesting result that the pitch angle has no influence on the calculated axial length.

The effect of ϕ in solid bed velocity is offset exactly by its effect on axial vs. helical length while the effect of the wider channel is compensated by the more effective removal of molten material from the meltfilm.

SCREW DESIGN

In figure 1 a number of different screw designs is shown. The standard constant depth screw (a) is not very usefull and gives the longest melting lengths. An improvement is the compression screw (b). The multichannel screw (c) is not popular because difficulties may arise with the continuous supply of solid material into the narrow channels. The Mailleferscrew (d) is the first to use a melt separation principle by providing an extra screw flight with a somewhat larger clearance with the barrel. No solids can pass, only melt. It does not decrease melting length considerably. The screws by Barr (e), Dray & Lawrence (f) and Kim (g) all use this melt separation principle. Each gives a different solution to create room for a melt discharge channel in his attempt to reach $Z = \frac{1}{2} Z_{st}$ of the extreme tapered screw.
As argued above a change of screw pitch does not influence the melting length. The dissipation increases but its effect, which depends on the Brinkman number, is still neglected. The increased channel width, however, allows us now to combine the two major effects $\frac{1}{2}$ of the extreme tapered screw and $n^{-\frac{1}{2}}$ of the multichannel screw without resulting in prohibitively narrow channels. Exemple (h) achieves a melting length which is essentially below those of all other screw designs $L/L_{st} = \frac{1}{2} n^{-\frac{1}{2}}$. The increased screw pitch sacrifices pressure generating capacity to melting capacity. In the extreme case, $\phi = 90^{\circ}$, the melting section is a completely passive pressure using element, a development analoguous to the one in the metering section. Calculations show that the graph of melting length versus pitch angle is rather flat between 45° and 90°. The calculated optimum number of channel pairs for a 60 mm extruder, taking into account flight widths, is about 10. We must, however, realize that smaller pitch angles and more channel pairs reduce the inlet channel width, which inhibits flow of solids into these channels. Figure 2 shows some possible examples of this new concept.

The results of more elaborate calculations, taking into account a.o. screw clearance, powerlaw behaviour and convective heat transport in the meltlayer, are plotted in figure 3. It shows the absolute melting lengths of some of the screws discussed before as a function of screw clearance, thereby showing the calculated effect of wear for the various screws. In all cases the new concept (three channel pairs; $\phi = 60^{O}$) is superior.

EXPERIMENTS

The results of the comparison of two screw types for a 60 mm extruder are given in figure 4 which shows the throughput as a function of the screw speed.
Screw 1 is a traditional compression screw, length 24 D, divided into three sections of equal length 8 D; the channel depth in the feed section is 6.7 mm, in the pumping section it is 2.7 mm, the compression ratio being 2½.
Screw 2 equals the new screw concept of figure 2b, the length of 16 D is divided into two sections, an 8 D feed section with a channel depth of 6.7 mm and an 8 D melting section, divided into three channel pairs with a pitch angle of 60^{O}. Shear and mixing elements are omitted, a special short barrel is used. Because of the melt separation flights only molten material can reach the die, while in the traditional screw 1 unmolten material may reach the extra 8 D length of the pumping section and may even reach the die.
Results are given for three materials LDPE, PP and HDPE and for two feed sections, a traditional smooth bore barrel and an axialy grooved one. The dotted lines give the maximum transport capacity of the feed sections for these materials with these granule shapes working with a simulated characteristic back pressure and measured in the absence of a die (the material did not have to melt). The conclusions of figure 4 are clear. Only with the grooved feed section big differences arise.
In contrast to screw 1 the new concept of screw 2 tends to melt all material which can be transported by the feed section. In some cases (PP) a somewhat longer melting section is required at high screw speeds, in other cases (HDPE) a real spectacular increase in throughput is observed (100%). In all cases the average temperature of the melt of screw 2 was 10 - 20^{O}C above the melting point of the material and much lower then the melttemperatures of screw 1.

CONCLUSION

A new concept with a radically improved melting performance compared to existing screws has been proposed and tested. A prototype screw demonstrates that for a correct melting zone design the output of feed zone, over a large range of screw speeds, may be molten homogeneously without restricting this output. The action of the melting zone is restricted to melting, the molten material is delivered at a temperature not much above the melting temperature and no extra heating up of the melt takes place. Only melt, free of solids, passes the melt separation flights and enters the die (or mixing etc. sections, if proveded). 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 maximum efficiency.

