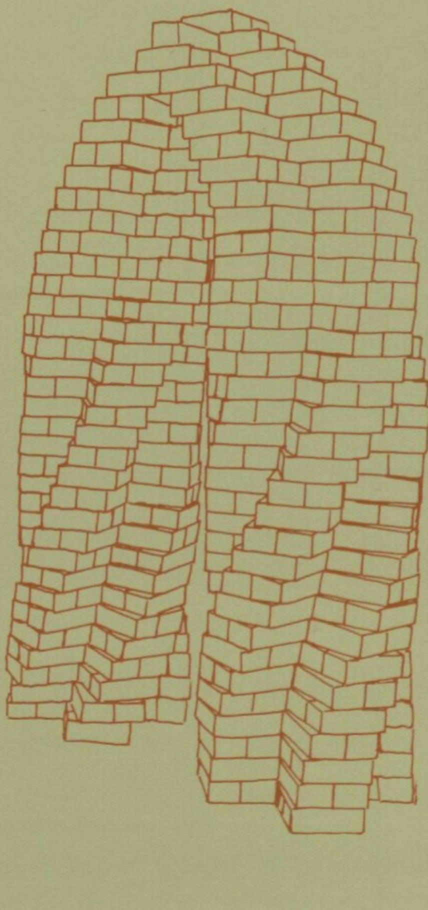
RESIDENCE TIME DISTRIBUTION IN TWIN-SCREW EXTRUDERS



T. Jager

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Proefschrift
ter verkrijging van de graad van
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op gezag van de rector magnificus,
dr. H.C. van der Plas,
in het openbaar te verdigen
op, woensdag 22 april 1992
des namiddags te vier uur in de aula
van de Landbouwuniversiteit te Wageningen.

VOORWOORD

Het onderwerp van dit proefschrift, verblijftijdspreiding in dubbelschroefextruders, is een onderdeel van het extrusie-onderzoek aan de Landbouwuniversiteit. Dit onderzoek werd begonnen en wordt nog steeds gestimuleerd door Dick van Zuilichem en Willem Stolp. Het meten van verblijftijdspreiding aan extruders begon in 1975 in samenwerking met John de Swart van het ITAL. Enig werk uit de periode van voor de aanvang van dit promotieonderzoek is opgenomen in deze thesis. De metingen tijdens het promotieonderzoek zijn voornamelijk uitgevoerd door Ernst-Jan Spaans en Pien de Ruig, met ondersteuning van Willem Stolp en de technische werkplaats.
Bij het schrijven van de publicaties waaruit dit proefschrift is samengesteld zijn taalkundige en inhoudelijke adviezen gegeven door Dick van Zuilichem, Klaas van 't Riet, Ronald Jowitt en Brian McKenna. Leo van Dorp heeft mij bij de omzetting naar een proefschrift door enkele handige schakelingen nog 250.000 handelingen bespaard. De tekening op de kaft is een weergave van de 'hemelpoort' uitgevoerd in baksteen door Herman Helle. De tekeningen in het binnenwerk zijn voor het grootste deel het werk van Willem Stolp. Het overige deel is uitgevoerd door de tekenkamer.
Verder moet een grote groep studenten vermeld worden, die '131c' tot een begrip hebben gemaakt in de levensmiddelenindustrie. Hun precieze functie voor dit proefschrift is moeilijk te omschrij-ven, maar kan mogelijk verduidelijkt worden met een citaat uit 'The taming of the screw' van Shakespeare: 'Without pleasure no fortune is taken'.
Het werk aan extruders is zeer dankbaar wat betreft toepassingen. Bij theorievorming blijkt echter dat dit eenvoudige werktuig een groot aantal facetten heeft waardoor het eerder door een team moet worden bestudeerd dan door een enkeling. Het was mij een buitengewoon genoegen om samen met Willem Stolp, Jaquelien Gaakeer, Dick van Zuilichem, Monique van der Berg, Paula Santbulte en kamergenoot Eric van der Laan een team te vormen, dat op een bizonder grondige en prettige manier de grenssteen der menselijke kennis een eindje verder heeft gerold.

TABLE OF CONTENTS

1. GENERAL INTRODUCTION

Twin-screw extruders have been applied succesfully for approximately 120 years (Janssen 1976). Still considerable scientific programs are founded in order to understand their working mechanism. These efforts are a result of the advantages that twin-screw extruders have in a production environment and their promise of a wide range of new applications. Twin-screw extruders can handle extreme viscous fluids in a continuous process for an intensive treatment in a short time. They need a small working space given their capacity and can run several weeks with only minor adjustments. The twin-screw extruder is an established unit operation with a growing number of applications.

Other reasons for the considerable research efforts in twin-screw extrusion are the complications they give for research and development. For the extrusion-cooking of biopolymers accurate measurement of relevant variables as: viscosities, temperatures and internal leakage flows are problematic as they exist only in the environment of the extruder. The possibilities to simulate this environment are limited (Van Zuilichem 1992). A second reason is the absence of a standard geometry for twin-screw extruders. Therefore studies on different machines can not be compared, which increases the research efforts considerable .

Comparable problems exist for the up-scaling of processes from a small pilot plant to a large production plant. For this reason some companies have considered to do their entire extrusion research on a production plant scale.

In order to compare the processes in different extruders the mass flow, heat flow and mixing properties must be examined. Mixing can be divided in dispersive mixing, which generates a large part of the heat flows and distributive mixing, which is strongly related to the leakage flows in the chambers of the twin-screw extruders. A description of different leakage flows is given by Janssen (1976). The heat is generated partly by viscous dissipation from the dispersive mixing and partly by the barrel heaters (Van Zuilichem 1992). The heat is transported from the barrel to the extrudate by radial distributive mass flows. From these descriptions it follows that mass flow, heat flow and mixing are related phenomena.

In this paper the comparison of mass flow in different extruders is studied by residence time distribution (RTD). The mass flow in a twin-screw extruder results in a RTD of the extrudate, which can be used to check theories on the mass flow present, with the condition that a similarity in RTD does not prove a similarity in mass flows. However, a similarity in measured and modelled RTD can be a first condition in order to describe the differences in mass flows present between different twin-screw extruders.

This requires the development of a model which describes the axial mass flow in a twin-screw extruder and its relation with the RTD. The main part of this thesis deals with the development of this model, which is finally described in Chapter 7.

In the Chapters 4, 5 and 7 RTDs for twin-screw extruders are measured, modelled and discussed. Chapter 4 and 5 describe respectively the feed zone and the compression zone of a conical, counter-rotating, twin-screw extruder, while Chapter 7 deals with a corotating type. The results from these chapters are summarized in Chapter 2, which gives an introduction and review of residence time distribution (RTD) in twin-screw extruders. Several models to predict or describe the RTD are compared with the published data. By comparing the available literature the average response of the RTD on changes in process conditions, feed material properties and extruder geometry are given and discussed. Generally three elements can be recognised in all measured RTDs. A zone of the extruder can be described with a plug flow, while the main part of the axial mixing is generated by the leakage flows in other zones of the extruder. The third recognised element is a stagnant-like behaviour which can be observed in the tail of the RTD. The detection of this stagnancy requires an accurate detection system. In this thesis the RTD is measured by a coincidence detector which counts the radiation of an annihilating ^{64}Cu tracer. The merits of this system are discussed in Chapter 3, while its accuracy is calculated in Chapter 7.

A main problem in extrusion research is the large number of variables necessary to describe an extrusion-cooking process. Process conditions such as the rotational velocity of the screws, feed rate, temperatures, screw geometry, die design, RTD, distributive mixing and viscous dissipation are accompanied by material related properties as: contents, density, particle size, reaction rates, water absorption, melting behaviour, protein dispersion, expansion, appearance, texture, tribology, rheology and nutritional aspects. This large number of variables, combined with the different types of twin-screw extruder designs can make it difficult and time consuming to recognize which variables affect each other.
The use of a predictive model is not always helpful as its validity can be limited to a small number of applications and the confirmation of such a model to a specific application is, by the large number of variables, also time consuming. In Chapter 6 the use of statistical methods is discussed in order to deal with this complexity and to improve the suitability of the predictive models. The discussed statistical method can generate a statistical likely hypothesis. A separate empirical proof of these statistical relations remains necessary. This approach was, besides for the example given in Chapter 6, useful for the improvement of two different commercial extrusion processes with more than thirty variables.

The Chapters 3 to 7 have been published as part of a series in the Journal of Food Engineering and contain a large number of internal references.

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Janssen, L.P.B.M. (1976) A phenomenological study on twin-screw extruders. Thesis of the technical university of Delft, the Netherlands.
Van Zuilichem, D.J. (1992) Extrusion-cooking, Craft or Science? Thesis of the agricultural university of Wageningen, the Netherlands.

2. THE MEANING OF RESIDENCE TIME DISTRIBUTION IN TWIN-SCREW EXTRUSION

ABSTRACT

The residence time distribution (RTD) of twin-screw extruders can be described as a combination of plug flow, axial mixing and stagnancy. The RTDs can be modelled for these three elements in several ways. Purposes to measure the RTD are: the longitudinal smoothing of the variations in the feed stream, indications of wear, prediction of reaction rates and optimization of the axial mixing. Guidelines are given which models can be used for each application. The reactions of the RTD on changes in the extruder geometry and process parameters are also compared with three predictive models.

NOTATION

a	tangent of the tail of the logarithmic RTD (s^{-1})
A	dimensionless residence time corrected for the minimum residence time
c	constant
C(t)	extinction
d	barrel diameter (m)
D	degree of fill
D_e	dispersion coefficient (m^2s^{-1})
E(t)	exit age distribution
F(t)	cumulative exit age distribution
G	coefficient for the mixing of leakage flows and chamber content
h	channel depth (m)
H	hold-up volume (m^3)
H_{min}	minimum hold-up volume (m^3)
H_r	$H-H_{min}$ (m^3)
I	specific feed rate
i	counting variable
k	number of chambers on one screw channel
l	extruder length (m)
L	dimensionless extruder length
M_i	moment of the RTD (s^i)
N	number of CSTRs
N_c	corrected number of CSTRs
p	percentage of the filled volume above the minimal fill which is occupied by plug flow

This chapter has been submitted for publication.

Pe	ratio of transport by convection and by diffusion (Peclet number)
Q	feed rate (kgs^{-1})
Q_{max}	maximal feed rate (kgs^{-1})
R_i	constant
t	time (s)
t_x	time in which x percent of the tracer has passed the detector (s)
U	rotational speed of the screws (s^{-1})
<v>	average velocity (ms^{-1})
V(i)	volume of the i-th chamber (m^3)
V_{tot}	reactor volume (m^3)
w	screw pitch (m)
Y	end time of RTD measurement or the time in which a bend can be found in the logarithmic RTD (s)
z	number of thread starts on one screw
Z	reduction percentage of a
τ	average residence time (s)
ρ	specific density (kgm^{-3})
θ	dimensionless residence time
θ_m	dimensionless minimal residence time

INTRODUCTION

Twin screw extruders are used in various types of industry for rubber, metal, glass, plastic, ceramic, food and paper pulp processing to form, heat, devolitilize, shear and mix materials with highly viscous properties. The different types of twin-screw extruders can be divided by their geometrical design. They have two parallel screw axis in a closely fitting barrel. In the case of the conical twin-screw extruders the axis are nearly parallel. The screws rotate in the same or in the opposite direction (co- or counter-rotating).

The screw elements are closely intermeshing, self-wiping or non-intermeshing (Van Zuilichem et al. 1983), resulting in C-shaped chambers (Fig. 1) separated by clearances (Janssen 1976). The screw elements can vary in pitch, channel depth, reversed or forwarding direction of pumping action (Martelli 1982; Ziminski and Eise 1980; Rauwendaal 1990; White et al. 1987) and the dimensions of the clearances between the C-shaped chambers and barrel. Except for the continuous cut screws other geometrical elements are used such as screw elements with cut flights, reversed elements (Tayeb et al. 1988), kneading elements, drossel elements (Jager et al. 1990), barrel valves (Todd 1980) and other valve types (Elsner 1990).

The large number of extruder types and process applications is an invitation to develop models with a general validity. The internal flow in extruders is laminar (Rauwendaal 1990). The viscosity is high and heat generation occurs due to viscous dissipation. The rheology is for most process applications non-Newtonian and shear-thinning with elastic properties while slip between extruder and extrudate is possible. Combined with the complex geometry of the C-shaped chambers or other elements a three

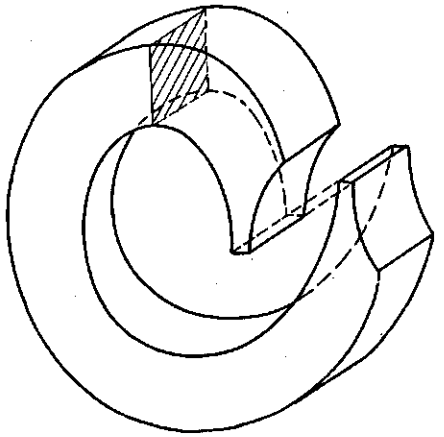

Fig. 1. C-shaped screw chamber.

dimensional model of the internal mass flow can become quit complicated.

The residence time distribution is the result of the complex three dimensional mass flow in the extruder. It gives a limited information on the internal mass flows as they are not measured directly. The RTD is used as an indication of the axial mass flow as it can be measured faster and more easily than the three dimensional mass flow. Consequently it gives a possibility for an experimental validity check for two or three dimensional mass flow models.

A second reason to measure the RTD is given by Potente and Koch (1989) and Potente and Schultheis (1988). The RTD is used to determine the capacity of the extruder to smooth out the variations in the inlet feed stream. As twin-screw extruders have narrower RTDs than single screw extruders there output streams are considered to be more sensitive to feed variations than single-screw types (Potente and Schultheis 1988). Hasal et al. (1985) give a theoretical analysis of this type of smoothing for a Gaussian RTD. For twin-screw extruders equipped with loss in weight feeders the axial smoothing is only limiting for extreme demands in product uniformity or for a very narrow RTD.

A third and more important application of RTD measurement is the prediction of the reaction rate in twin-screw extruders. In polymerisation and depolymerisation reactions the RTD does not only influence the average chain-length of the product but also the chain-length distribution. In forming and devolitilization applications the material in the tail of the RTD can be overprocessed which can give unwanted side reactions as thermal degradation (Zeitler 1989). The sterilisation of food material can also be modelled as a chemical reaction. Bouveresse et al. (1982) and Van de Velde et al. (1984) study the sterilisation by extrusion-cooking of heat-resistant spores of *Bacillus stearothermophilus*. The samples with the highest dose of these spores can be found just after the minimum residence time or breakthrough time. Accuracy and stability of the first part of the RTD is a premise for these applications. Also Schott and Saleh (1978), Madeleine et al. (1990), Ferry-Wilczek et al. (1988), and Komolprasert and Ofolli (1990) describe the use of the RTD to forecast the reaction rate. A wide RTD may improve the reaction rate of reactions with a higher order than one when three conditions are valid.

- The RTD curve width is representative for the axial mixing.
- More axial mixing should give a better distributive mixing.
- The distributive mixing limits the reaction rate.

The first condition can not directly be measured from the RTD. Jager et al. (1988) shows that with equal axial mixing the RTD width decreases when the amount of plug flow in the reactor increases. The second and third condition can also not be checked from the average residence time and curve width of the RTD but have to be checked by additional measurements. Kim et al. (1978) uses the RTD curve width as a possible indication for the distributive mixing without additional measurements.

The fourth application is the detection of wear of the extruder screws and barrel. Miller (1984) describes that the average residence time on a commercial applied corotating twin-screw extruder with a reversed element increases with 3.5 seconds by wear. Byars (1990) finds on a similar machine that after 3650 hours of operation the RTD curve width increases significantly. The Peclet number, a RTD curve width indicator described in the 'RTD measurement and representation' section decreases from 37 to 20. Also the minimum breakthrough time decreases with 14% or 2.5 s which is an indication of wear for the reversed element.

RTD MEASUREMENT AND REPRESENTATION

The tracer is for most RTD measurements on twin-screw extruders used as a Dirac pulse. Only Curry et al. (1988) use a tracer concentration in the feed with a cyclical nature. The extinction curve of a Dirac pulse is known as the E-curve (Danckwerts 1953). The integrated form, the F-curve, is used with a linear or a logarithmical scale for the tracer concentration. The time axis is made dimensionless by using the ratio of residence time and the average residence time. The amount of axial mixing in an extruder is for most cases represented by a figure based on the curve spread of the E-curve. It can be described as the dimensionless variance of the RTD the number of CSTRs, Peclet number, the number of continuously stirred tank reactors (CSTR), an axial length on a standardised height of the E-curve or as a ratio of two characteristic residence times. The average residence time (τ) and the curve width expressed as the number of CSTRs (N) can be defined with the zero, first and second time moment (M_0,M_1,M_2) of the measured extinction C(t) as:

$$M_i = \int_0^\infty t^i . C(t)\ dt \tag{1}$$

$$\tau = \frac{M_1}{M_0} \tag{2}$$

When the average residence time is known the hold up, H, can be calculated as:

$$H = \frac{\tau . Q}{\rho} = D . V_{tot} \tag{3}$$

in which Q is the feed rate, ρ the specific density, D the degree of fill and V_{tot} the reactor volume of the extruder. the number of CSTRs can be calculated as:

$$N = \frac{M_1^2}{M_0 . M_2 - M_1^2} \tag{4}$$

RTD models

RTD models can be divided in curve fit models which describe the curve shape and in models which describe the axial mixing in the reactor. This last type can by divided in predictive and descriptive models. An example of a descriptive model is the plug flow model with axial dispersion (Levenspiel 1972), which is often used as a reference model. The axial dispersion is described by a pseudo diffusion coefficient D_e. The Peclet number, the ratio of the average axial convective transport and the transport by dispersion is for this model equal to:

$$Pe = \frac{\langle v \rangle . l}{D_e} \tag{5}$$

in which l is the extruder length and $\langle v \rangle$ the average axial velocity. The axial dispersion model and a cascade of CSTRs do give comparable RTDs (Levenspiel 1972).

Stagnancy

The RTD of the most thorough processed material can be seen in the tail of the logarithmical F-curve. Quality problems due to partly overprocessed products should be studied with this curve rather than with the not integrated E-curve, which shows the RTD around the average residence time.

A bend in the logarithmical F-curve which increases the length of the tail is a sign that there are regions with fast and slow flow velocities or regions with stagnancy (Shinnar 1987). In this paper only the term stagnancy will be used to describe the mass flow which results a the bend in the logarithmical RTD.

The effect of such a bend on the Peclet number is given in Fig. 2 (Jager et al. 1991) as a function of the change in the logarithmical slope of the RTD (Z) for two values of Y, the time on which the bend occurs. When Y increases the deviation of the Peclet number becomes less. Only in extreme cases the Peclet number is changed significantly. This means that the Peclet number or any other curve width indicator can not be used to describe the curve width in the tail of the RTD. Therefore the description of the RTD shape with stagnancy requires at least three parameters: the curve width of the E-curve, the volume in which stagnancy can be observed and the axial mixing of the tracer which enters the region of stagnancy. When a part of the RTD has to be described with a plug-flow the minimal number of parameters is four.

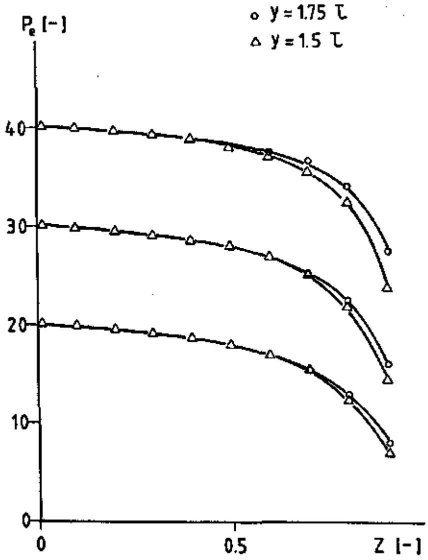

Fig. 2. Effect of stagnancy on the Peclet number. The logarithmical RTD shows a bend at Y=1.5τ and Y=1.75τ.

Accuracy of measurements

As all RTD measurements are ended after a time period (Y) there is still a small fraction of the tracer present in the reactor. This truncation error can affect the values of the moments described in eqn. 1. Todd (1975) assumes an exponential curve for the RTD after truncation:

$$C(t)=C(Y).\exp(-a.t) \qquad \text{for } t>Y \tag{6}$$

while:

$$\log(1-F(t))=-a(t-Y)-\log(M_0.a/C(Y)) \tag{7}$$

The truncation error of the zero moment is according to Todd (1975):

$$\frac{C(Y)}{a} \tag{8}$$

The correction terms for the first and second moments are respectively (Jager et al. 1991):

$$\frac{(a.Y+1)\ C(Y)}{a^2} \tag{9}$$

$$\frac{(a^2.Y^2+2a.Y+2)\ C(Y)}{a^3} \tag{10}$$

The correction of the zero moment is necessary for the correct representation of the logarithmical F-curve. Without this correction the stagnancy of the reactor is underestimated. Correction terms for the first and second moments are necessary to calculate the truncation error for the average residence time and the RTD curve width. Jager et al. (1991) gives a calculation of the measurement accuracy of an on-line radiotracer method by a Monte Carlo analysis. Both the average residence time and a curve width indicator could be measured within 1% accuracy. In other papers the reproducability is studied by duplicate RTD measurements. Janssen et al. (1979) splits all samples and studies the measurement accuracy in the tail of the RTD by the difference in extinction.

Tracer

Different types of colours, measured by a photospectrometer are used as tracers for of-line measurement of RTD by Todd (1975), Mosso et al. (1982), Collona et al. (1983), Von Lengerich (1984), Lim et al. (1985), Altomare and Ghossi (1986), Altomare and Anelich (1988), Ollet et al. (1989), Komolprasert and Ofoli (1990), Pan et al. (1990), Byars (1990). An on-line optical detection system is used by Kim et al. (1978) and Potente et al. (1988).
Golba (1980), Curry et al. (1988) and Schule et al. (1988) use an on-line induction measurement with conductive carbon or iron dust as tracers. Schule et al. (1988) compare this method with an off-line measurement of the specific density of the iron dust with good results. An on-line electromagnetic resonance method with iron oxide (Fe_2O_3) is described by Stratil et al. (1988). Janssen et al. (1979) use manganese dioxide powder, radiated off-line in a gamma-plant by measuring the activity of

manganese 56. Speur (1988) used the same tracer and detected it off-line by atomic absorption spectrometry. On-line use of a radiotracer is reported by Olkku et al. (1980) and Wolf et al. (1986) for manganese 56, by Mange et al. (1984) for pottasium 42 nitrate and by Van Zuilichem et al. (1988a) and Jager et al. (1991) for copper 64. Two miscellaneous off-line methods described are the use of tallow, which is detected with a Foss-Let (Miller 1984) and detection of cadmium selenide (Walk 1982) or antimony oxide (Rauwendaal 1981) by X-ray fluorescence.

Accurate measurement of the minimum residence time and the shape of the tail requires a detection system with a low noise level. Except for transparent extrudates on line colour detection systems generally give more noise than systems based on other tracer properties. This is in particular valid for High Temperature Short Time (HTST) food applications were the dyes can be chemically changed or bound by one of the multitude of chemical components present.
On-line Radiotracer systems are shielded against background radiation and premature measurement of tracer. Van Zuilichem et al. (1988a) describes a double detector system based on annihilation radiation which guarantees a minimum noise error. However on-line methods based on electromagnetic resonance or induction might have a similar level of noise. Off-line systems should have less noise problems as their measuring equipment does not have the time constraints of the on-line systems. But, as the off-line systems require more handling as each sample must by labelled and measured separately, the on-line systems can compensate for this difference in accuracy by a greater number of measurements.
The flow-, and adsorption behaviour of the tracer used in RTD experiments must, ideally be equal to that of the feed material in order to prevent an unrepresentative RTD. As the tracer deviates mostly from the extrudate in more than one property the RTD of tracer and extrudate do not have to be identical. By using tracers with different properties the differences between the RTDs and the tracer can give some information on the mass flow inside of the reactor (Shinnar 1987). Bounie (1986) uses two different tracers, erythrosine and ZnO for the extrusion of maize grits. The solubilities of these tracers in water are different. As the curves of both tracers are comparable for the shape of the E-curve and the average residence time, this experiment is an indication that water and maize do not separate inside of the extruder.

Weiss and Stamato (1989) developed a sulfonated polystyrene which should have similar properties as the original polystyrene. They compared the RTD of this tracer with that of glass microspheres and carbon lampblack in a single screw extruder. They observed a smaller RTD with the sulfonated polymer than with the other two tracers in some of there experiments. Weiss and Stamato (1989) do not give information on the shape of the RTD tail where the differences in tracer properties should, relatively give the greatest deviations. The sulfonated and the untreated polystyrene have almost equal viscosities but they are not identical. Therefore it is still unknown whether the RTDs of tracer and extrudate are identical. For the average residence time this can be checked by the following procedure; The RTD is measured after which the extruder is brought to a sudden stop. The material inside the extruder is weighted and the average residence time of the polymer, calculated by eqn. 3 can be compared with the average residence time of the tracer.

The formulation of the tracer also affects the RTD. Janssen et al. (1979) describes that when in a single screw extruder the tracer is not mixed with a solid feed material it can cause slip on the metal surfaces of the extruder which increases the length of the tail of the RTD. This effect can be prevented by making a premix of the tracer and the extrudate. The viscosity of this masterbatch must be comparable to that of the extrudate and the tracer particles must not separate from the extrudate in the extruder.

RESULTS OF RTD MEASUREMENTS

The described responses of the RTD are ranged on the originating experimental variable. The variables found are divided in: the geometry of the extruder and changes in the process parameters.

Co-, or counter-rotating

Due to their construction corotating twin-screw extruders have a low pumping efficiency when compared to counter-rotating, twin-screw extruders. In a screw design with only continuous screw elements the corotating extruder will be mostly empty, except for a small volume just before the die. The higher pumping efficiency of counter-rotating twin-screw extruders results in a higher degree of fill. Therefore geometrical elements such as reversed elements, kneading disks, blocks, and valves are frequently used in corotating twin-screw extruders to increase the hold up on different positions along the barrel. As the pumping efficiency of the corotating extruder is lower it needs a higher screw speed and consequently more leakage flow and axial mixing in order to obtain an average residence time equal to that of the counter-rotating type. Therefore the counter-rotating, twin-screw extruder can operate at a lower shear rate. The greater amounts of leakage flows of the corotating type are claimed to give a better distributive mixing in the extruder.

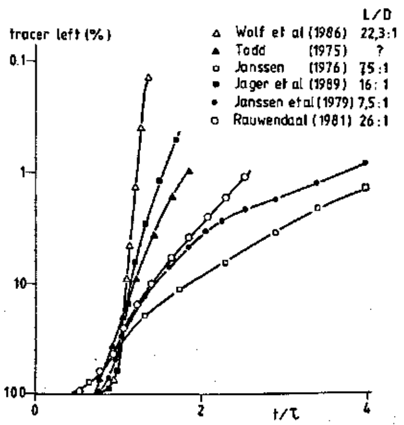

Fig. 3. Logarithmical RTD of counter-rotating, twin-screw extruders.

Rauwendaal (1981), Kim et al. (1978) and Potente and Schultheis (1988) measured the RTD of a co-, and counter-rotating, twin-screw extruder and found that in comparable circumstances the counter-rotating type has a steeper RTD. In Fig. 3 and 4 some logarithmical RTDs of co-, and counter-rotating, twin-screw extruders are shown. Fig. 5 gives some extreme curve widths expressed as the ratio of the times in which 84% and 16% of the tracer has been measured or as a Peclet number according to the method of Todd (1975). It can be seen that the steepest RTDs are measured on counter-rotating types and that the curve width tends to increase with the length diameter ratio (L/d), as is described by eqn. 5. On the dotted line the Peclet number increases linear with the L/d ratio. Therefore it can be seen in Fig. 5 that the Peclet number of one diameter extruder length decreases when the L/d ratio increases. As the RTD of twin-screw extruders is in most cases measured for L/d<20, it is possible that future measurements on extruders with L/d>20 will result in larger Peclet numbers.

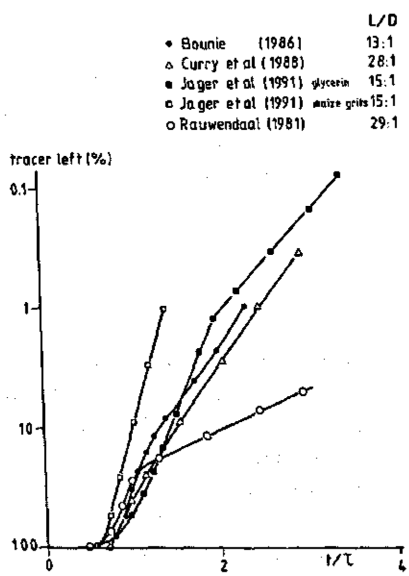

Fig. 4. Logarithmical RTD of corotating, twin-screw extruders.

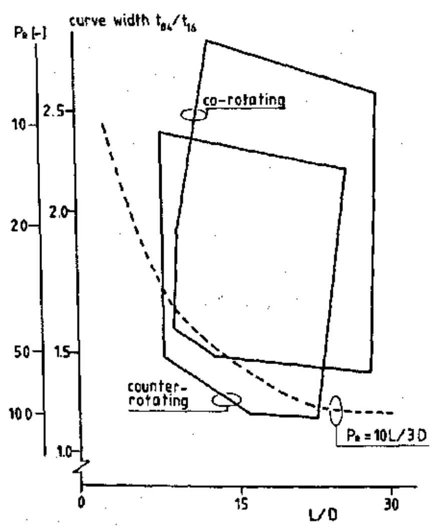

Fig. 5. Extreme curve widths found in co-, and counter-rotating, twin-screw extruders. The Peclet numbers are calculated according to Todd (1975).

Extruder zones

Wolf et al. (1986) measured the RTD of one Dirac pulse at several locations on the barrel. Accidentally the curves have similar curve widths. Therefore, according to eqn. 5, the dispersion coefficient D_e must increase in the direction of the die outlet. Kim et al. (1978), Bounie (1986) Van Zuilichem et al. (1988b), Jager et al. (1988), Jager et al. (1989) measured the RTD at several points along the barrel. The axial mixing was in all cases dependant of the choice in which axial length the RTD was measured. Jager et al. (1988) and Jager et al. (1989) analysed the axial mixing in the feed zone and the compression zone of a counter-rotating, twin-screw extruder and found different responses of the RTD for changes in the specific feed rate. It was calculated that in some cases the curve width of the RTD at the die was more influenced by the axial mixing in the feed zone than by that from the 'High Temperature Short Time' compression zone near the die. When the RTD is used for the modelling of chemical reactions the model must have the flexibility to give each zone a specific axial mixing.

Transport zones

Van Zuilichem et al. (1988b) describes zones consisting of screw elements without leakage flows as transport zones. The minimal hold up volume (H_{min}) for these zones is:

$$H_{min} = \frac{2z.k.Q}{U.\rho} \qquad (11)$$

in which U is the rotational speed of the screws, k is the number of chambers on one screw channel and z is the number of thread starts on each screw. The absence of leakage flows limits the axial mixing to a neglectable level, that can be represented by a plug-flow. When different extruders are compared for their axial mixing by their curve width a correction for these transport zones is necessary. The remaining hold up volume (H_r) is now:

$$H_r = \frac{\tau.Q}{\rho} - H_{min} \qquad (12)$$

The axial mixing of different twin-screw extruders can be compared by a corrected number of CSTRs, N_c, (Jager et al. 1988):

$$N_c = N \frac{{H_r}^2}{H^2} \qquad (13)$$

Feed rate and screw speed

The RTD responses on changes on these two process variables have been described by more than thirty authors. Changes in feed rate and screw speed can be compared when they are converted to changes in the specific feed rate, I, which is defined as:

$$I = \frac{Q}{2z.V(1).U.\rho} = \frac{Q}{Q_{max}} \qquad (14)$$

in which, Q, is the mass flow which enters the extruder, V(1), is the chamber volume of the first chamber and Q_{max} is the theoretical maximum mass flow. Typical values for the specific feed rate are between 0.1 and 0.3. When a chamber in a continuous cut screw with equal chambers is completely filled, while the specific feed rate is 0.2, the remaining 80% of the volume in this chamber must be filled due to the leakage flows.

Table 1
Average residence time (τ), hold-up volume (H), stagnancy and curve spread for corotating twin-screw extruders versus changes in specific feed rate (I), rotational screw speed (U), and feed rate (Q).

author	screw type	change in:	τ	H	spread	stagnancy
Janssen et al.(1979)	CO	U constant I	p	p	-	m
Jager et al. (1989)	CO	U constant I	i	i	m	?
Mosso et al.(1982)	RS	U constant I	i	p	i	?
Jager et al. (1989)	DO	U constant I	i	-	i	?
Altomare and Ghossi (1986)	KS	U constant I	i	-	-	?
Bounie (1986)	CS	I constant Q	p	p	i	i
Lim et al (1985)	CS	I constant Q	p	p	m	?
Schule et al. (1988)	CS	I constant Q	p	p	i	i
Ollet et al. (1989)	CS	I constant Q	p	p	i	i
Kao and Allison (1985)	CS	I constant Q	p	p	?	?
Oliveira (1990)	CS	I constant Q	p	p	i	?
Von Lengerich (1984)	CS	I constant Q	p	p	i	?
Rauwendaal (1981)	KS	I constant Q	i	i	i	i
Walk (1982)	CN	I constant Q	p	p	p	?
Speur (1988)	CO	I constant Q	p	p	p	?
Tucker and Nichols (1987)	CN	I constant Q	p	p	?	?
Rauwendaal (1981)	CO	I constant Q	-	-	i	i
Todd (1975)	CO	I constant Q	p	m	p	m
Bounie (1986)	RS	I constant Q	p	p	i	i

Lim et al (1985)	RS	I constant Q	p	p	m	?
Mosso et al.(1982)	RS	I constant Q	p	p	i	?
Boissonnat et al. (1988)	RS	I constant Q	p	p	i	i
Pan et al. (1990)	RS	I constant Q	p	p	i	?
Oliveira (1990)	RS	I constant Q	p	p	i	?
Altomare and Ghossi (1986)	KS	I constant Q	p	p	-	?
Jager et al.(1991)	KS	I constant Q	p	p	i	p
Komolprasert and Ofoli (1990)	KS	I constant Q	i	i	m	?
Kao and Allison (1985)	KS	I constant Q	p	p	?	?
Altomare et al. (1990)	KS	I constant Q	p	p	?	?
Potente and Schultheis (1988)	CS	I constant U	p	p	m	?
Kao and Allison (1985)	CS	I constant U	i	p	?	?
Von Lengerich (1984)	CS	I constant U	p	p	i	?
Oliveira (1990)	CS	I constant U	i	p	p	?
Janssen et al.(1979)	CO	I constant U	-	p	-	i
Janssen (1976)	CO	I constant U	p	p	p	i
Walk (1982)	CN	I constant U	i	m	i	?
Jager et al. (1989)	CO	I constant U	i	p	i	?
Tucker and Nichols (1987)	CN	I constant U	i	p	?	?
Rauwendaal (1981)	CO	I constant U	i	p	i	-
Todd (1975)	CO	I constant U	p	p	i	i
Mange et al.(1984)	RS	I constant U	i	p	?	?
Mosso et al.(1981)	RS	I constant U	i	p	i	?
Noguchi (1986)	RS	I constant U	i	p	?	?
Boissonnat et al. (1988)	RS	I constant U	i	?	p	i
Olkku et al. (1980)	RS	I constant U	i	?	i	i
Pan et al. (1990)	RS	I constant U	i	p	i	?
Oliveira (1990)	RS	I constant U	i	p	i	?
Altomare and Ghossi (1986)	KS	I constant U	i	p	i	?
Jager et al.(1991)	KS	I constant U	i	i	i	-
Kao and Allison (1985)	KS	I constant U	i	p	?	?
Rauwendaal (1981)	KS	I constant U	i	i	i	-
Jager et al. (1989)	KO	I constant U	i	p	p	?

C: Continuous screw-pair
D: Drossel zone
K: Kneading elements
R: Reversed elements
S: Corotating, twin-screw extruder
O: Counter-rotating, twin-screw extruder
N: Non-intermeshing, counter-rotating, twin-screw extruder

p: Parallel response
i: Inverse response
-: No significant response
?: Unknown

When only the feed rate or the screw speed is changed, changes in the hold-up (H) are caused by both changes in H_r and H_{min}. This is a cluttered result that can be corrected when H_{min} is known. When the curve width and the hold-up volume are corrected with eqn. 13 and 12 the relation between the curve width and H_r can be observed. These variables will show a parallel response in most cases. The cluttered result can also be avoided by measuring changes in the rotational speed at a constant specific feed rate. Advantages of this last method are: that the specific viscous dissipation of the extruder can remain, for most cases, at a level which is representative for industrial applications and that the response due to an increase in shear rate can be observed.
Despite these advantages only a few authors (Mosso et al. 1982; Janssen et al. 1979; Jager et al. 1988; Jager et al 1989) have measured this response (see Table 1). The response for Altomare and Ghossi (1986) in Table 1 was calculated from the published data.

The responses of the average residence time, the hold-up volume the dimensionless curve width and the stagnancy for changes in the process parameters are described in Table 1. In this table the notation 'I constant Q' means that measurements were made with different specific feed rates at a constant throughput. When instead of the dimensionless curve width the normal curve width is used, the changes in the curve width are dependent of the changes in the average residence time and their responses would be similar for most cases. The circumstances of the RTD experiments are given in Table 2. When in Table 1 the specific feed rate is increased the hold-up volume increases in most cases. For changes at a constant screw speed the average residence time decreases which signifies, that in most cases the hold-up increases at a slower rate than the specific feed rate. This behaviour can be found for all measurements in Table 1 on food applications, except for one group of measurements by Jager et al. (1991) with maize grits. The plastic applications show 7 exceptions out of 19 (36%).

Table 2
Author, extruder type, extrudate and L/d ratio of the RTD measurements described in Table 1.

author	type	extrudate	L/d
Altomare and Anelich (1988)	W&P C-37	rice flour	16
Altomare et al. (1990)	W&P C-37	rice flour	32
Altomare and Ghossi (1986)	W&P ZSK-57	rice flour	16
Boissonat et al. (1986)	Clextral BC-45	wheat flour	13
Bounie (1986)	Clextral BC-45	maize starch	13
Bouveresse et al. (1982)	Clextral BC-45	wheat flour	
		corn starch	
		soy protein	
		sucrose mix	13
Collona et al. (1983)	Clextral BC-45,72	maize starch	14
Curry et al. (1988)	W&P ZSK-30	PE	28

Ferry-Wilczek et al. (1988)	Clextral BC-45	maize starch	13
Janssen et al.(1979)	Pasquetti	PP	7.5
Janssen (1976)	Pasquetti	PVP solution	7.5
Jager et al. (1989)	Cincinnati	maize grits	16
Jager et al. (1991)	APV MPF-50	maize grits	15
		glycerin	15
Kao and Allison (1984)	W&P ZSK-30	polymer	28
Kim et al. (1978)	co/counter	glycerin	7.5
Komolprasert and Ofoli (1990)	APV MPF-50	maize starch	15
Lim et al. (1985)	Clextral BC-45	wheat flour	13
Mange et al. (1984)	Clextral BC-45-105	wheat flour	?
Mosso et al. (1982)	Clextral BC-45	starch, protein, sucrose mix	13
Noguchi et al. (1986)	Clextral BC-45	okara	13
Oliveira (1990)	Clextral BC 45	fishmeal	13
Olkku et al. (1980)	Clextral BC-45	wheat flour	13
Ollet et al. (1989)	APV MPF-50	wheat starch	10
Pan et al. (1990)	Clextral BC-45	rice	11
Potente and Schultheis (1988)	corotating	PVC-xii	?
Rauwendaal (1981)	W&P ZSK-28	HDPE	29
	Leistriz LSM 30,34		26
Schule et al. (1988)	W&P ZSK-23	?	?
Speur (1988)	Pasquetti	PE	7.5
Todd (1975)	counter-rotating	polybutene	?
Tucker and Nichols (1987)	non-intermeshing	?	?
Von Lengerich (1984)	W&P C37/C120	wheat starch	12
Van Zuilichem et al. (1990)	APV MPF-50	maize grits	15
Walk (1982)	Welding Engineers	p-MMA	26
Wolf et al. (1986)	Krauss-Maffei	PVC	22.3

The dimensionless curve width in Table 1 decreases in 20 cases when the specific feed rate increases while the opposite reaction occurs only five times, mainly for counter-rotating, twin-screw extruders with a continuous screw pair processing non-food materials. The increase in the specific feed rate will increase the H_{min} linearly which will make the RTD more plug-flow like and consequently decrease the curve width. When also H_r increases the axial mixing increases and the decrease in the curve width can change in an increase. The stagnancy in Table 1 for an increasing specific feed rate could for 24 cases not be determined from the given data. For the remaining measurements it decreases 12 times while only one increase is observed. The RTD reactions for changes in the screw speed, at a constant specific feed rate in Table 1 show five different response patterns out of five. The number of measurements is too small to form a meaningful pattern.