SYMBOLS USED

c_s = specific heat (J/kg K)

H = channel depth (m)

L = axial melting length (m)

n = number of channels (-)

T_b = barrel temperature (K)

T_h = hopper temperature (K)

T_m = melting point (K)

V = relative velocity between barrel and screw (m/sec)

V_b = relative velocity between barrel and solids (m/sec)

V_{sz} = solid bed velocity (m/sec)

W = channel width (m)

X = cross channel solid bed width (m)

z = channel direction (m)

Z = helical melting length (m)

ϕ = pitch angle (rad)

ξ = auxiliary quantity in mass balance eq. (1) ($kg/m^{3/2}$ sec)

λ_m = coefficient of heat conduction (J/m sec K)

Λ = latent heat of fusion (J/kg)

μ = viscosity ($N\ sec/m^2$)

ψ = auxiliary quantity in eq. (5) (–)

ρ = density (kg/m^3)

indices

s = solids

m = melt

b = barrel

h = hopper

c = compression

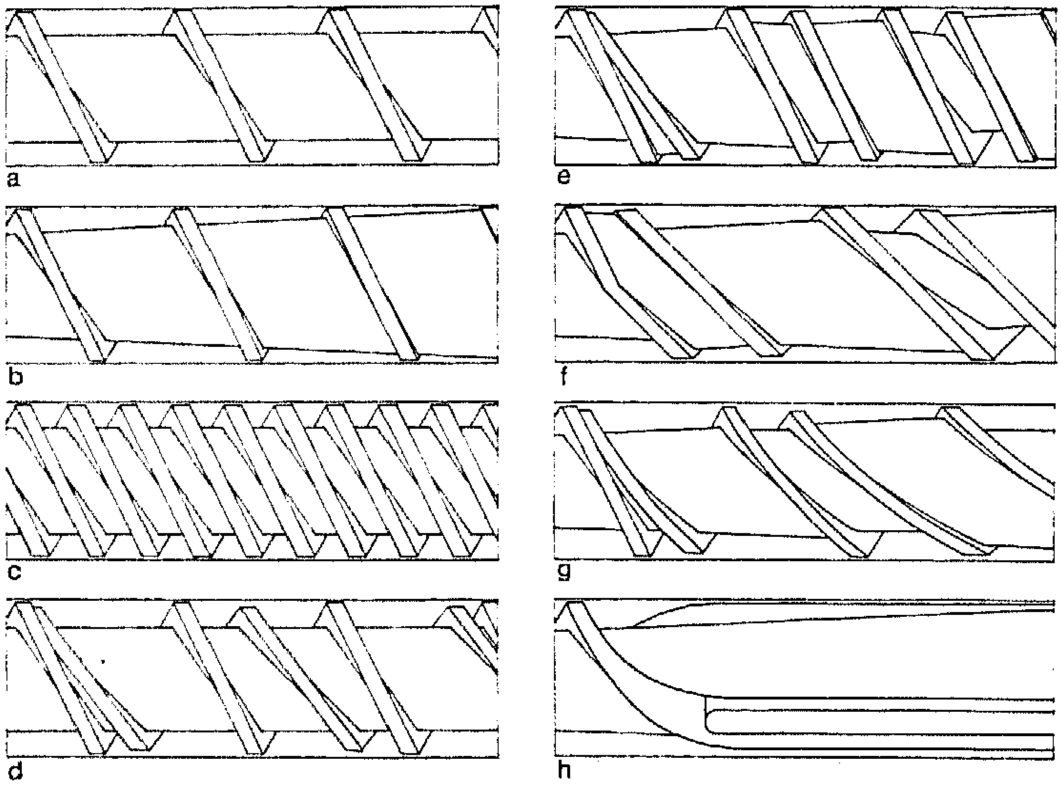
n = multichannel

st = standard

REFERENCES

1. Tadmor, Z., 1966, Pol. Eng. Sci., 6, 185.

2. Vermeulen, J.R., Scargo, P.G., Beek, W., 1971, Chem. Eng. Sci. 46, 1457.



a	Standard constant depth screw				
b	Compression screw				
c	Multichannel screw				
d	Maillefer screw	Swiss Pat.	363.149	Appl.	31-12-1959
e	Barr screw	U.S. Pat.	3.698.541	Appl.	11-08-1971
f	Dray & Lawrence screw	U.S. Pat.	3.650.652	Appl.	05-05-1970
g	Kim screw	U.S. Pat.	3.867.079	Appl.	10-08-1972
h	New concept	Netherlands Pat.		Appl.	7702020, 25-02-1977