Kneading elements

The influence of a kneading element can be observed when it is introduced in a continuous cut screw or when the total length of the kneading elements is increased. Table 3 gives the responses of the RTD in average residence time, curve width and stagnancy for both type of experiments. The hold-up is not given as it reacts similar to the average residence time at a constant feed rate (see eqn. 3).

Table 3
Average residence time, stagnancy and curve spread for twin-screw extruders versus changes in screw geometry, extruder length and die diameter.

author	screw type	change in:	τ	spread	stagnancy
Boissonnat et al. (1988)	RS	Die resistance	i	-	p
Von Lengerich (1984)	CS	Die resistance	p	p	p
Altomare and Ghossi (1986)	KS	Die resistance	-	-	p
Altomare et al. (1990)	KS	Die resistance (slit viscosimeter)	p	?	?
Jager et al.(1991)	KS	Barrel-valve resistance	p	p	-
Jager et al.(1989)	DO	Die resistance	p	i	?
Eise et al. (1981)	CS	Length reversed element	p	p	?
Lim et al. (1985)	CS	Length reversed element	p	p	?
Bounie (1986)	CS	Length reversed element	p	i	p
Altomare and Anelich (1988)	CS	Length reversed element	p	p	?
Boissonnat et al. (1988)	RS	Length reversed element	p	p	p
Altomare and Anelich (1988)	RS	Length reversed element	p	p	?
Lim et al. (1985)	RS	length reversed element	p	p	?
Kao and Allison (1984)	CS	Length kneading element	p	i	i
Altomare and Anelich (1988)	CS	Length kneading element	p	i	?
Eise et al. (1981)	CS	Length kneading element	p	i	?
Curry et al.(1988)	CS	Length kneading element	p	i	?
Jager et al.(1988)	CO	Length kneading element	p	i	?
Jager et al.(1989)	CO	Length kneading element	p	i	?
Jager et al.(1991)	KS	Length kneading element	p	i	-
Walk (1982)	KN	length kneading element	p	i	?

Table 3 continued

Altomare and Anelich (1988)	KS Forwarding to reversed kneading element	p	p	p
Jager et al.(1991)	KS Forwarding to reversed kneading element (glycerin experiment)	p	p	p
Mange et al. (1984)	RS Extruder length	p	?	?
Collona et al. (1983)	RS Extruder length	p	p	p
Altomare and Anelich (1988)	CS Leads	-	-	?
Altomare and Anelich (1988)	CS Pitch	p	-	?
Altomare and Anelich (1988)	KS Staggered elements	-	p	?
Altomare and Anelich (1988)	CS Offset screw elements	p	p	?
Kim et al. (1978)	CS Gaps between chambers	i	i	-
Kim et al. (1978)	CO Gaps between chambers	i	m	?

C: Continuous screw-pair
D: Drossel zone
K: Kneading elements
R: Reversed elements
S: Corotating, twin-screw extruder
O: Counter-rotating, twin-screw extruder
N: Non-intermeshing, counter-rotating, twin-screw extruder

p: Parallel response
i: Inverse response
-: No significant response
?: Unknown

The kneading element is used in order to increase the average residence time and the viscous dissipation. By replacing a part of a continuous cut forwarding screw with a kneading element the curve width decreases in all cases for both co, -and counter-rotating, twin-screw extruders, while the stagnancy remained constant or increased. The decrease in the curve width is explained by Jager et al. (1988), Jager et al. (1989), Jager et al. (1991) with a RTD model which describes the mass flow in all parts of the extruder. The RTD of the kneading element can be described with this model by a plug-flow parallel to a structure with axial mixing. Fig. 6 shows that in the kneading element of a corotating twin-screw extruder the plug-flow part of the model becomes more prominent at a greater local degree of fill (Jager et al. 1991) and that a considerable part of the mass flow in the model is plug-flow like, which will decrease the curve width. The decrease in curve width of the other experiments in Table 3 can be explained likewise. The kneading element has a lower pumping efficiency when compared to the continuous screw elements. Therefore the extrudate is pushed through the kneading element by the adjacent screw element. This can theoretically result in a plug-flow like mass flow which is different from the backmixing by leakage flows in the screw elements.

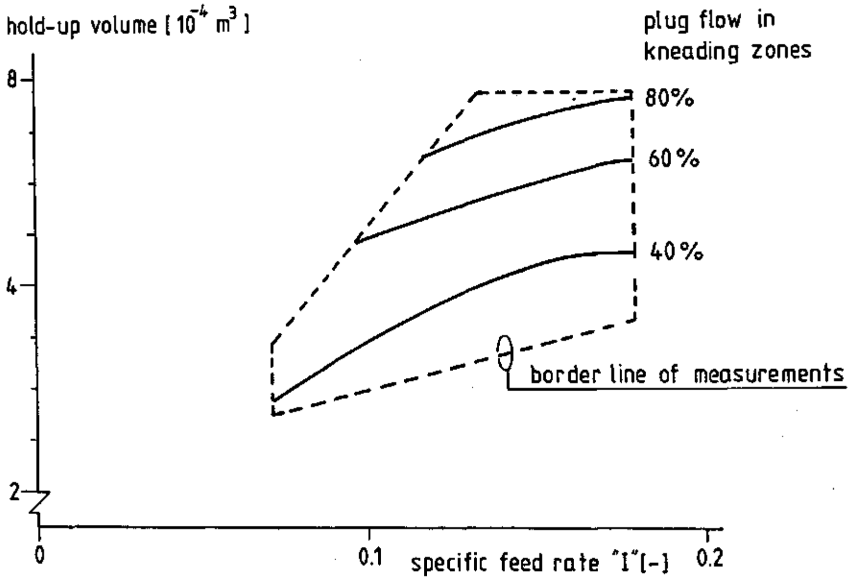

Fig. 6. Percentage of the volume in a kneading element which is filled up by plug-flow.

When the Peclet number is used to indicate the amount of distributive mixing a correction is necessary for the plug-flow like mass flow in the kneading elements. Jager and Van der Laan (1992) found that when the RTD of a kneading element becomes more plug-flow like the apparent heat exchange coefficient decreases. This may reflect a decrease of the radial distributive mixing in the kneading element. However this single experiment can not be used as a positive proof for all extrusion processes.

The degree of fill and the calculated percentage of plug-flow in a kneading element are strongly dependent of the possible geometrical configurations of the kneading paddles which form a kneading element. They can be placed at different angles in order to form kneading elements with forwarding or a reversed pitch. The reversed kneading element has an increased average residence time, a wider curve and more stagnancy when compared to the forwarding element (Altomare and Anelich 1988). When a forwarding kneading element is split into two parts and when a screw element ia placed inbetween, the average residence time increases while the curve width becomes steeper (Altomare and Anelich 1988). This shows that the axial mixing in a kneading element is not uniform over the total length. When kneading elements are placed in a more staggered configuration the curve width increases to a level between the forwarding and the reversed geometry (Altomare and Anelich 1988)

Reversed screw element

The reversed element also increases the average residence time in Table 3, but in most cases, contrary to the kneading element the curve width and stagnancy increases. Bounie (1986) finds a decrease in curve width when a reversed element is used while the stagnancy increases. The radiotracer measurements of Olkku et al. (1980) with six detectors along the barrel show that the main increase in the curve width can be found on the position of the reversed element. The reversed element pumps the extrudate back to a forwarding screw element. An increase of the axial mixing by this action is not surprising. The pumping capacity of the reversed element can be decreased by sloths in the flights (Tayeb et al. 1988).

Drossel element and offset screw elements

The drossel element works as a shear element (Jager et al. 1990). It was designed originally as a pressure barrier in front of a devolatilization zone (Albers 1976) and increases the average residence time Jager et al. (1988). The average residence time in Table 3 shows a parallel response with the specific feed rate. Comparable with the kneading element its RTD can be described as a parallel combination of axial mixing and plug-flow. Therefore the introduction of a drossel element does not result in lower Peclet numbers (Jager et al. 1988). Altomare and Anelich (1988) increase the shear rate by turning different screw elements in an offset position. When the material flows through such a barrier the material is reoriented. An offset element does not increase the degree of fill but gives a wider RTD.

Number of threads

According to Harper (1989) single lead screws have less curve spread than double lead screws. The double lead screw has a more uniform shear rate across the channel depth than the single lead screw, which can result in improved processing uniformity. In contrast to this Altomare and Anelich (1988) and Ollet et al. (1989) find that when a single lead screw is replaced by a double lead that the curve spread remains equal, while the average residence is nearly constant (see Table 3). The double lead screws used by Ollet et al. (1989) are self-wiping, while the single lead screw is closely intermeshing.

Die resistance

Table 3 show that the die can influence the RTD in several ways. Jager et al. (1989) and Von Lengerich (1984) found that a small die can increase the average residence time. This mechanism has been described by Janssen (1976). A smaller die will increase the die pressure and this will increase the filled length in front of the extruder which is necessary to push the material trough the die. Boissonat et al. (1988) found the opposite reaction but does not describe the mechanism of this phenomena. A neutral reaction was observed by Altomare and Ghossi (1986).
The apparent viscosity of the material at the die can be measured as a pressure gradient in an extended slit die (Bruin et al. 1978). The geometry of these dies can be varied by using different slit

widths. The measurements of Altomare et al. (1990) show that the use of a slit viscosimeter can result in a change of the mass flows present just as with a normal die. Therefore the measured viscosities can be unrepresentative.

The barrel-valve is a device to increase the compounding and the average residence time in a kneading element (Todd 1980). Here it is considered to be an internal die. The axial flow goes through a bypass outside of the screws. In this bypass a valve is located which can be adjusted outside of the barrel during processing. When a barrel-valve is placed just before a continuous screw it does not give significant changes in the RTD except for an increase in the average residence time (Van Zuilichem et al. 1990; Jager et al. 1991).

Barrel temperature, viscosity and moisture content

Table 4 shows the RTD responses of changes in barrel temperature and moisture content. Plastics have a greater thermal resistance when compared to food material. Consequently Changes in the RTD by the barrel temperature are more important in food than in plastic applications. Still a decrease of the average residence time is found by Kao and Allison (1985) for a plastic application by increasing the temperature at a low screw speed. When the screw speed is increased this effect disappears. In most food applications an increase in the barrel temperature gives a small decrease in the average residence time while the stagnancy increases.

For most food materials an increase in moisture content will decrease the viscosity. This decreased viscosity reduces the shear dissipation in the first part of the extruder. As the food materials in Table 2 will all be depolymerized by shear the viscosity at the die outlet will, in most cases increase when the moisture content is increased. Therefore it can be understood that the responses in Table 4 of curve spread, stagnancy and average residence time are divers. For a good analysis of these phenomena the RTD should be modelled for all sections of the extruder simultaneously with a heat transfer and a viscosity model. This requires the measurement of the RTD combined with different temperatures and pressures.
The only measurements made with a varying viscosity (Todd 1975) show an increasing stagnancy when the viscosities increases. Other responses are mixed.

Stagnancy

Stagnancy can be observed in all but one RTD in Fig. 3 and 4. Whether this stagnancy is caused by the complex geometry of the extruder or by changes in the rheological properties of the extrudate is unknown as it is extremely difficult to develop an uncluttered experiment. Hypothetical it is possible for RTD measurements of non-food polymers that a stagnant, unscraped layer is present between screws and barrel, which temporary absorbs the tracer and gives a too long tail to the RTD. This process is unlikely for the measured high temperature short time (HTST) food applications as the food polymers degrades rapidly by the high temperatures and the stagnant layers can not be permanent. In some cases a bend has been found in the RTD while still 10% to 30% of the tracer was present in

Table 4
Average residence time, stagnancy and curve spread for twin-screw extruders versus changes in moisture content and barrel temperature.

author	screw type	change in:	τ	spread	stagnancy
Todd (1975)	CO	viscosity	m	m	p
Walk (1982)	KN	Barrel temperature	-	p	?
Kao and Allison (1984)	CS	Barrel temperature	m	?	?
Altomare and Ghossi (1986)	KS	Barrel temperature	p	-	?
Jager et al.(1991)	KS	Barrel temperature	i	i	-
Kao and Allison (1984)	KS	Barrel temperature	m	?	?
Bounie (1986)	RS	Barrel temperature	i	i	p
Boissonnat et al. (1988)	RS	Barrel temperature	i	p	p
Bouveresse et al. (1982)	RS	Barrel temperature	i	-	p
Ferry-Wilczek et al. (1988)	RS	Barrel temperature	p	i	?
Bounie (1986)	CS	Moisture content	p	m	m
Von Lengerich (1984)	CS	Moisture content	-	i	p
Oliveira (1990)	CS	Moisture content	p	m	?
Altomare and Ghossi (1986)	KS	Moisture content	p	-	?
Altomare and Anelich (1988)	KS	Moisture content	p	p	-
Komolprasert and Ofoli (1990)	KS	Moisture content	i	m	?
Bounie (1986)	RS	Moisture content	m	m	m
Mosso et al.(1981)	RS	Moisture content	-	-	?
Ferry-Wilczek et al. (1988)	RS	Moisture content	m	p	?
Oliveira (1990)	RS	Moisture content	i	p	?

C: Continuous screw-pair
D: Drossel zone
K: Kneading elements
R: Reversed elements
S: Corotating, twin-screw extruder
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N: Non-intermeshing, counter-rotating, twin-screw extruder

p: Parallel response
i: Inverse response
-: No significant response
?: Unknown

the extruder. These percentages are too high for just a scraped layer. Therefore this hypothesis can not explain all experiments.

The location where the stagnancy originates is not limited to the C-shaped chamber as they travel too fast through the extruder to influence the shape of the tail of the RTD. In four cases stagnancy is found in a continuous cut screw element (Janssen et al. 1979;Janssen 1976; Jager et al. 1991; Todd 1975). Therefore the stagnancy must be caused by the leakage flows.

There are some observations described in the literature which give information on the nature of the stagnancy. According to Table 4 an increase in the barrel temperature results in a smaller viscosity and more stagnancy. Opposite to this an increase in viscosity (Todd 1975) also increases the stagnancy. The reversed screw elements which give an intensive treatment in a small volume give more stagnancy than the kneading elements (see Table 4) which spread their viscous dissipation over a larger volume. The measurements of Byars (1990) show that wear of the reversed element decreases the stagnancy. The process of wear will decrease the intensity of the backmixing. For all these observations the stagnancy increases when the possibility for small local variations in temperature increases. Therefore it is suggested to study stagnancy dependant of the Griffith or Nahme number which gives an indication of the presence of temperature non-uniformities (Rauwendaal 1990).

CURVE FIT MODELS

In Fig. 3 measured RTDs are presented in a logarithmical form for corotating twin-screw extruders and in Fig. 4 for counter-rotating types. With one exception the RTDs show a bend in the tail of the curve which is an indication for the occurrence of regions with fast and slow flow or stagnant regions (Shinnar 1987). Janssen (1976) describes the bend in Fig. 3 with the summation of two exponential functions:

$$F(\theta) = (1-c)\ \exp(-\theta/\theta_1)+c.\exp(\theta/\theta_2) \qquad (15)$$

in which θ is the dimensionless residence time and θ_1 and θ_2 are time constants. Potente and Koch (1989) use a five parameter Weibull distribution:

$$F(G) = [1-\exp(-R_1.A^{R_2})].[1-\exp(-R_3.A^{R_4})] \qquad (16)$$

A is the dimensionless residence time corrected for the fifth parameter the dimensionless minimum residence time θ_m:

$$A = \frac{\theta-\theta_m}{1-\theta_m} \qquad (17)$$

Curry et al. (1988) uses a Weibull distribution with only three parameters:

$$F(G) = 1-\exp(-R_1.A^{R_2}) \tag{18}$$

R_1 describes the curve width of the first part of the curve while R_2 indicates the curvature of the RTD tail. The Weibull functions do give a more accurate description of the RTD than eqn. 16. A relation between these three eqn. and RTD modelling standard elements such as a CSTR are not described by the authors. Only the number of parameters in eqn. 17 is sufficient for the description of a RTD curve with stagnancy and a plug-flow as discussed in the 'RTD measurement and representation' section.

DESCRIPTIVE MASS FLOW MODELS

Todd (1975) uses the axial dispersion model described by Levenspiel (1972) for the RTD of a counter-rotating, twin-screw extruder. The curve width is expressed with the Peclet number. This model gives according to Levenspiel (1972) similar RTDs as a cascade of CSTRs. Walk (1982), Bounie (1986), Altomare and Ghossi (1986) and Altomare and Anelich (1988), compare this one parameter model with a cascade of CSTRs in series with a plug flow. This two parameter model gives a better description of the measured RTD.

The bend in the logarithmical RTD, which is associated with stagnancy in Fig. 3 and 4 has been modelled by several authors. Bounie (1986) uses six different RTD models which all contain one or two cascades of CSTRs. The most simple model is a cascade of CSTRs. In the second model a plug flow in series is added and a dead volume in the third model. The fit of these models improve in this order. Only the last model can describe stagnancy by the introduction of the dead volume. The three other models have recycle or forwarding loops but these do not improve the curve fit significantly. The third model of Bounie (1986) can describe the bend found in Figs. 3 and 4 with four parameters: a plug-flow time, the number of perfect mixers, the part of the tracer which enters the dead volume and the time that it remains there. Boissonnat et al. (1988) uses a model consisting of two parallel cascades of CSTRs with three parameters: the number of CSTRs in both cascades and a mass flow partitioning coefficient of both cascades. The fit of this model is comparable to that of the 'dead volume' model of Bounie (1986).

In the RTD models of Bounie (1986) and Boissonat (1988) the direction of the leakage flow is assumed to be equal to that of the transport of the C-shaped chambers. However the direction of the leakage flows in the extruder is always in opposite direction. Therefore the relation between the number of CSTRs and the number of filled C-shaped chambers is different for each measurement on each extruder. When, at a constant degree of fill the specific feed rate increases, these models show a decrease in the calculated number of CSTRs. A similar response can be observed when the specific feed rate remains constant and the degree of fill of the chambers decrease. Therefore these models have limited use for upscaling, the modelling of sterilisation applications or the calculations of a temperature dependent reaction.

Janssen et al. (1979) and Speur (1988) describe a two-part RTD model for a counter-rotating, twin-screw extruder in which the leakage flows and the chamber transport have opposite directions. The first part is a plug flow which describes a zone in which the material is only transported in chambers without leakage flow. The second part is a cascade of CSTRs which move in the same direction as the plug flow. The leakage flows however are in opposite directions. Each turn of the screws the CSTRs move one position forward. Adjacent to the plug-flow one CSTR is added to the model and at the die end one CSTR disappears. Each CSTRs corresponds to one fully filled chamber in the modelled extruder and travels with a velocity comparable to that of the chambers in the modelled extruder. This model without degrees of freedom gives a reasonable curve fit for the measured E-curves of Janssen et al. (1979) but, as it does not describe the observed stagnancy the model shows considerable deviations with the logarithmical F-curve. The E-curves measured by Speur (1988) can not be described by this model. Speur (1988) described that there is a strong flow through the chamber: ' Due to this flow wash out of the chambers may occur, leading to longer break trough times than calculated from the model..'. Janssen (1978) also gives a description of this process. As, in this model the leakage flows and the chamber content are assumed to be completely mixed,the 'wash out' is not described in this RTD model.

Van Zuilichem et al. (1988), Jager et al. (1989) and Jager et al. (1991) describe the 'wash-out' of the leakage flows by a distribution pattern which sends a part of the leakages flow directly through the chamber. One possible pattern is shown in Fig. 7 (Jager et al. (1991) with the partitioning coefficient

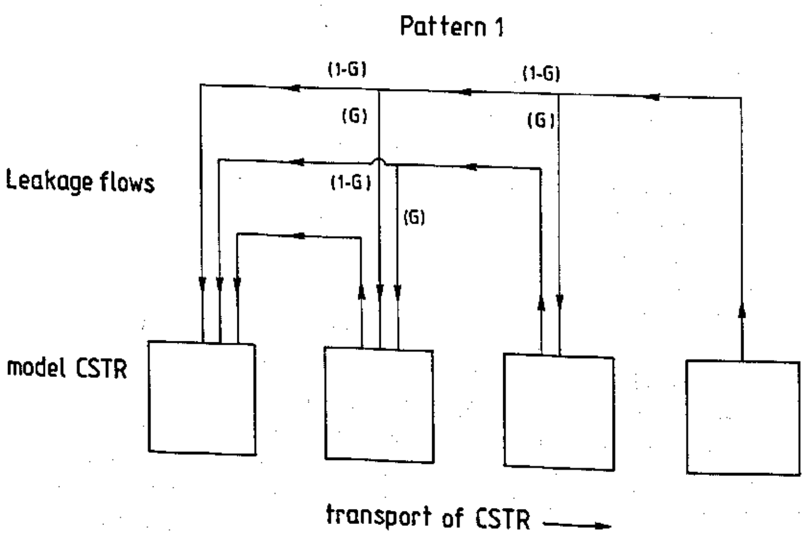

Fig. 7. Pattern of the distribution of leakage flows over different CSTRs.

G as the only parameter. There are more possible patterns which can result in similar RTDs. A second pattern which gives more axial backmixing was given by Jager et al. (1988). The zones in the extruder without leakage flows are not modelled by a plug-flow but by CSTRs without leakage flows. The CSTRs travel through the extruder as in the model of Janssen (1979).

The volume and degree of fill of the CSTR can vary axially which makes it possible to simulate both counter-rotating, twin-screw extruders with minimal-, and fully filled screw elements and corotating types which also have intermediate filled chambers. The fit of this model can be observed in Fig. 8. The model used by Van Zuilichem et al. (1988) and Jager et al. (1989) is formed by a row of CSTRs and such models can not describe stagnancy (Shinnar 1987; Shinnar and Naor 1967; Jager et al. 1991). However it is possible to fit a curve with stagnancy by this model by increasing the value of the partitioning coefficient after a certain time as can be seen in Fig. 9 from Jager et al. (1991). As this RTD model is an accurate description of the internal mass flow in an extruder, this curve fit procedure might describe the process in the extruder. In order to prove this it is necessary to measure which pattern of backflow is present in the extruder.

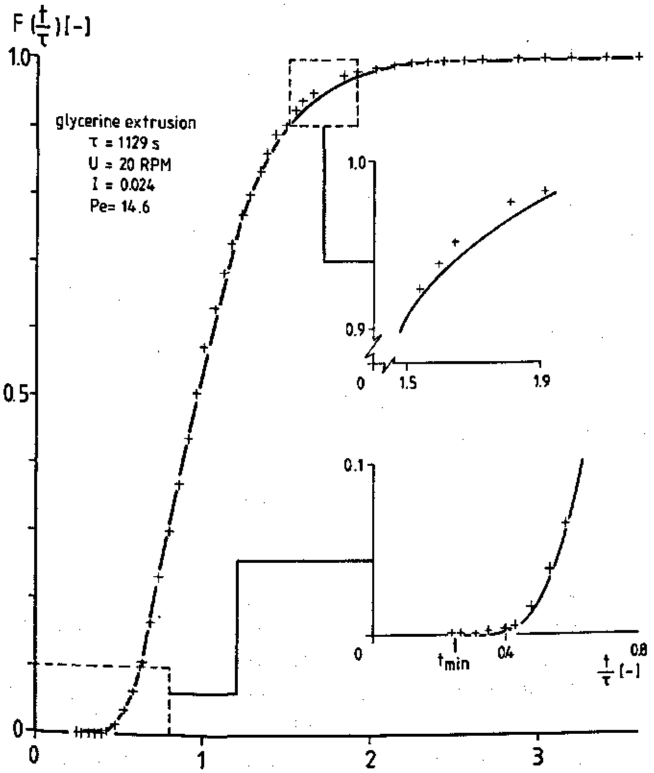

Fig. 8. RTD of a corotating twin-screw twin-screw extruder fed with glycerine.

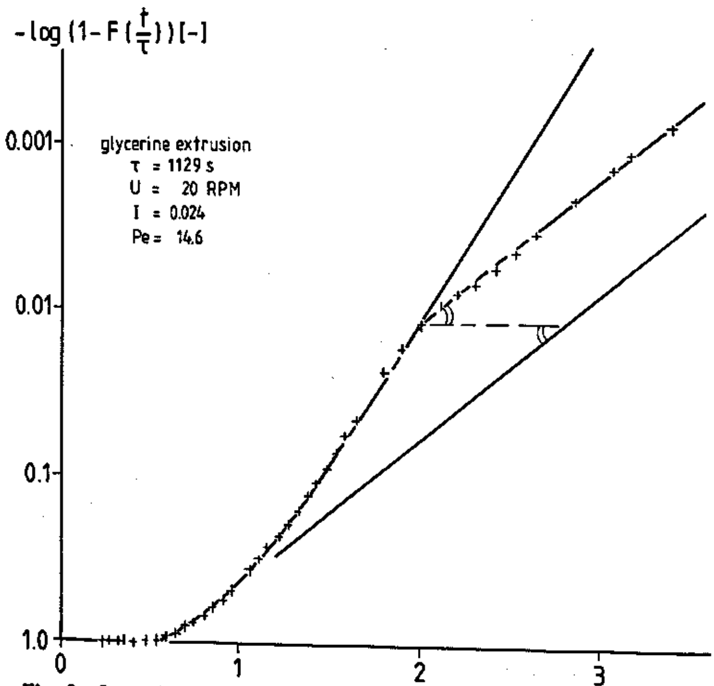

Fig. 9. Logarithmical RTD of a corotating twin-screw extruder fed with glycerin.

PREDICTIVE MODELS

Models which predict the RTD are given by Janssen (1976), Tayeb et al. (1988) and Kao and Allison. All models use Newtonian isoviscous fluids. And describe mainly the last zone of the extruder just before the die. Not one of the models can describe stagnancy. Three dimensional models of the flow in the chambers of a twin-screw extruder, where the RTD is used for confirmation of a theory were not found in the literature.

Janssen (1976) describes a model for the leakage flows and axial pressure profile in a counter-rotating, twin-screw extruder with an uniform screw profile. A two dimensional predictive RTD model for the reversed element is described by Tayeb et al. (1988). It solves the Navier-Stokes equation of pressure and mass flow for a fixed but representative position of the two screws. The pressure development of the reversed element in this model is reduced by several axial slots through the screw threads. Positive conveying flows go through these slots. Reversed flows through the intermeshing zone of the two screws. For cases without reversed elements, or with reversed elements without slots the model can not have any axial mixing. The model of Janssen (1976) but not that of these slots have not been found in the literature.

Kao and Allison (1985) calculate, for a variable degree of fill the pumping efficiency of a corotating twin-screw extruder by in order to predict the average residence time. The model is derived of a single-screw model. The described model acts as a plug-flow and consequently it does not describe the curve width. The specific feed rate, which is proportional to Q/U is in its turn proportional to the degree of fill D according to:

$$I \approx \frac{Q}{U} \approx D^2 \sum_{i+1=1,3..}^{\infty} n^{-3}.\tanh \frac{i.\pi.h}{4D.w} \tag{19}$$

In which h and w are respectively the channel depth and the screw pitch. The RTD responses of these three models are given in Table 5 accompanied by the average RTD and other responses from Tables 1 and 4. During the measurements solid material are converted to liquids. As this process is not described by the predictive models the results of Table 5 can not be used as a proof that these models are not valid. The model described by Tayeb et al. (1988) and Kao and Allison (1985) react for the average residence time and hold-up conform to the average behaviour from Table 1. However, the first model goes wrong on the prediction of the curve spread, while the second model neglects it.

Some other differences between models and measurements can be found: The average residence times predicted by Kao and Allison (1985) are approximately 50% of their observed values. All models suggest a fixed relation between the specific feed rate and the degree of fill. In contrast to this the relation found in some cases has to be described by an area as in Fig. 6. The models do not predict changes in the barrel temperature or viscosity. Similar studies on fluids with a more complex rheology than Newtonian case might result in a better understanding of industrial extrusion processes.

CONCLUSIONS

The RTD of a twin-screw extruder consists of three elements: plug-flow, axial mixing and stagnancy. These elements can be observed in all papers on this subject in which logarithmical F-curves, or an equivalent method to quantify the curve shape are used. The question which type of RTD modelling is necessary is governed by the experimental goal, but in order to model the listed elements adequately a minimal number of four parameters is required.

For the measurement of wear and the longitudinal smoothing of variations in the feed stream it is sufficient to describe the shape of the RTD with a Gauss-Weibull distribution (Potente and Koch 989), a model with a combination of plug-flow, a dead volume and a cascade of CSTRs (Bounie 1986) or a model with two parallel cascades of CSTRs (Boissonnat et al. 1988). Only the first model has the minimal required number of five parameters necessary to describe the shape of the RTD.

Table 5
Comparison between measured and predicted RTD responses.

predicted	change in	τ	H	spread	measured
Tayeb et al. (1988)	I constant U	i	p	i	
Kao and Allison (1985)	I constant U	i	p	?	
	I constant U	i	p	i	average response Table 1
Tayeb et al. (1988)	I constant Q	p	p	p	
Kao and Allison (1985)	I constant Q	p	p	?	
	I constant Q	p	p	i	average response Table 1
Kao and Allison (1985)	U constant I	-	-	-	
Janssen (1976)	U constant I	-	-	-	
	U constant I	p	p	-	Janssen et al. (1979)
	U constant I	i	i	m	Jager et al. (1989)
	U constant I	i	p	i	Mosso et al. (1982)
	U constant I	i	-	i	Jager et al. (1989)
	U constant I	i	-	-	Altomare and Ghossi (1986)
Tayeb et al, (1988)	Sloth width	i	i	i	no measurements found
Janssen et al. (1976)	Die resistance	p	p	p	
	Die resistance	i	i	-	Boissonnat et al. (1988)
	Die resistance	p	p	p	Von Lengerich (1984)
	Die resistance	-	-	p	Altomare and Ghossi(1986)
	Die resistance	p	p	?	Altomare et al. (1990) (slit viscosimeter)
	Barrel-valve resistance	p	p	p	Jager et al.(1990)
	Die resistance	p	p	i	Jager et al.(1989)
Kao and Allison (1985)	Barrel temp.	-	-	?	
	Barrel temp.	p	p	-	Altomare and Ghossi(1986)
	Barrel temp.	i	i	i	Jager et al.(1991)
	Barrel temp.	m	m	?	Kao and Allison (1985)
	Barrel temp.	i	i	i	Bounie (1986)
	Barrel temp.	i	i	p	Boissonnat et al. (1988)
	Barrel temp.	i	i	-	Bouveresse et al. (1982)
	Barrel temp.	p	p	i	Ferry-Wilczek et al.(1988)

p: Parallel response
i: Inverse response
-: No significant response
?: Unknown

The axial mixing in the twin-screw extruder is different for each section. When the RTD is used to model a sterilisation application or to monitor the reaction rate of a temperature sensitive reaction, the extruder must be modelled in a way that the different geometrical parts of the extruder can be identified. The only model which can describe the RTD while each chamber of the twin-screw extruder is represented by a specific part of the model is described by Van Zuilichem et al. (1988), Jager et al (1988) and Jager et al. (1991). This model can also be used for the analysis of RTD in scale-up projects for the description of stagnancy and to evaluate two or three dimensional models of the complex flow in the C-shaped twin-screw extruder chamber.

The described predictive models (Janssen 1976; Tayeb et al. 1988; Kao and Allison 1985) can not describe stagnancy and are only valid in model equipment. The extrapolation of these models towards non-Newtonian substances is hazardous. The responses of the measured RTD on changes in extrusion parameters are divers and can not be understood easily. Before these models can be improved it is necessary to identify the variables which cause this diversity.
The reactions of the RTD on the introduction of a kneading element, reversed element, drossel element or by placing the screw elements axially offset, given in Table 6 show less diversity.

Table 6
Effect of geometrical changes on the viscous dissipation and RTD in twin-screw extruders. The neutral situation is for a continuous cut screw.

change	viscous dissipation	τ	curve spread	stagnancy
reversed element	+	+	+	+
kneading element	+	+	-	0 or -
drossel element	+	+	-	?
offset screw elements	+	0	+	?

+: increased 0: No significant response
-: decreased ?: Unknown

An investigation of the influence of material properties on the RTD has only been described for the viscosity and the moisture content of food materials. Other material properties might affect the mass flow in the twin-screw extruder but their effects on the RTD still have to be measured.

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3. COINCIDENCE DETECTION OF RADIOTRACER

ABSTRACT

A method suitable for the measurement of residence time distributions in food extruders based on radiotracer techniques has been improved by the introduction of a coincidence detection system which replaces the single detector system with its asymmetrical sight angle of detection. The major advantage of the new system is the better resolution due to minimization of the sight angle. The influence of the detector arrangement on the residence time distribution curves for a single-screw extruder was measured and is discussed with the help of a residence time distribution model. ^{64}Cu was used as the tracer.

NOTATION

B(i)	filter coefficient
E(t)	exit age distribution (s^{-1})
F(t)	cumulative exit age distribution (s^{-1})
D_e	dispersion coefficient (m^2s^{-1})
i	counting variable
l	extruder length (m)
m	counting variable
S(x)	ratio of signal strengths measured from point x and from the centre line of the detector, with both points on a line normal to the centre line of the detector
t	time (s)
τ	average residence time (s)
v	axial velocity of the extrudate (ms^{-1})
<v>	average axial velocity (ms^{-1})
σ^2	variance of E(t) curve (s^2)
x	length on a line normal to the centre line of a detector (m)
X	axial length in an extruder (m)

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INTRODUCTION

In high-temperature, short-time (HTST) extrusion cooking of food the process time, together with factors such as shear distribution and temperature, are very important. The chemical reactions of biopolymers are extremely rapid, which means that every element of food must be subjected to as near as possible the same treatment, despite the existence in extruders of a distinct and continuous variation in the movement of food particles. This results in a residence time distribution (RTD) which depends on such engineering aspects as extruder design and the rheological behaviour of the process materials.

This series of papers deals with the following aspects of residence time distribution in food extruders: detection systems; RTD in single screw food extruders working on soya and maize doughs; modelling of RTD in a twin screw extruder; RTD in the feed zone, transport zone and compression zone of a counter-rotating twin-screw extruder fed with maize grits; and a study on the transformation of mechanical energy to shear in a twin-screw extruder with the help of an RTD model.

Earlier work was performed using a measuring system containing a single detector for measurement of RTD in a single-screw extruder (Van Zuilichem et al. 1973). The residence time distribution could be described by a model consisting of several continuously stirred tank reactors (CSTRs) in cascade in series with a plug-flow. Such a coincidence detector was used by Bartels et al. (1982) on a singl-e-screw extruder and by Van Zuilichem et al. (1982) on a counter-rotating twin-screw extruder.

THEORETICAL RTD ANALYSIS

The theory of residence time distribution as developed in chemical engineering uses the F-diagram and the E-diagram to summarize the RTD. The F-diagram shows the response at the output of the system when a stepwise change in the inlet concentration, e.g. of a tracer, is made. The E-diagram is the response of the system to a pulse-like injection of a tracer at the inlet (Danckwerts 1953; Levenspiel 1972; Kooyman 1972). Danckwerts defined the E(t)-function so that E(t)dt is the fraction , at the exit, of flow which has spent a time between t and (t+dt) in the system. The F(t)-function is obtained by integration to give a cumulative RTD function:

$$F(t) = \int_0^t E(t)\ dt \qquad (1)$$

The average residence time (τ) of the material in the extruder can be defined as:

$$\tau = \int_0^\infty t.E(t)\ dt \qquad (2)$$

The width of the E(t) curve can be described by the Peclet number (Pe) or the variance (σ^2) of the E(t) curve. The variance of the residence time can be calculated as:

$$\sigma^2 = \left[\int_0^\infty t^2 . E(t) dt \right] - \tau^2 \tag{3}$$

The Peclet number is the ratio of the average axial convective transport to the transport by dispersion, normally written as:

$$Pe = \frac{\langle v \rangle l}{D_e} \tag{4}$$

in which l is the extruder length, <v> the average axial velocity, and D_e the axial dispersion coefficient, defined by Levenspiel (1972), in a dispersed plug-flow model, by:

$$\frac{\delta E(t)}{\delta t} = De \frac{\delta^2 E(t)}{\delta X^2} \tag{5}$$

in which X gives the axial location in the extruder. For large extents of dispersion, which is the case in extrusion, the exit-age curve of eqn. 5 becomes asymmetrical and can only be solved numerically. However, the variance of this curve can be derived from eqn. 5 as:

$$\frac{\sigma^2}{\tau^2} = 2 \frac{Pe - 1 + \exp(-Pe)}{Pe^2} \tag{6}$$

PRINCIPLE OF THE DETECTION SYSTEM

^{64}Cu with a half-life of 12.75 hours has been used as a pulse-type tracer. It decays to two different stable isotopes, ^{64}Ni and ^{64}Zn, by four different pathways shown in Fig. 1. Electron capture (E.C.) and ß+ emission, both produce the stable ^{64}Ni, as one proton is transformed into a neutron. The detection system makes use of the ß+ emission mode of decay. The positron will be annihilated together with an electron with the radiation of two equal gamma quanta of 0.511 MeV each, in exactly opposite directions.

This phenomenon is used for a coincidence detection system consisting of two opposed detectors. Only when two quanta are detected coincidentally in both detectors are they counted. This will only happen when an annihilation occurs exactly on the centre line of the detectors (Fig. 2). This electronic discrimination enables residence time distributions to be detected with high resolution and free from the influence of background radiation. In earlier work (Van Zuilichem et al. 1973) a single collimated detector was used, reacting to all gamma quanta at a characteristic energy level. This detector reacted not only on radioactivity directly in line with the detector, but also to radioactivity on either side of

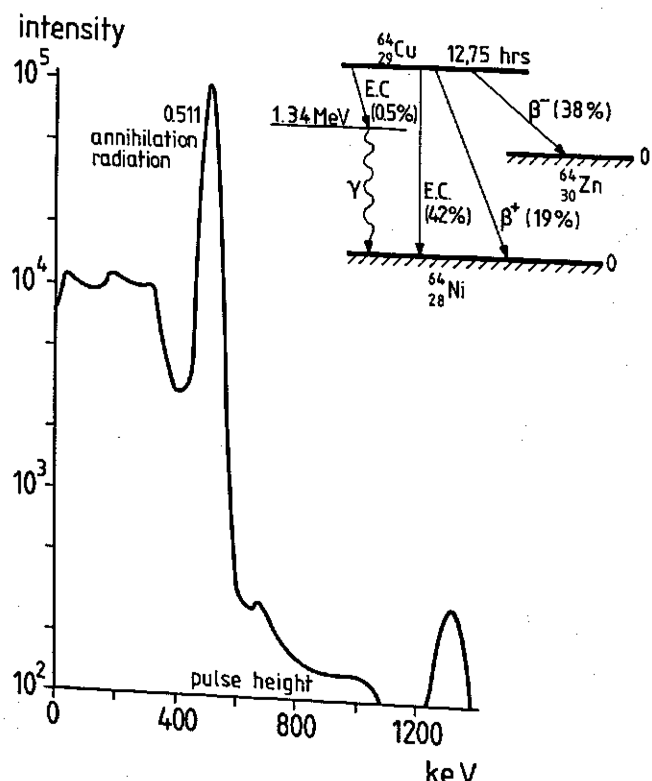

Fig. 1. Spectogram and decay modes of ^{64}Cu (Radiological Health Handbook, (1970).

it, the so-called sight angle of detection (see Fig. 2). The operating principle of the coincidence detector guarantees a minimal view angle, which is its main advantage over the single-detector arrangement.