figure 1. Different screw designs

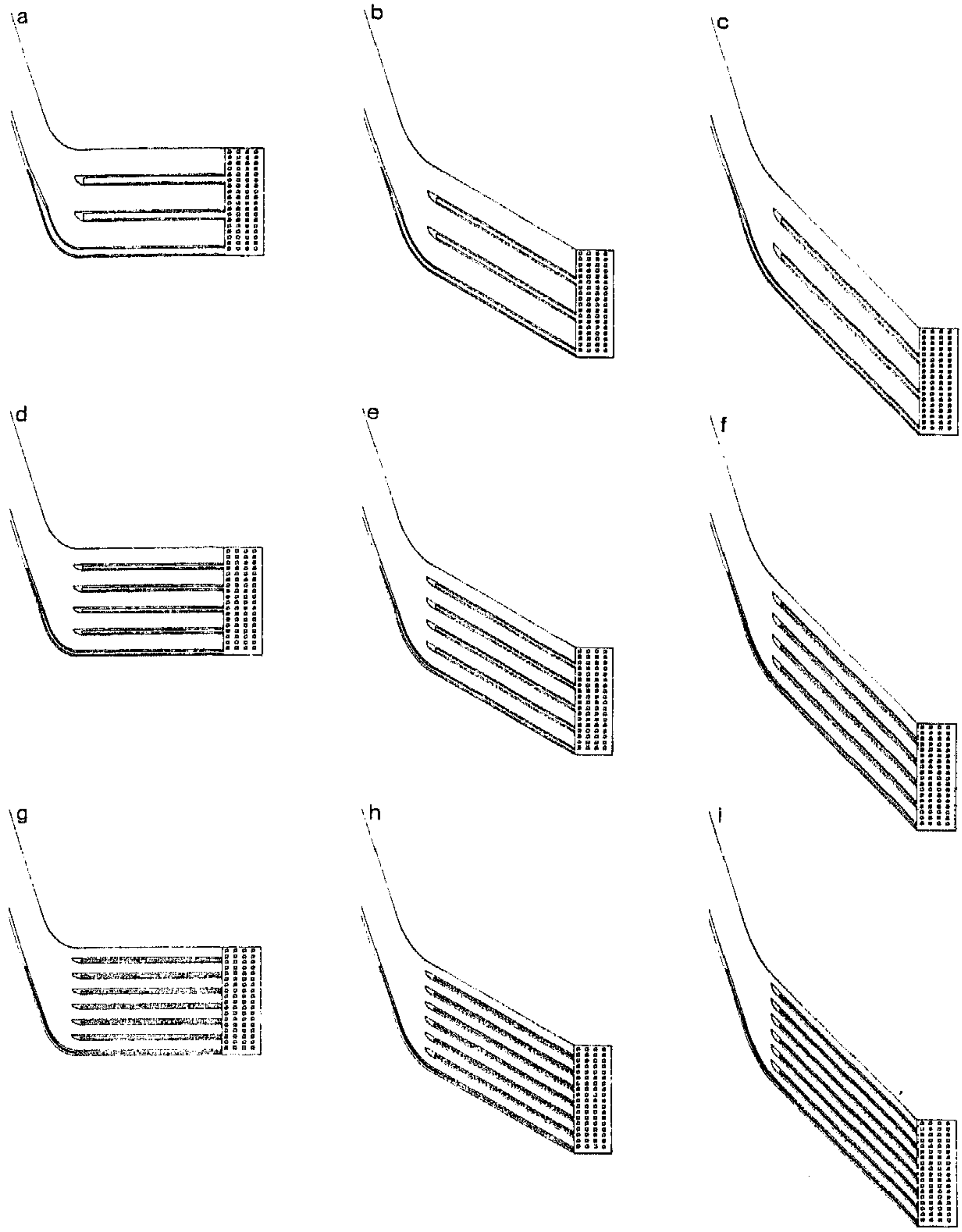
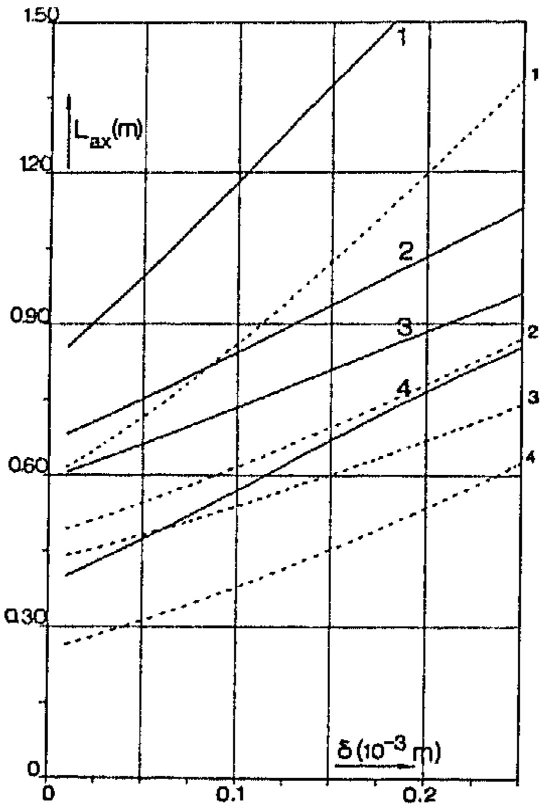
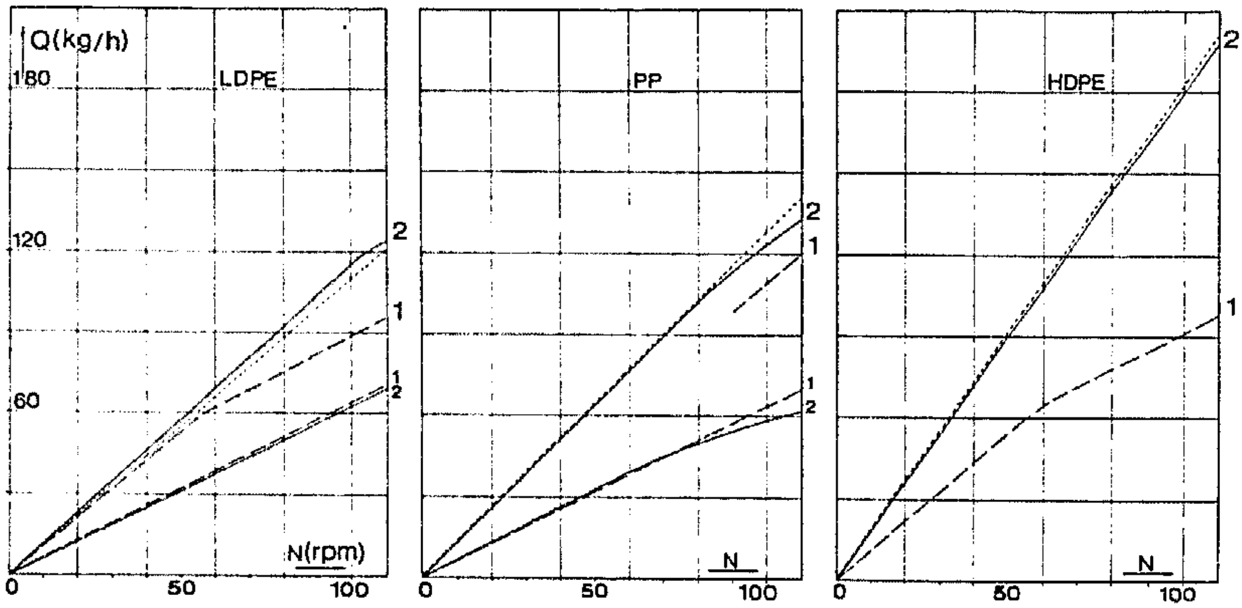


figure 2. Some exemples of the new screw concept



1 Standard screw
2 Dray & Lawrence screw
3 Extreme tapered screw
4 New concept
Dotted lines: newtonian solutions

figure 3. Calculated absolute melting length as a function of screw clearance



1 Traditional compression screw
2 New concept
Dotted lines: maximum transport capacity of the grooved feed sections

figure 4. Measured throughput as a function of screw speed