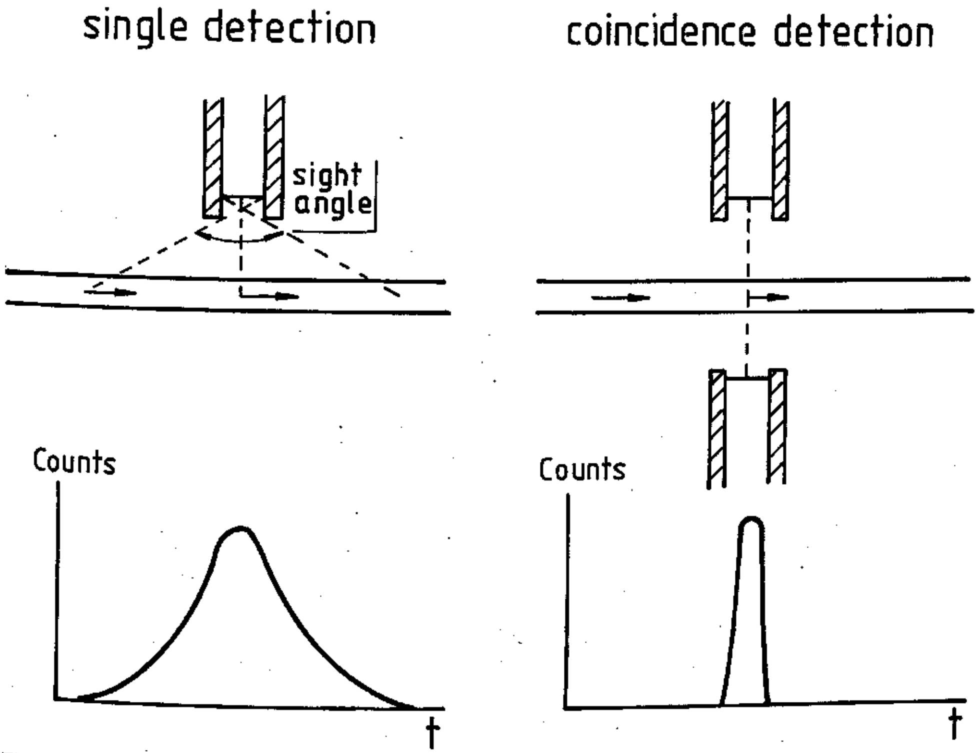

Fig. 2. A comparison of the view-factors for single detection and for coincidence detection.

SIGHT ANGLE DETECTION ERROR IN RTD MEASUREMENT

The sight angle of detection of a detector modifies the true RTD curve E(t), the curve required, to $E_m(t)$, the curve actually measured by the detector. The transformation from E(t) into $E_m(t)$ can be calculated from eqn. 7. The characteristic sight angle of detection of the detector used is here simulated by the mathematical filter B(i) having 2m+1 elements.

$$E_m(t) = \sum_{i=-m}^{i=+m} E(t - i\Delta t)B(i) \tag{7}$$

The filter coefficients B(i) were calculated by eqn. 8 from S(x), the ratio of signal strengths at a point x and at the centre line of the detector, with both points located on a line normal to the centre line of the detector.

$$B(i) = \frac{\int_{i.\Delta t.v}^{(i+1)\Delta t.v} S(x)dx}{\int_{-m.\Delta t.v}^{(m+1)\Delta t.v} S(x)dx} \qquad (8)$$

In which v is the velocity of the material leaving the extruder. This velocity depends on the extruder output and the average weight per metre of extruder output. When this velocity increases, the difference between E(t) and $E_m(t)$ decreases.

DETECTOR ARRANGEMENT

The detectors used consisted of a Harshaw scintillator (1¾×2 in) and an EMI photo-multiplier (type 6097). The pulses were selected at an energy level of 0.51 MeV by a single-channel analyser. Coincidence detection requires two detectors. In the coincidence detector arrangement, as shown in Fig. 3, a Laben multichannel analyser in time mode stores the counts in 1024 channels, but only when both detectors detect pulses of 0.51 MeV coinciding within 10^{-6}s.
After each RTD measurement the data are stored on magnetic tape. As the single detector reacts to background radiation it is equipped with a 3 cm thick lead collimator with a cylindrical aperture. This reduces the background radiation detected to the amount which passes through the aperture. Correction is made by subtracting from the total signal measured the average background radiation, which is measured before and after each measurement. The sight angle of the single detector is dependent on the dimensions of the aperture of the collimator and the distance between radiation source and collimator.

EXTRUDER

The RTD measurements were carried out on a 48-mm-diameter, single-screw, Almex/ Battenfeld extruder (Fig. 4), with a compression type screw of compression ratio 3:1. Maize grits, containing 85% starch and 8% protein, were extruded adiabatically with a maximum temperature of 200°C and a maximum pressure of 300 bar. As the scintillators are sensitive to small temperature fluctuations, a distance of 63 mm was allowed between the collimator and the hot extrudate.

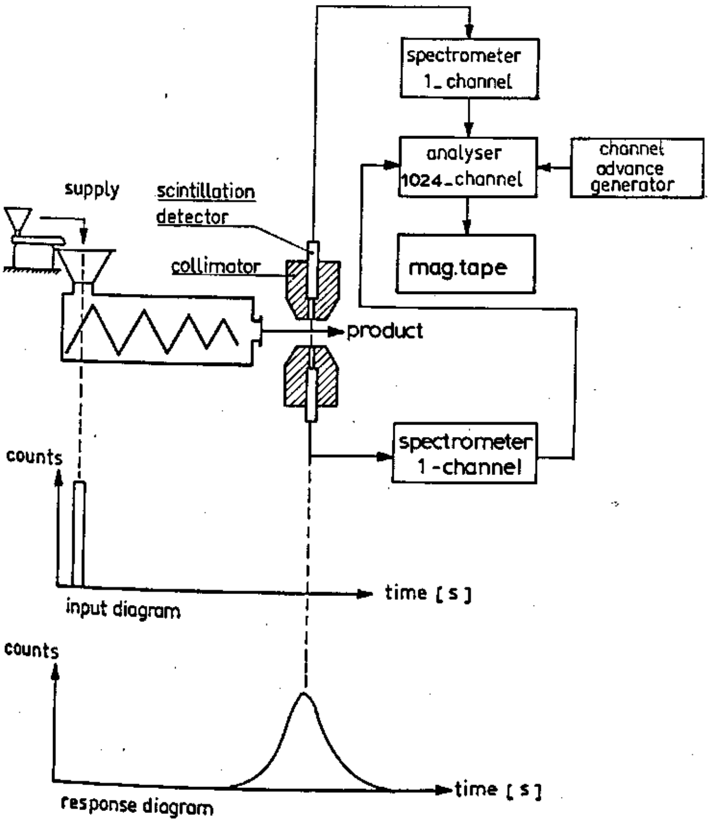

Fig. 3. Block diagram of the experimental arrangement.

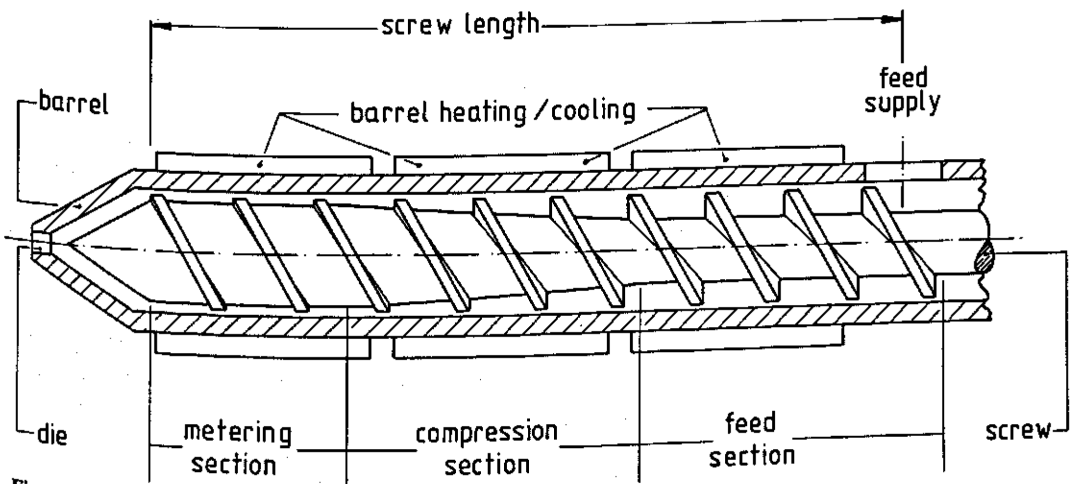

Fig. 4. Simplified representation of the extruder.

EXPERIMENTAL

The sight angles of the single detector and the coincidence detector were measured. A ^{64}Cu source 0.1 mm in diameter by 30 mm long was connected across the width of the paper strip of a chart recorder and drawn by the instrument past the detectors at right angles. The number of counts detected was plotted directly on the paper chart. This experiment gave plots, hereafter called sight angle detection plots, of measured intensity versus distance between the radiation source and the centre line of the detectors. The peak levels of these plots, when corrected for differences in source activity, could be used to compare the relative efficiency of the detector arrangements.

In the second experiment the RTD of a single-screw extruder fed with maize grits was measured, with both single detector and coincidence detector systems, to investigate the influence of the sight angle on the RTD-curves. The tracer was used in the form of maize grits soaked in $CuCl_2$ (copper chloride solution) and dried to a moisture content of about 12%.

The detector arrangement is shown in Fig. 2, one of the two detectors also being used as a single detector simultaneously. The detectors were shielded against background radiation by collimators having a detection opening of 44 mm. The minimum distance between collimator and the hot extrudate was 63 mm. The third experiment was concerned with determining the influence of the sight angle on the average residence time and the Peclet number. The output E(t) of a residence time distribution simulation model was modified to $E_m(t)$ by a mathematical filter B(i) as in eqn. 7. In the simulation the velocity of the extrudate leaving the extruder (v) was taken to be 0.01 ms^{-1}. The sight angle in the simulation model is the sight angle of the single detector arrangement in the second experiment, both as a symmetrical and as an asymmetrical sight angle. The asymmetry here is caused by the shielding of the tracer in the extruder by the extruder itself. The average residence time was calculated by eqn. 2. Equations 3 and 6 were used to calculate the Peclet number.

RESULTS

The sight angle detection plots, corrected for differences in source activity, showed the coincidence detector to have a considerably narrower and smaller signal than the single detector (Fig. 5). The maxima of both single-detector measurements are arbitrarily scaled as 100% signal strength. The signal strength of the coincidence detector, under comparable circumstances, is 25 - 30% of that, independently of source-to-scintillator distance. The signal strengths in both single and coincidence detection were proportional to the area of the aperture. In Fig. 5 the curve widths for the 10-mm aperture single detector and the 45 mm coincidence detector are comparable and have therefore comparable sight angles.

As the area of the 45 mm aperture is about 20 times the area of a 10 mm aperture, a 45 mm aperture detector provides, with an equal source, about 20 times the signal strength of a 10 mm aperture detector. The signal strength of the 45 mm coincidence detector is 25 - 30% that of the 45 mm single detector. Therefore the signal strength of a 45 mm coincidence detector, with equal sources, is five to six times that of a 10 mm aperture single detector. When the influence of the sight angle can not be neglected, the use of coincidence detection has to be preferred to single detector improved by a reduction in its aperture size. Fig. 6 gives the RTD-curves for a single-screw food extruder measured simultaneously by coincidence and single detectors. The single detector E-curve has been corrected for background radiation. The amount of tracer which is detected before the major peak by the single detector is falsified by its sight angle. Here the single detector gives a premature indication of the presence of tracer material. Two other differences between these curves caused by the difference in sight angle are: The peak of the single detector curve is later than the peak of the coincidence curve by about 0.4 s, and the decline of the coincidence curve after the peak-time is steeper than that of the single detector curve. The different peak-time is caused by an asymmetrical sight angle, as proved by the following experiment.

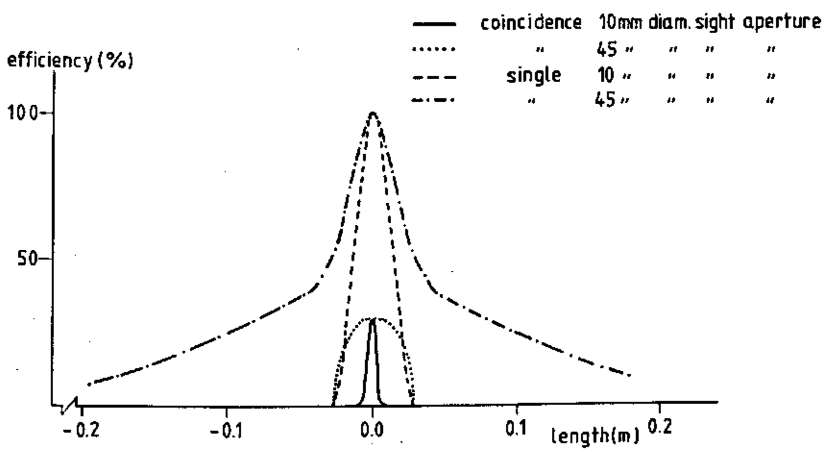

Fig. 5. Influence of sight angle on detection.

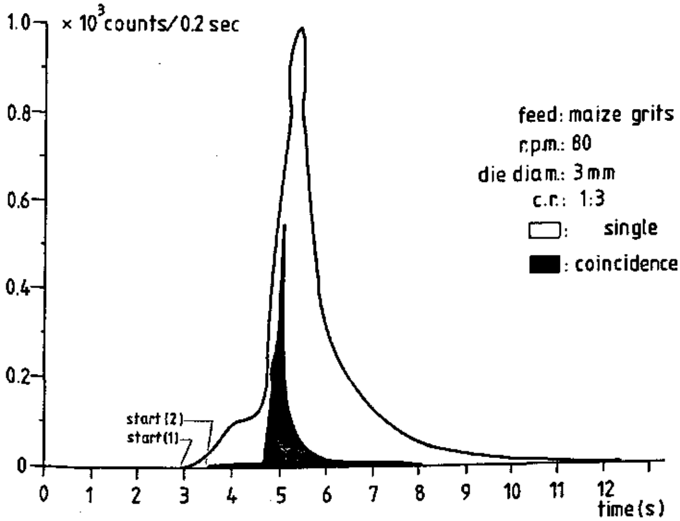

Fig. 6. RTD curves for coincidence and single detector.

As the influence of the sight angle on the average residence time and the Peclet number is small, accurate estimate of deviations of the average residence time and the Peclet number are calculated with help of an RTD simulation model. The results of some simulation runs of: a coincidence detector and single detectors with symmetrical or asymmetrical sight angles, all with collimators having an aperture diameter of 45 mm, can be found in Table 1. The symmetrical sight angle is shown in Fig. 5. The asymmetrical sight angle is identical, except for locations where the tracer is shielded by the extruder where S(x) becomes zero.

Differences in the average residence time (τ) (see Table 1) are only present with an asymmetric sight angle detection, because in the case of a symmetrical sight angle the detection before balances that after the point of detection. The Peclet number is reduced in the case of a symmetrical sight angle. The effect of an asymmetrical sight angle is more complex, as the increase in the average residence time increases the Peclet number. At low Peclet numbers the asymmetrical sight angle increases the Peclet number, whilst at high Peclet numbers a reduction is found.

Table 1
Influence of sight angle on RTD coefficients

Coincidence detector		Single detector			
		Symmetric sight angle		Asymmetric sight angle	
τ (s)	Pe (-)	τ deviation (%)	Pe deviation (%)	τ deviation (%)	Pe deviation (%)
13.5	21	0	-15	+4	-1
14.1	17	0	-12	+4	+1
14.7	14	0	- 9	+4	+2
15.5	12	0	- 7	+3	+3
16.3	10	0	- 6	+3	+4
17.1	8.6	0	- 5	+2	+4
18.0	7.4	0	- 4	+2	+4

CONCLUSIONS

The coincidence detector is far superior to the single detector in respect of sight angle and noise reduction. A single detector can have a sight angle comparable to that of a coincidence detector if the size of the detector aperture is reduced. In the practical range of detector-to-source distances, for extruder RTD measurement, the aperture area should be reduced to 5%, in order to obtain a sight angle, comparable to a coincidence detector with the original aperture size. As the coincidence detector measures 30% of the number of counts a single detector measures in comparable circumstances. And the number of counts detected is proportional to the detector aperture area, the use of a single detector with a sight angle comparable to that of a coincidence detector requires six times the amount of tracer material for the same signal strength.

The RTD measurement shows the influence of sight angle to be significant, and the sight angle of the single detector used to be asymmetrical. This results in small differences in both the average residence time and the Peclet number, which affects the accuracy of RTD measurement.

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4. THE FEED ZONE OF A CONICAL, COUNTER-ROTATING, TWIN-SCREW EXTRUDER PROCESSING MAIZE GRITS

ABSTRACT

The residence time distributions in the feed zone of a counter-rotating, twin-screw extruder processing maize-grits, were measured by means of a ^{64}Cu tracer. The detection system was mounted above the transport zone of the extruder. Three different screw pairs were investigated. The residence time distribution measurements were analysed by means of an axial mixing model developed for a twin-screw extruder. The feed rate was found to be the most important variable affecting the average residence time. The average residence time was inversely proportional to the screw speed. Measurements could be simulated by assuming backmixing action over approximately 15% of the axial length of the screw. Geometrical devices in these screw pairs, such as kneading zones and so-called drossel zones (high shear throttle valves), resulted in a significant increase in the average residence time. Their action can be simulated by means of an axial plug-flow model.

NOTATION

B	the fraction of backmixing mass-flow going to the first CSTR of the model
exo	a series of measurements of residence time
I	feed rate as ratio of the maximal theoretical possible volumetric feed rate
L	dimensionless axial screw length
M	number of backmixing CSTRs in the feed zone
N	number of CSTRs in cascade
N_a	the apparent number of CSTRs without correction for the plug-flow time
P	plug-flow time (s)
Pe	Peclet number; ratio of transport by convection to transport by diffusion
per	a series of measurements of residence time
t_{min}	minimum residence time (s)
Q	volumetric feed rate (m^3s^{-1})
U	rotational speed of the screws (s^{-1})
σ^2	variance of residence time distribution curve
τ	average residence time (s)

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INTRODUCTION

The feed zone of the twin-screw extruder is rarely subjected to scientific attention except in relation to feeding problems. In Chapter 3 a significant degree of axial mixing in both the feed and compression zones of a conical, counter-rotating, twin-screw extruder was reported. Olkku et al. (1980), however, could not detect any axial mixing in the feed and transport zones of a co-rotating, twin-screw extruder, which is consistent with a low degree of fill in the chambers between the inlet and the reversed screw described by Collona et al. (1983), Yacu (1985) and Roberts and Guy (1986). This is not as contradictory as might appear as the pumping efficiencies and other characteristics of these two extruders are too different (Martelli 1982) for the same mechanism of axial mixing to be expected in them.

The axial mixing in the feed zone (in Chapter 3) is not caused by any physical barrier such as a reversed screw or barrel valve, and its causative mechanism could not be found in the literature. Therefore, the feed zone of the conical, counter-rotating, twin-screw extruder has to be regarded as a reactor distinct from the HTST (high temperature short time) reactor of the compression zone. This present discussion considers the residence time distributions of this reactor when the extruder is fed with maize grits.

THEORY

In the transport zone the content of each of the chambers is approximately equal to the amount of grits fed during the time for one screw rotation. The dough expands by evaporation of the water it contains and a porous material is formed, as the leakage flow between the chambers of the transport zone is zero or very small. The hold-up volume in the feed zone and compression zone is increased by leakage flows through the gaps of the C-shaped chambers. In the compression zone mass flow occurs due to an axial pressure gradient between the chambers (Janssen 1978), resulting in zero porosity of the contents of these chambers (Van Zuilichem et al. 1988b). The pore contents are squeezed out of the dough at the beginning of the compression zone and leave the extruder through the feed inlet or condense in the feed zone.

Axial mixing was reported to take place in the feed zone of a screw set without physical barriers (Chapter 3). It is believed that the leakage flows between chambers in the feed zone arise from the backblowing of grits by expelled pore gases. By the combined action of backblowing and the conveying action from the first chambers, a small high-density zone is formed. Here grits are compressed by screw rotation and lose their structure. The high degree of fill in this high-density zone is caused by substantial leakage from the chambers immediately beyond.

The mass flows in the feed zone are caused by complex interactions of such factors as the pressure in the transport zone, the condensation of water in the feed zone, the lubricating effects of water, the water content and temperature of the gas stream, the filling degree of the chambers and the flow properties of the bulk solid.

The amount of axial mixing in a system can be quantified by the Peclet number (Pe), the variance of the residence time distribution (σ^2) or by the number of equivalent CSTRs (N) (continuous stirred tank reactors). They are related (Levenspiel 1972) by

$$N = \frac{Pe^2}{2(Pe-1+\exp(-Pe))} \tag{1}$$

and

$$\frac{\sigma^2}{\tau^2} = \frac{1}{N} \tag{2}$$

in which τ is the average residence time. When a system with N CSTRs is enlarged by the addition, in series, of a system without axial mixing, the apparent number of CSTRs (Na) increases. The introduction of the plug-flow time (P) will not affect the variance of the residence time distribution but the average residence time τ is increased by P. Hence the apparent number of CSTRs (N_a) according to eqn. 2 is

$$N_a = N \frac{(\tau+P)^2}{\tau^2} \tag{3}$$

This equation is useful in studying axial mixing in a twin-screw extruder independently of plug-flow times for all possible values of N.
The residence time distribution curves are analysed by means of the axial mixing simulation model of a twin screw extruder, as described by Van Zuilichem et al. (1988a) in Chapter 3. This model consists of an endless row of CSTRs travelling with the velocity of the screw chambers through a simulated extruder. After one rotation of the screws all chambers have moved forward one position in the row. Each CSTR represents the extruder chambers on a diagonal plane through both screws. The CSTRs can only lose their contents by backward leakage flows to CSTRs nearer to the feed-inlet of the simulated extruder.
The feed zone of the model consists of CSTRs, numbered in the direction of the die of the simulated extruder, of which the last M CSTRs produce leakage flows. In the first two CSTRs, located in the open feed-inlet, the velocity of the backblowing gases is too low to cause a mass-flow. In the model it is possible to vary the average velocity of the backblown grits with the so-called backmixing coefficient (B). A fraction B of the mass-flow leaving the j-th CSTR, goes directly to the first CSTR in order to simulate the backblowing of grits. The remainder (1-B) goes to the (j-1)-th CSTR.

The simulation model produces residence time distribution curves, average residence times, Peclet numbers and an axial profile of the degree of fill, as described in Chapter 3. The average residence time is simulated within 0.1 s, and the Peclet number within 0.1 units, of the measured values. The degree of fill of the extruder chambers was not measured during the residence time distribution measurements. In Fig.1 the average residence time multiplied by the rotational speed of the screws, which equals the number of screw rotations, and the Peclet numbers are given from simulations of screw type 506, for different values of the number of backmixing CSTRs (M) and the backmixing coefficient B. When M=9 the combinations of mean residence time and Peclet numbers are sensitive to the value of B for B<0.5. For B>0.5 the number of backmixing CSTRs and the value of B itself have less effect on the combinations of mean residence times and Peclet numbers.

The leakage flows in the simulation model of the feed zone are proportional to the contents of the CSTRs with a constant ratio for all the M backmixing CSTRs. Other leakage flow profiles which can simulate the measured RTD curves with M leaking chambers are possible, but the velocity coefficient B is more important in determining which combinations of average residence times and Peclet numbers can be simulated. When, for example, a leakage flow profile with a linearly increasing ratio of leakage flow to CSTR content is used, the combinations of average residence times and Peclet numbers are nearly identical to the results of a leakage flow profile with a constant ratio. This last leakage flow profile is preferred as it requires the smaller number of coefficients.

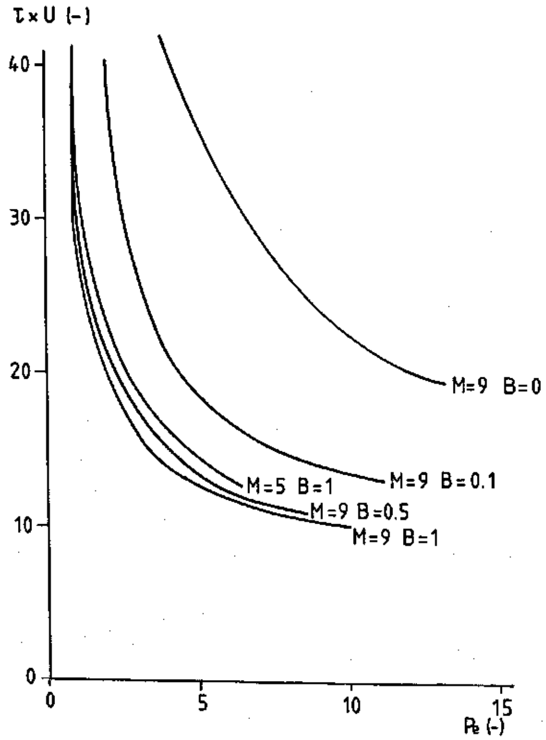

Fig. 1. Possible combinations of average number of screw rotations (T×U) and Peclet numbers in feed zone simulations of screw type 506 with five or nine backleaking chambers (M) and variable velocity coefficient (B).

MATERIALS AND METHODS OF MEASUREMENT

Extruder and screw geometry

The extruder used was a Cincinnati CM45 conical, counter-rotating, twin-screw extruder. The geometry of the screw pairs used is stated in Tables 1 and 2, which specify their number of thread starts, axial chamber length, the ratio of channel volume to thread volume, the volumetric compression ratio and gap dimensions.

Table 1
Screw geometries

Screw pair	Axial length L	Channel width (mm)	Thread width (mm)	No. thread starts	Chamber length (mm)	Volumetric compression rate
1552	0.00 - 1.00	13	11	2	48	2.1 : 1
506	0.00 - 0.89*	12	8	2	40	1.6 : 1
	* with kneading zones at L=0.37 and L=0.64.					
	0.89 - 1.00	17	7	3	66	
507	0.00 - 0.37	22	19	1	41	1.5 : 1
	0.37 - 0.42*	* drossel zone				
	0.43 - 0.62	15	12	4	108	
	0.62 - 0.89	17.5	15	2	65	
	0.89 - 1.00	13	9	3	66	

Table 2
General screw geometry

Length	1.00	m	
Calender gap	0.5	mm	
Flight gap	0.2	mm	
Maximum diameter	90	mm	(one screw)
Minimum diameter	45	mm	(one screw)

The dimensionless screw length (L) is the axial length at a position on a screw, divided by the total screw length. A schematic representation of the screw pairs is given in Fig.2. Screw pair 1552, the simplest design used, has a single continuous section on each screw. Screw pair 506 has two sections on each screw: the first section has two kneading zones, of which the first is located at the boundary between the feed and transport zones. Screw pair 507, designed for PVC extrusion is provided with a drossel zone in the feed zone, which functions as a high-shear throttle valve.
The material fed to the extruder has to be pumped through this zone by a section of fully filled chambers. The minimum residence times (t_{min}) for the detection system, located at L=0.5, can be calculated from the geometrical data given in Table 1, with the assumption that the minimum residence times in the kneading zone and drossel zone are equal to the minimum residence time in a normal screw zone of the same length. With screw pairs 1552, 506 and 507 the minimum residence times are equal to the times necessary for, respectively, 7,7 and 8 rotations of the screws.

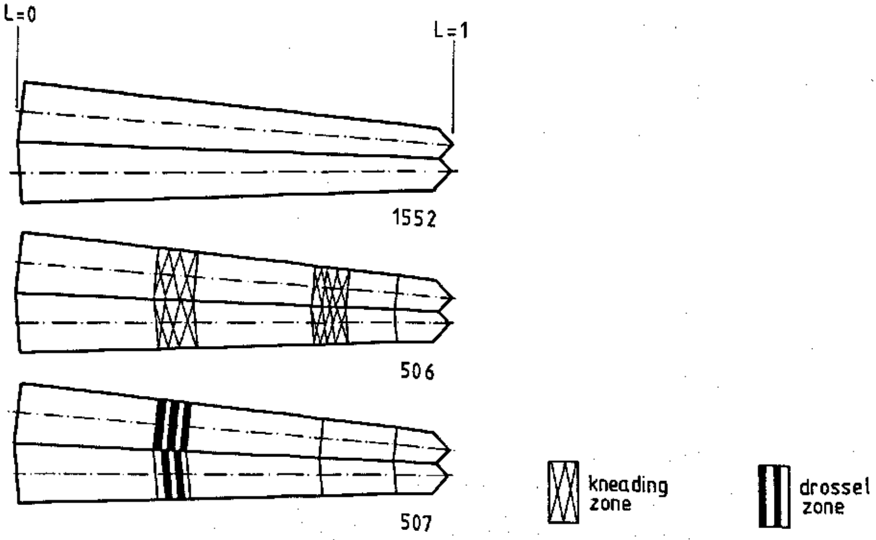

Fig. 2. Schematic screw geometry.

Table 3
Size distribution of maize grits used. (Moisture content 13.1%, wet basis)

Size (mm)	Fraction (%)
< 0.50	0.8
0.50 - 0.60	1.7
0.60 - 0.70	9.2
0.70 - 0.85	26.5
0.85 - 1.00	54.2
> 1.00	7.5
total	99.9

Material processed and extrusion conditions

The extruder was fed with coarsely milled, degermed maize grits containing 85% starch and 8% protein. The water content was either 13%-14% or 25% (wet basis). The particle size distribution is given in Table 3. The barrel temperature in the first section of the feed zone was 65-70°C, rising to 100°C in the last section. The diameter of the die was 20 mm, 15 mm or 10 mm.

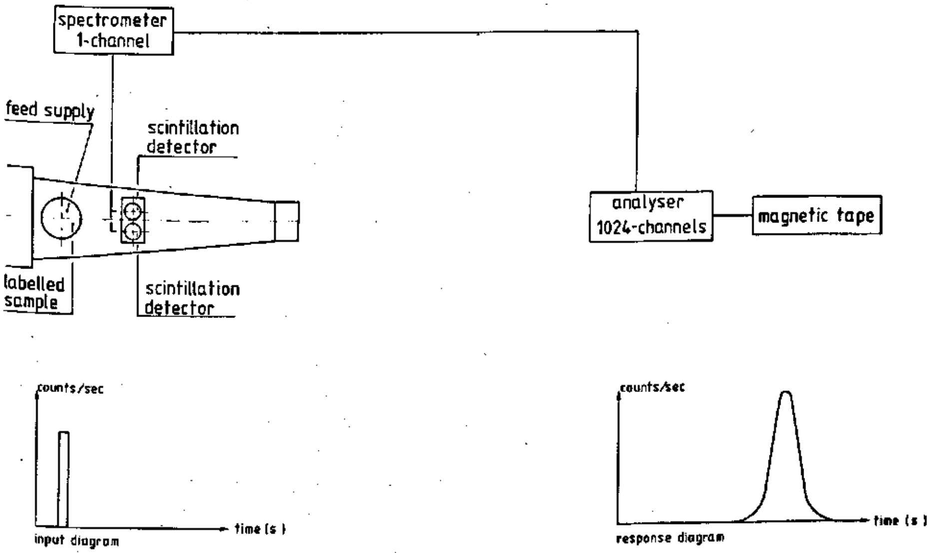

Fig. 3. Block diagram of the arrangement for measurement of residence time distribution.

Methods of measurement

Two scintillator detectors were placed at the midpoint of the screw length (L=0.5) one normal to the axis of each screw. The merits of the detection system are discussed in Chapter 3. A schematic diagram of the whole arrangement is shown in Fig.3. The background radiation noise was measured before and after each measurement and corrected for. The detected average residence time distributions were processed in a computer in order to produce Extinction-curves, average residence times and Peclet numbers as described in the Chapters 1 and 3.

RESULTS AND DISCUSSION

The RTD measurements and simulations in Table 4 are chosen as a representative 30% of all measurements. Each series of measurements is identified by a particular group of letters and each measurement in a series by a number in sequence.

Screw pair 1552

Per 5 is the only measurement during which there was no pressure build up in the compression zone of the extruder. This was caused by slip of the extrudate in the die outlet. The steam, which evaporated in the transport zone, could leave the extruder directly through the die.
The absence of backblowing gases resulted in a small backmixing coefficient B, a minimal degree of axial mixing, a short average residence time, and a large Peclet number. All other measurements with screw pair 1552 (see Table 4 and Fig.4) can be simulated with a minimum number of five backmixing CSTRs, and a backmixing coefficient B of between 0.2 and 1.

Fig. 4. Measurements and simulations of average number of screw rotations (T×U) versus Peclet numbers for the feed zone of screw type 1552.

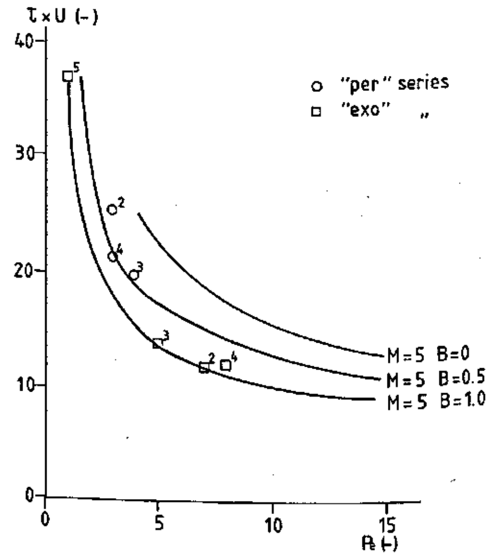

Table 4
Results: Measured average residence time and Peclet number and simulation parameters for the backmixing coefficient and plug-flow time used for a representative number (30%) of measurements.

Measurement	Screw type	I	Moisture content (%ww)	Die diameter (mm)	U (s_{-1})	τ (s)	Pe	B	P (s)
per 2	1552	0.14	25	15	0.33	77	3	0.2	0
per 3	1552	0.14	25	15	1.00	20	4	0.2	0
per 4	1552	0.15	25	15	1.33	16	3	0.5	0
per 5	1552	0.10	13	15	1.33	9	18	0.018	0
exo 3	1552	0.20	25	20	1.00	14	5	1.0	0
exo 4	1552	0.20	25	20	1.33	9	8	0.5	0
exo 5	1552	0.05	25	20	1.33	28	1	1.0	0
nif 3	506	0.21	25	20	1.33	24	5	1.0	5
nif 7	506	0.12	14	20	1.33	31	5	1.0	6
nif 9	506	0.09	14	20	1.33	39	5	1.0	9
nif 10	506	0.04	14	20	1.33	73	4	1.0	21
eex 2	507	0.12	14	10	0.67	41	5	1.0	8
eex 3	507	0.11	14	10	0.50	49	9	1.0	22
eex 4	507	0.15	25	10	0.93	29	10	1.0	10

If the number of backmixing CSTRs is reduced to four only, measurement per 2 cannot be simulated. When B=0 the velocity of the backmixing mass flow in the feed zone is equal to the transport velocity of the screw chambers and some backmixed particles would remain at the same axial location. For B>0, a fraction of the backmixing mass flow must have a velocity which exceeds the transport velocity of the chambers.

In Fig. 4 two clusters of measurements are shown: exo 2,3,4 and per 2,3,4. One important difference between the two clusters (see Table 4), due to an as-yet unknown factor, is the smaller velocity coefficient B of cluster per 2,3,4. It might be expected that the value of B is related to the pressure and gas transport magnitudes in the transport zone. The longer average residence times at the same rotational speed of the screws are mainly caused by smaller feed rates.
The average residence time is inversely proportional to the screw speed. In the clusters per 2,3,4 and exo 2,3,4 the rotational speed of the screws increases with the measurement-number from 20 to 80 rpm for per 2,3,4 and from 40 to 80 rpm for exo 2,3,4 (see Table 4). In Fig. 4 there is no evidence of a systematic influence of the rotational screw speed on the number of screw rotations, $T \times U$, or the Peclet number.

Screw pairs 506 and 507

Residence time distribution measurements on screw pair 506, with a kneading zone situated at about one-third along the screw length, gave a much longer average residence time than screw pair 1552 (compare exo 4 to nif 3, and exo 5 to nif 10 in Table 4). The minimum number of CSTRs necessary to simulate the 506 measurements is twelve, equal to 56% of the screw length, whereas screw pair 1552 could be simulated with five backmixing CSTRs.

Differences in average residence times and number of CSTRs may be explained by the presence of the kneading zone, as other geometrical differences are small (Table 1). Assuming the axial mixing effects of both screw pairs to be similar, proper simulations can be made with the introduction of a plug flow time P in the kneading zone of the 506 screw pair. This implies that axial mixing action in this zone is small, which is consistent with the absence of pressure build up across it. When the plug-flow time is added to the average residence time of the model, the Peclet number is corrected by means of eqns. 1 and 3. Optimal combinations of these average residence times, Peclet numbers and plug-flow times are found by means of a random-search algorithm. In Fig.5 the residence time distribution measurements are in this manner projected on to the maximal backmixing curve (B=1). The vertical axis now gives the number of screw rotations during the average residence time in the feed zone excluding the plug-flow residence time in the kneading zone.

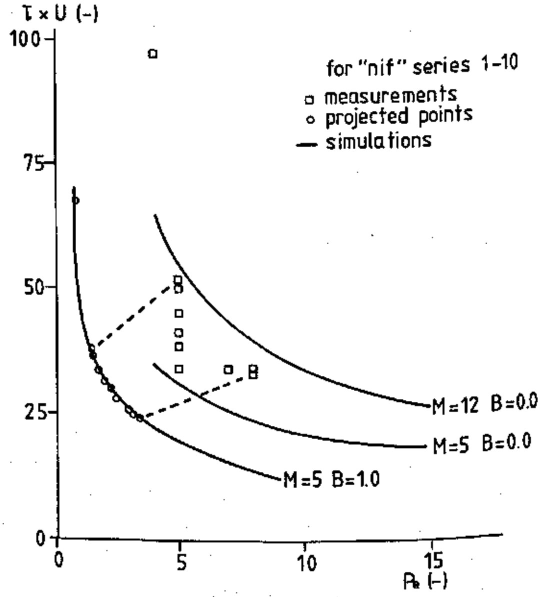

Fig. 5. Measurements and simulations of average number of screw rotations (T×U) versus Peclet numbers for the feed zone of screw type 506.

The error in the plug-flow time due to the assumption that the backmixing coefficient B=1 was estimated to be the time for four screw rotations, by comparing the values of P on the maximal velocity curve in Fig.5 with values for which B=0.1. This value of the velocity coefficient is less than the minimum value found with screw pair 1552. The error in the mean residence time is equivalent to about half a screw rotation.

When the plug-flow time is taken to be zero, the results of the 507 measurements can be simulated by assuming small leakage flows between all the chambers of the feed zone and a low velocity for the backmixing mass flows, resulting in an almost equal degree of fill in all chambers of the feed zone. However, when screw pair 507 was brought to a complete stop, during extrusion of maize grits, the porosity of the contents of the chambers in the feed zone was different, ranging from nearly zero in the drossel zone to a high porosity in the transport zone. Such a variable porosity could be simulated by the introduction into the model of a plug-flow component.

Plug flow

The plug-flow component for the 507 and 506 screw type measurements, calculated by the procedure described in the previous section, are shown in Fig.6. The measurements with a plug-flow time equal to or smaller than the calculation error and a feed rate I>0.15, are excluded from this figure. The

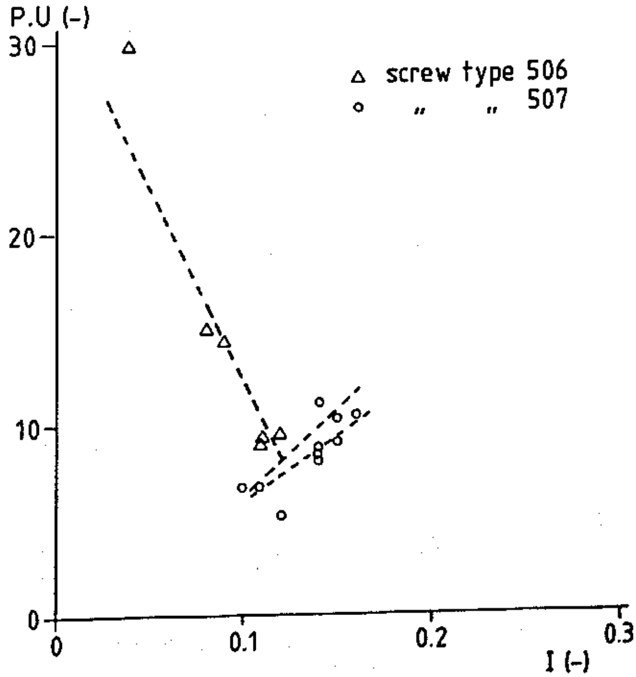

Fig. 6. Calculated plug-flow time 'P' multiplied by the rotational speed of the screws 'U' versus the feed rate 'I' for measurements on screw types 506 and 507.

relationships between the plug-flow time and the feed rate appear very different. With screw pair 507 the plug-flow time increases with increasing feed rate. As the filled volume in the drossel zone is constant and as the mass flow rate through the drossel zone increases with increasing feed rate, the mass flows which cause the increase in the plug-flow time cannot be located inside the small channels of the drossel zone but must be sought just in front of the drossel zone. This suggests a hold-up mechanism which functions as a funnel.

The material fed to the extruder has to wait before it can enter the drossel zone and this waiting time increases with the feed rate. However, additional measurements have to be carried out to prove this relationship for feed rates below I<0.1. The plug-flow component for the screw pair with two kneading zones (506) increases when the feed rate decreases, suggesting that the dough in the kneading zone only moves when a minimum degree of fill is reached. It is not suggested that all the material in the kneading zone moves in plug-like flow. As the model does not predict the location of the calculated leakage flows, a part of the axial mixing in the feed zone might actually occur in the kneading zone.

Average residence time

Figures 7 and 8 show the effect of the feed rate on the average residence time, adjusted for the plug-flow time P and the rotational speed of the screws (U), for all three screw pairs. Measurements

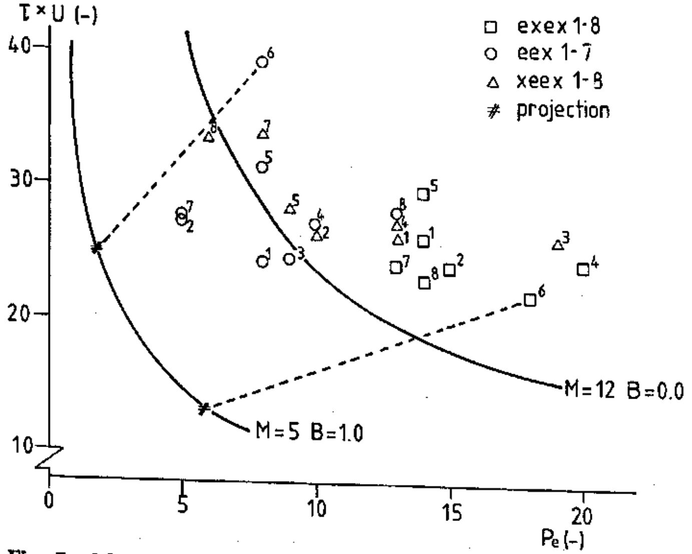

Fig. 7. Measurements and simulations of average number of screw rotations (T×U) versus Peclet numbers for the feed zone of screw type 507. Two points, for which the average residence time 'T' is reduced by the plug-flow time 'P', are projected over the dotted lines onto the line for simulations with five backleaking chambers and a maximal backmixing coefficient 'B'.

for screw pairs 506 and 1552 are similar in behaviour, as can be seen in Fig.7; a decrease in the feed rate results in an increase in the average residence time. The feed rate for measurement exo 5 is a quarter of that for measurements exo 2,3,4 (Table 4) which results in a threefold increase in average residence time. This shows the feed rate to be the most important variable affecting the average residence time. This conclusion can also be drawn from measurements on screw pair 506 (Figs. 6 and 7).

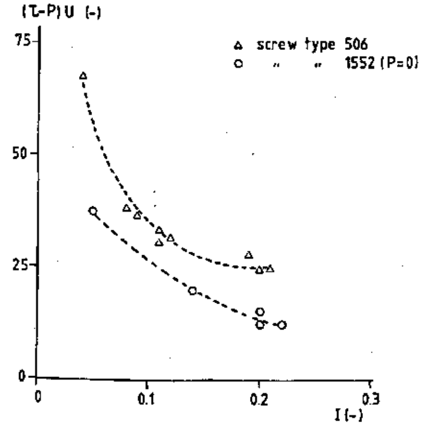

Fig. 8. Average number of screw rotations 'T×U' corrected for the plug-flow time 'P' versus the feed rate 'I' for measurements on screw types 506 and 1552.

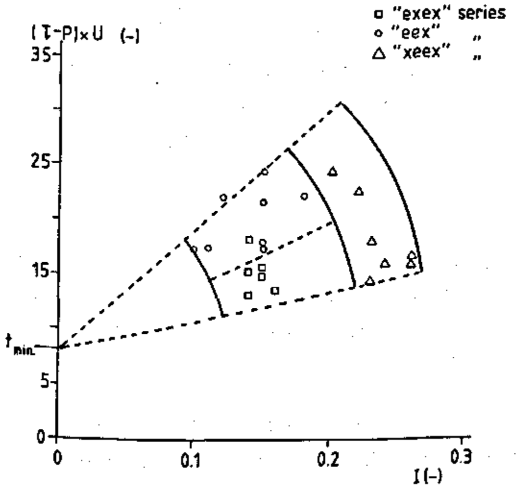

Fig. 9. Average number of screw rotations 'T×U' corrected for the plug-flow time 'P' versus the feed rate 'I' for measurements on screw type 507. The dotted lines are extrapolations.

The measurements from screw pair 507 given in Fig.8 show a tendency to cluster in three separate groups which was absent in Fig.9. Figures 7 and 8 show the mechanism of axial mixing of screw-pair 506 and 1552 to be different from that in screw set 507. The greater scatter of the 507 measurements compared with the 1552 and 506 measurements points to a hold-up mechanism which is irregular in nature, probably caused by the small dimensions of the channels in the drossel zone in relation to the high viscosity of the dough.
When the feed rate increases, the resistance of these small channels increases and a longer length of fully filled chambers upstream of the drossel zone is necessary to pump the material through. This results in an average residence time which increases when the feed rate increases, as suggested by the dotted lines in Fig.8. When these lines are extrapolated towards zero feed rate the minimum residence time (t_{min}), calculated from the geometry of screw set 507, is found. This extrapolation is an indication that the amount of axial mixing in the feed zone can be changed by varying the dimensions of the channels in the drossel zone, and thereby its resistance. As this particular drossel zone was designed for PVC and the RTDs of screw set 507 were not measured at feed rates below $I < 0.1$, this has to be regarded as speculative.

CONCLUSIONS

A backmixing action could be found in the feed zone of a continuously cut screw set (type 1552). When slip occurred in the die, the extruder could not build up pressure in the compression zone, which changed the RTD towards a minimal average residence time and curve spread.
As in these extrusion conditions the steam, which evaporates in the transport zone, can leave the extruder through the die, and as this screw set lacks any physical barriers, it is believed that the backmixing is caused by backblown gases from the transport zone.

The minimal number of backmixing CSTRs in the simulation model of screw set 1552, necessary to simulate the residence time distribution measured, is equivalent to approximately 15% of the screw length. These RTD's could be simulated by the RTD model by assuming that a part of the leakage flows did not mix with the chamber contents.

The measurements on the screw pairs with impeding devices, such as drossel or kneading zones could be simulated by assuming that all the chambers in the feed zone of both screw pairs of the simulation models are filled to the same extent. As the degree of fill in the chambers of these screw pairs was different, a plug-flow time component has to be introduced, in order to match the measured combinations of Peclet number and mean residence time.

The plug-flow time for the screw pair with two kneading zones (506), calculated with B=1 and M=5, was found to be strongly influenced by the feed rate. When the feed rate increased, the plug-flow time and the mean residence time decreased. The average residence time for the screw pair without impeding devices (1552) reacted similarly to changes in the feed rate. Minimal axial mixing in the feed zone can be achieved by maximizing the feed rate for these screw sets.

The average residence time and plug-flow time in the feeding zone of screw pair 507 were irregular compared with the other screw pairs investigated. The plug-flow time and the average residence time did not decrease with increasing feed rate.

The average residence times in all screw sets were inversely proportional to the rotational speed of the screws. The rotational speed of the screws did not influence the Peclet number.

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5. THE COMPRESSION ZONE IN A COUNTER-ROTATING, TWIN-SCREW EXTRUDER FED WITH MAIZE GRITS

ABSTRACT

Residence time distributions in a Cincinnati CM 45 counter-rotating, twin-screw extruder with three different screw designs were measured. The results were analysed by means of a model specially developed to simulate the residence time distribution for a given screw geometry. It was found that a kneading element in the compression zone increases the average residence time considerably. The residence time in this zone is feed-rate dependent and 10-60% of the hold-up volume is occupied by plug flow. In screw pairs without a kneading element the average residence time in the compression zone was independent of the feed rate, but dependent on the moisture content and the diameter of the die.

A decrease in moisture content increased the average residence time. The 20 mm and 15 mm dies gave almost identical average residence times, but a 10 mm die resulted in an increase in the average residence time which in turn was greatly influenced by the moisture content.

NOTATION

E(t)	exit-age curve (s^{-1})
eex	reference identification of measurement series
exo	reference identification of measurement series
F(t)	cumulative exit-age curve
H	hold-up volume (m^3)
I	specific feed rate expressed as ratio of volumetric feed rate and maximum feed rate
j	chamber number
L	dimensionless axial screw length
n	counting variable
nif	reference identification of measurement series
Pe	Peclet number
per	reference identification of measurement series
Q_v	volumetric feed rate (m^3s^{-1})
t	time (s)
U	rotational speed of the screws (s^{-1})
V_j	volume of chamber j (m^3)
xeex	reference identification of measurement series

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z number of thread starts on one screw
τ average residence time (s)

INTRODUCTION

The compression zone of a counter-rotating, twin-screw extruder is the zone in which HTST reactions occur. The amount of leakage occurring in this zone affects the temperature and the distribution of shear (Martelli 1982). Janssen (1978) gives a theoretical analysis of events in this zone for a counter-rotating, twin-screw extruder. The large number of variables in his models makes them difficult to use, but they do deal comprehensively with the different leakage flows in the compression zone.

Yacu (1985) developed a model of a co-rotating, twin-screw extruder processing wheat flour, which simulates the temperature and pressure profiles, the material rheology and the energy input, entirely for the purpose of screw design. This model does not include the leakage flows in the extruder which reduces the number of variables considerably. Both models have several zones of ignorance: slip, and mass-flow pattern in the feed zone and interactions between feed zone and compression zone, which makes it unwise to rely on theoretical screw designs.

To minimize the size of 'trial and error', and thereby the number of experiments and experimental screw sets, it is necessary to include the benefit of extrusion measurements to extrusion theory, by means of models which represent more closely the complex extrusion process. A model of the mass flows in a twin-screw extruder was described by Van Zuilichem et al. (1988a). Accurate RTD measurements with a coincidence detector, described in Chapter 3 (Van Zuilichem et al. 1988b), make it possible to measure both the average residence time and the Peclet number, a dimensionless number which represents the degree of axial mixing.

This use of measuring equipment and model makes it possible to detect the existence of plug flow in twin-screw extruders, to calculate the plug flow time and to calculate the extent to which chamber contents and leakage flows mix. Residence time distribution measurements were carried out on three different screw designs. The results of these measurements are analysed with help of the RTD model from Van Zuilichem et al. (1989), which was used in Chapter 4 to explain events in the feed zone of the same twin-screw extruder.

THEORY

The RTD model is used to describe the axial mixing in a screw pair with continuous cut screw sections and geometrical devices such as kneading elements. The introduction of a kneading element in the feed zone results in an increase in the mean residence time (Chapter 4). A kneading element has to be filled to a greater extent than a continuous screw in order to convey the extrudate. The large contribution to the mean residence time made by such elements is caused not only by their greater degree of fill, but also by the larger free volume of such elements.

The chamber volume is increased by gaps in the flight walls. The mass-flow pattern in the kneading

element is a combination of plug flow, and leakage flow.
When a kneading element is located near the compression zone, a large amount of axial mixing can be expected if the kneading element is filled by leakage flows from the compression zone. This is likely to occur as the gaps in the kneading element are larger than those in the compression zone and the chambers can be 'back-filled' by quite a small upstream pressure gradient.
A kneading element in the feed section required the introduction of a plug-flow time in the RTD model. In an axial mixing model the addition of such a plug-flow time increases the Peclet number (Jager et al. 1988). The average residence time (τ), the volumetric feed rate (Q_v) and the hold-up volume (H), of a twin-screw extruder or of one of its zones are related by:

$$\tau = \frac{H}{Q_v} = \frac{H}{2z.I.U.V_1} \quad (1)$$

Where z is the number of screw starts per screw, U is the rotational speed of the screws, V_1 is the volume of the chambers under the feed hopper and I is the ratio of the volumetric feed rate and the maximum volumetric feed rate, herein after called the specific feed rate.

MATERIALS AND METHODS OF MEASUREMENT

The extruder, the extrusion conditions and the methods of measurement and the RTD measurement equipment are as described in Chapters 3 and 4. The RTD was measured at two locations: the die and midway along the screw.
Details of the three screw sets employed are given in Fig. 1. Screw pair 1552, the simplest design used, has a single thread on each screw. Screw pair 506 has two sections, the first section has two kneading regions, the first in the feed zone and the second just before the compression zone. Screw pair 507, designed for PVC extrusion, is provided with a 'drossel' element in the feed zone, which functions as a high shear throttle valve. Detailed information on the geometry of the three screw sets was given in Chapter 4.

Mathematical procedures

The residence time distribution measurements were analysed using the model described by Van Zuilichem (1988a). The components of this model for screw pair 1552 were determined by an equal optimization procedure.
In Chapter 4 a plug-flow time was introduced as an additional component into the model to match the axial mixing effects of features such as 'drossel' elements and kneading elements in the feed sections of screw sets 506 and 507. This reduced by one the degrees of freedom in the optimization method, which made an assumption necessary concerning the velocity of the material in the feed zone before it was possible to simulate both the feed zone and the compression zone of screw pairs 507 and 1552.

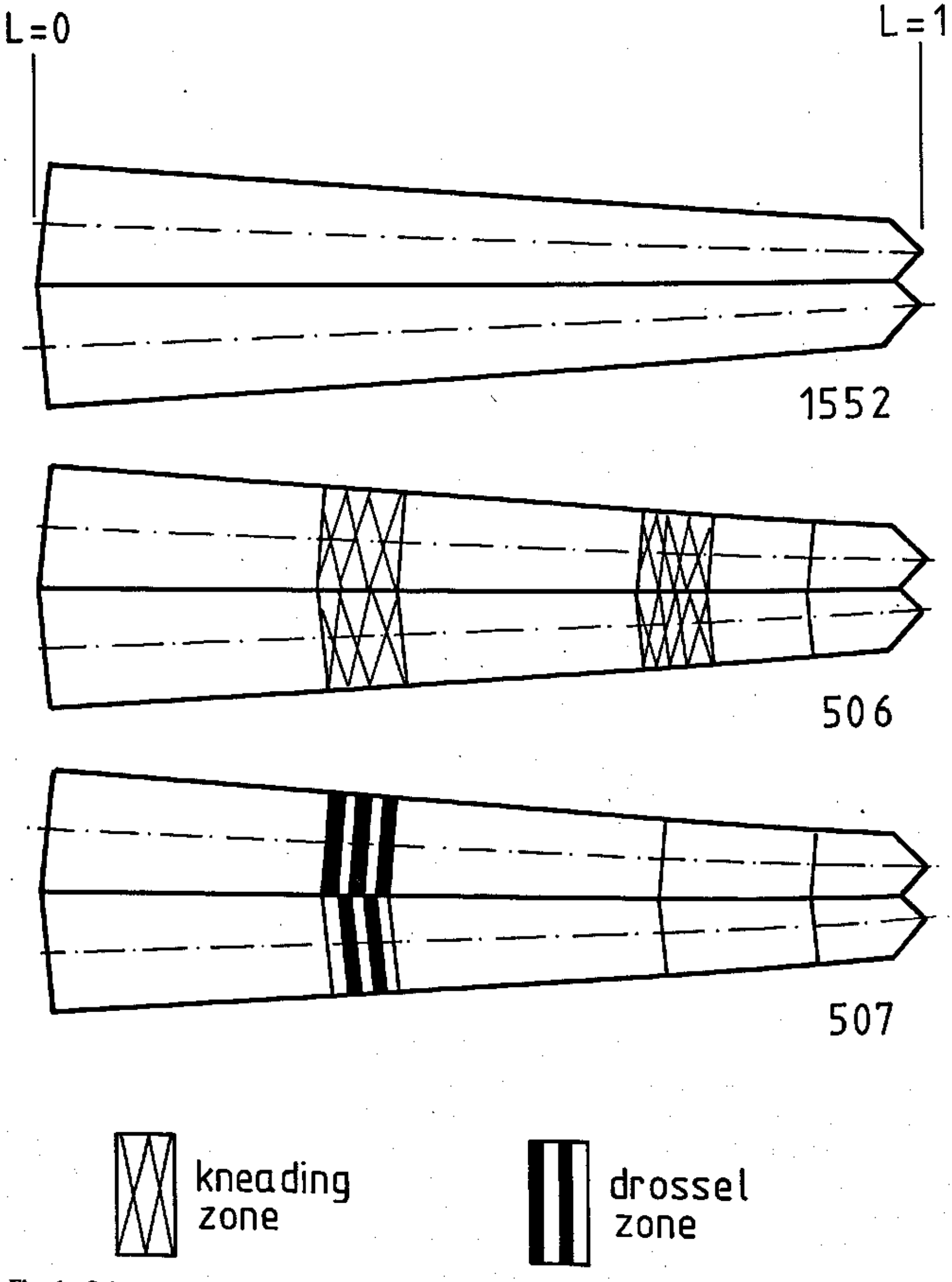

Fig. 1. Schematic screw geometry.

In addition to the plug-flow time in the feed zone of screw set 506, it can be expected that the kneading element in the compression zone will introduce a second plug-flow time. This again reduces by one the number of degrees of freedom in the optimization method, which makes it necessary to introduce another assumption.
Van Zuilichem et al. (1988a) reported that the chambers in the compression zone of the extruder were always completely filled during extrusion. This fact was also assumed in the model, requiring an optimization strategy to evaluate the components of the model corresponding to completely filled chambers in the compression zone. The leakage-flow profiles for completely filled chambers in the compression zone could be found following minor adaptation of the RTD model.
This model is an accurate simulation of the geometry and movements of the extruder chambers in a twin-screw extruder. To simulate RTD measurements the model is 'fed' at time t=0 with a pulse of tracer. When instead of a pulse of tracer, a constant rate of tracer is 'fed', equivalent to the specific feed rate (I), which resembles the continuous feeding of an extruder, the model is able to simulate the degree of fill in each extruder chamber.
A completely filled n-th chamber is simulated by increasing the leakage flow assumed to leave the n-th chamber by small increments until the nth chamber is completely filled. This is no paradox, as will be explained later. The amount of leakage flow leaving the n-th chamber is then fixed, and the procedure is repeated for the (n-i)th chamber (i= 1,2,3...) until the average residence time in the model equals that of the RTD measurement.
The leakage flow profiles of the compression zone, developed with this procedure, and the leakage-flow profiles of the feed zone, described in Chapter 4, are used in the original model given by Van Zuilichem et al. (1988a) to produce RTD-curves similar to the RTD measurements. During the time that a leakage flow leaves chamber n and enters chamber (n-1) both chambers are travelling through the extruder towards the die. When the nth chamber reaches the location of the (n+1)th chamber the contents of the nth chamber becomes the contents of the (n+1)th chamber. Simultaneously the contents of the (n-1)th chamber is transferred to the nth chamber, which is the explanation of the above apparently paradoxial statement above that the leakage flow leaving the nth chamber is able to fill this chamber.
The procedure, which is used to find the equivalent plug-flow time of the kneading part of the compression zone of the 506 screw pair, is the same as that used for the feed zone of the same screw pair which was described in Chapter 4. When an extruder with a continuously cut screw-pair operates without leakage flows, the mean residence time for this extruder, calculated from the number of threads and thread starts and the rotational velocity of the screws is equal to the theoretical minimum residence time. This calculated mean residence time, called the 'transport time' acts in the RTD as a plug flow. Differences between the actual average residence time and the transport time are caused by leakage flows and incremental plug-flows, called 'leakage-flow time' and 'plug-flow time' respectively.
A plug-flow time is only used in respect of the noncontinuous cut screw-elements such as: the drossel element in the feed zone of screwpair 507 and the kneading elements of screw-pair 506 which are described in Chapter 4.

RESULTS

The measurements are labelled with a combination of letters such as 'per', or 'exo' and a number. All measurements made in one extrusion run have the same letter combination. The number represents the position in the sequence of measurements.

Average residence time

The average residence time between the midpoint and die, for all three screw pairs was inversely proportional to the rotational speed of the screws (see Fig. 2). Multiplication of this residence time by the rotational speed results in a number of screw rotations, which is independent of the rotational speed of the screws. In Fig. 3 this number of screw rotations is plotted against the specific feed rate. With the continuously cut screw pair 1552, this number of screw rotations is independent of the specific feed rate.
Although in Chapter 4 this number of screw rotations in the feed zone for the same screw pair was shown to be strongly influenced by the specific feed rate. In Fig. 4 the F-curves for the whole extruder from measurements 'exo 4' (I=0.20) and 'exo 5' (I=0.05) for screw set 1552 are given. The difference in the average residence time for these measurements is caused by the axial mixing in the zone before the midpoint, as the average residence times in the zone between the midpoint and die are almost equal (see Table 1). At the lower specific feed rate of the 'exo 5' measurement the transport contribution to the degree of fill becomes smaller and the leakage flow, necessary to fill the remaining part of the chambers, is greater. As the average residence time between midpoint and die is independent of the specific feed rate, the number of fully filled chambers has to decrease when the specificl feed rate decreases.

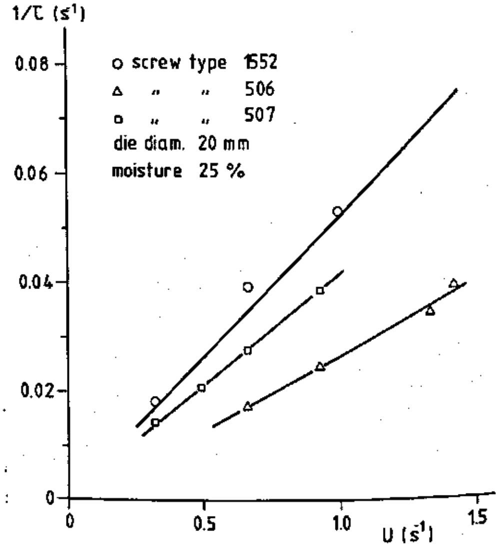

Fig. 2. The inverse of the average residence time between the two detectors for screw pairs 1552 and 506 and their rotational speed.

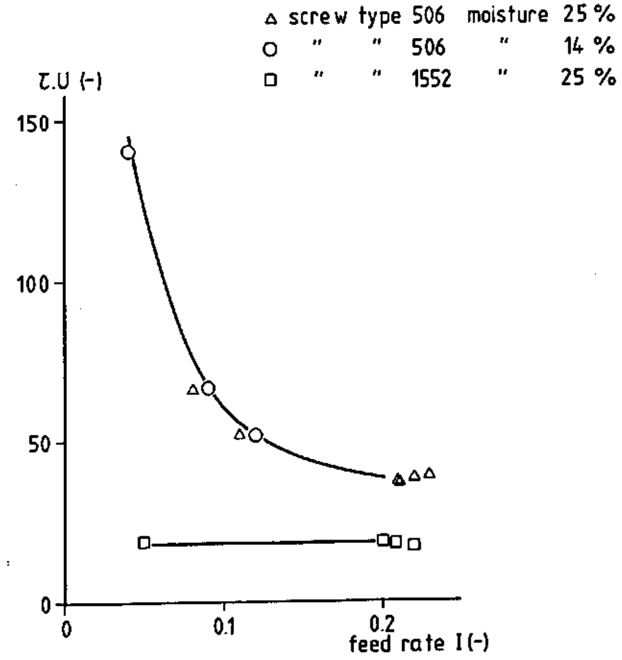

Fig. 3. The product of average residence time between the two detectors and the rotational speed of the screws versus the specific feed rate (I).

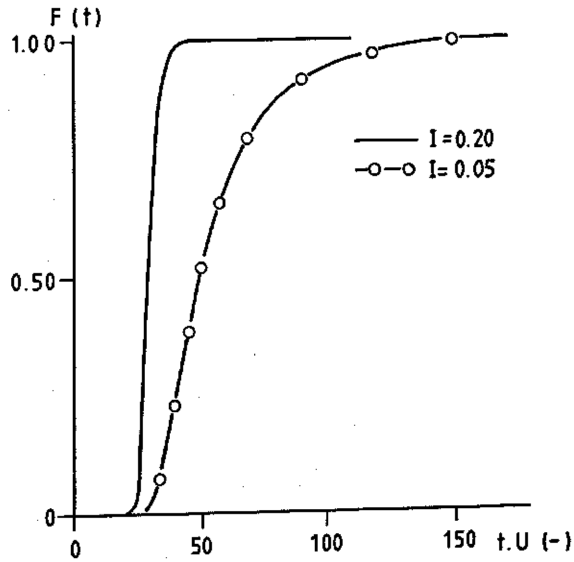

Fig. 4. F-curves of screw set 1552 measured at the die with different specific feed rates (I).

Table 1
Measurements with varying specific feed rate for screw pair 1552

Measurement		exo(4)	exo(5)
specific feed rate		0.20	0.05
torque used/maximum torque		0.80	0.40
rotational speed (s-1)		1.33	1.33
water content maize grits (%ww)		25	25
die diameter		20	20
average residence time centre detector (s)		9	28
average residence time die detector (s)		23	42
average residence time between detectors (s)		14	14
Section	% contribution of:		
feed zone to midpoint	transport	14	13
	leakage-flow time	24	53
midpoint to die	transport	40	22
	leakage-flow time	21	11
	Total	100	100

In Fig. 3 it can be seen that screw pair 506, with a kneading part in the compression zone, and the continuously cut screw 1552 react differently to changes in the specific feed rate. With screw set 506 the average residence time in the zone between the two detectors multiplied by the screw speed decreases as the specific feed rate increases.

Chapter 4 described a similar phenomenon in relation to kneading elements in the feed zone of the same screw pair. It is likely that both kneading elements have a similar effect on the RTD. The measurements for screw pair 506 in Fig. 3 are for a high (25%) and a low (13.8%) moisture content. No influence of moisture content, in the chosen range of the specific feed rate, could be found.

Table 2 gives the average of the product of average residence time between midpoint and die and screw speed, expressed as a number of screw rotations, for measurements with the same screw geometry, moisture content and die diameter. This average is only given if the measured values are independent of screw speed and specific feed rate, which excludes the measurements of the 506 screw pair. The average number of screw rotations for screw set 1552 is less than for screw set 507. The largest average number of screw rotations for screw set 507 is found when the die diameter is 10 mm and the moisture content is low (14%). When only one of these conditions applies a much smaller average number of screw rotations is found. The results for the 15 mm die and the 20 mm die in Table 2 are comparable. With screw pair 1552 a small increase in the average number of screw rotations is found when the die diameter decreases from 20 mm to 15 mm.

Table 2
The average residence time between the two detectors of screw pairs 507 and 1552, expressed as an average number of screw rotations (TxU), versus screw pair moisture content and diameter of the die.

Screw pair	Moisture content (%ww)	Die diameter (mm)	$\overline{(TxU)}$	Number of measurements
1552	25	20	18.2	4
1552	25	15	23.3	3
507	25	15	23.4	3
507	25	20	24.0	4
507	13	20	26.4	7
507	25	10	27.3	5
507	14	10	41.0	3

MODEL SIMULATION

Compression zone

In Table 3 the Peclet numbers, the minimum residence (or breakthrough) time and the average residence time for three almost identical sets of conditions, 'nif 1', 'xeex 3', 'exo 2', using different screws, are given. The screw speed, temperature profile, torque readings and feed characteristics are identical. The specific feed rate in the 'exo 2' set is 4% less than in the other two sets.
The results from the centre detector have already been discussed in Chapter 4. The main differences in the results from the die detector can be found in the minimum and the average residence times measured at the die. The longest average residence time is that for screw set 506, which has two kneading regions. Fig. 5 shows the E-curves based on the residence time measurements at the die for the three measurements just discussed. The tail of the curve of the 506 screw pair measurement, 'nif 1', is higher, which corresponds to a smaller Peclet number. These curves are very similar although the axial mixing processes in the three screw sets would be expected to be quite different. The RTD model makes it possible to link these RTDs to the screw set geometry. Table 4 gives the contributions of different screw sections to the average residence times measured at the die as predicted by the model in the way described in the section 'Mathematical procedures'. The compression zone of screw set 506 is seen to have a plug-flow time. When the specific feed rate decreases, the amount of leakage flow and plug flow necessary to fill this sets kneading elements increases. Fig. 6 shows that the calculated fully filled length of screw sets 506 and 507 are comparable and that both are longer than the fully filled length of set 1552.

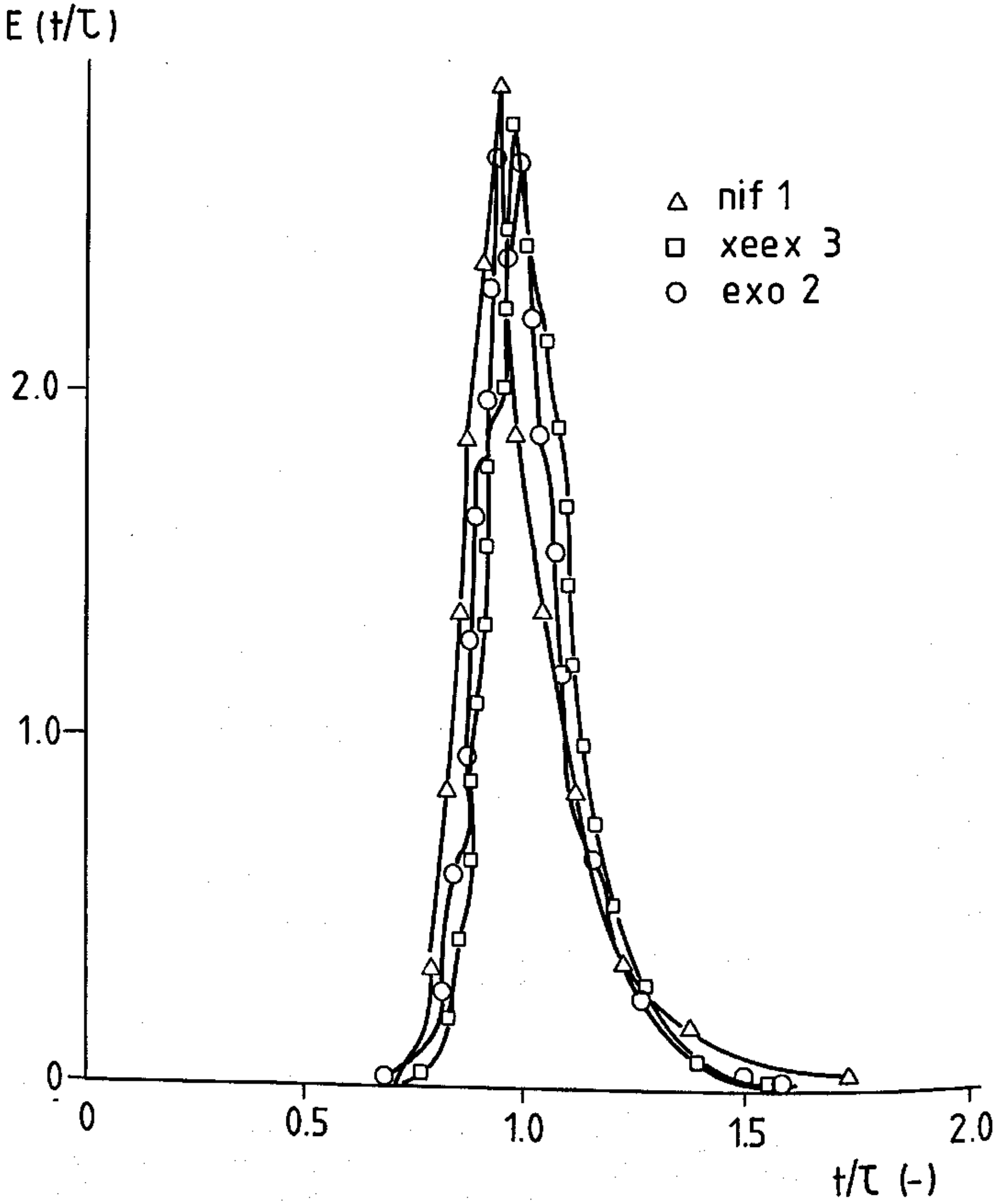

Fig. 5. E-curves measured at the die with comparable specific feed rate, moisture contents, rotational screw speed and die for three different screw geometries.

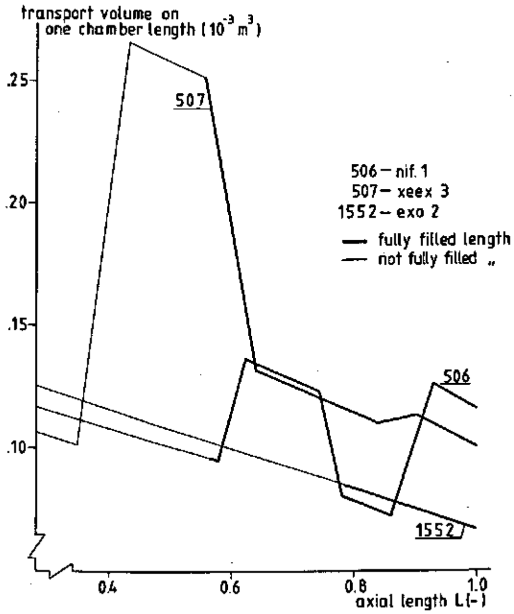

Fig. 6. The volume on a section of a screw pair with the length of a screw

Table 3
Measurements for the three screw pairs

Measurement	nif(1)	xeex(3)	exo(2)
screw set	506	507	1552
rotational screw speed (1/s)	0.67	0.67	0.67
specific feed rate	0.23	0.23	0.22
torque used/maximum torque	0.79	0.70	0.80
water content maize grits (%wet weight)	25	25	25
die diameter (mm)	20	20	20
minimum residence, time centre detector (s)	26	28	8
average residence, time centre detector (s)	52	39	18
Peclet number, centre detector	8	19	7
minimum residence time die detector (s)	81	58	33
average residence time die detector (s)	110	76	45
Peclet number, die detector	20	33	34

Table 4

Calculated contribution of transport, mixing and plug flow to the average residence time measured at the die

Section	%contribution of:	Measurement screw set	nif 1 506	xeex 2 507	exo 2 1552
feed zone to centre detector	transport		14	16	25
	leakage-flow time		20	11	15
	plug-flow time		13	24	-
	Section sub-total		47	51	40
midpoint detector to die detector	transport		18	16	41
	leakage-flow time		29	33	19
	plug-flow time		6	-	-
	Section sub-total		53	49	60
	Total		100	100	100
Average residence time at the die detector relative to measurement 'exo 2'			2.4	1.7	1.0

Table 5

Calculated contribution of transport, mixing and plug-flow time to the average residence time measured in screw set 506

Section	Measurement:	nif 7	nif 9	nif 10
	Specific feed rate:	0.19	0.12	0.04
	% contribution of:			
Feed zone to centre detector	transport	9	11	4
	leakage-flow time	27	27	29
	plug-flow time	8	7	9
	Section sub-total	44	44	42
Centre detector to die detector	transport	11	14	6
	leakage flow time	23	24	33
	plug flow time	12	18	19
	Section sub-total	56	56	58
	Total	100	100	100

Table 6

Calculated relative hold-up volume corresponding to the plug-flow time in the compression zone kneading section of screw pair 506

Measurement	nif 1	nif 4	nif 5	nif 7	nif 9	nif 10
specific feed rate I	0.23	0.21	0.08	0.12	0.09	0.04
rotational speed of the screws U (s-1)	0.67	1.42	0.67	1.33	1.33	1.33
moisture content (%)	25	25	25	14	14	14
plug-flow time in kneading element (s)	4	2	5	17	19	44
ratio of plug flow volume and volume in the kneading element (%)	13	21	10	55	43	45

chamber which is transported by one screw turn on the axial length of three different screw pairs. The thick lines indicate a completely filled section.

Kneading element

From Fig. 3 it was concluded that the kneading elements of screw set 506 cause the average residence time of the whole extruder to be feed-rate-dependent. In Table 5 the estimated contributions of transport, leakage-flow and plug-flow time to the average residence time for three measurements with different specific feed rates, are given. The feed-rate-dependent increase in the average residence time in all sections is caused by increments of both the plug-flow and the leakage-flow contributions.

The fraction of the volume in the kneading region which is occupied by plug flow can be calculated from eqn 1. This fraction and the plug-flow time is given in Table 6. The moisture content is the most important variable. With a moisture content of 14% this fraction is approximately 50%. When the moisture content increases to 25% this fraction decreases. The number of measurements is too small to show whether the small effects of the specific feed rate and screw speed on the plug-flow fraction of volume are significant or not.

Chamber mixing coefficient

The chamber mixing coefficient determines how much of the leakage flow entering a simulated chamber mixes with the contents of that chamber. The remainder leaves the chamber directly as a leakage flow. By Van Zuilichem et al. (1988a) it was shown that the influence of this coefficient on the RTD was too small for an accurate value for this coefficient be determined. All measurements discussed in this chapter could be simulated by using a zero chamber mixing coefficient, which corresponds to the complete mixing of leakage flow and chamber contents in the compression zone.

CURVE SHAPE

In Fig. 7 the measured E-curve for the continuous screw pair (1552) is compared with that of the axial dispersion model of Levenspiel (1972) and of the RTD model of Van Zuilichem et al. (1988). The average residence times and spreads of these curves are similar. The area under these curves is the same; the measured curve combines a high peak value with a long minimum residence time. The shape of the authors' extruder model curve resembles the measured curve more closely than does the axial dispersion model. Bounie (1986) measured RTDs in a co-rotating, twin-screw extruder fed with wheat flour and compared them with those from a number of models. One of the most representative

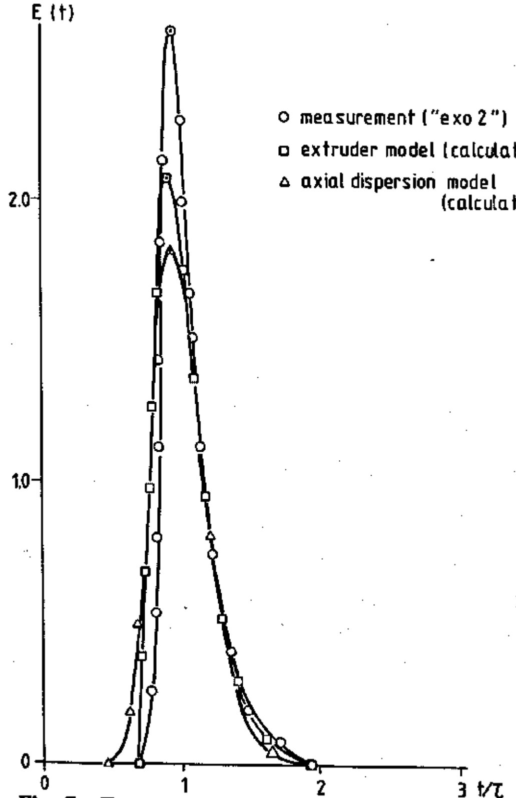

Fig. 7. E-curves of measurement 'exo 2', the axial dispersion model of Levenspiel (1972) and the extruder RTD model.

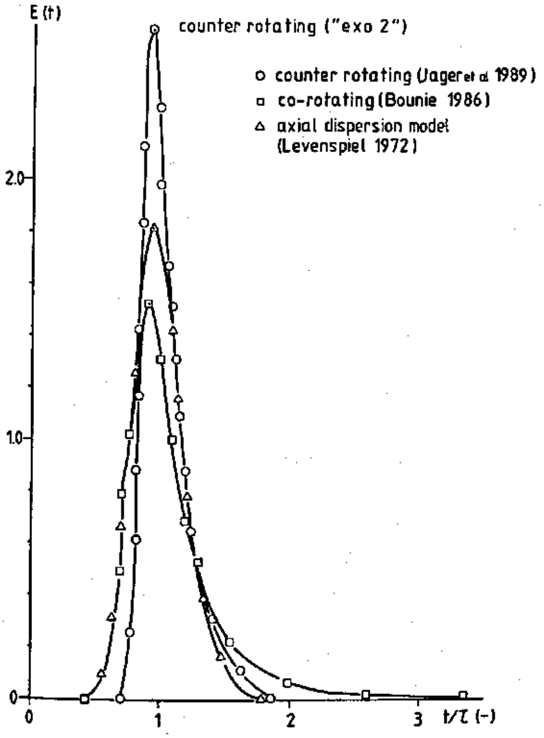

Fig. 8. E-curves of measurement 'exo 2' on a counter-rotating, twin-screw extruder, measurement no. 15 of Bounie (1986) on a corotating, twin-screw extruder and the axial dispersion model of Levenspiel (1972).

RTD models was that in which plug flow was followed by a dead volume and a cascade of perfect mixers. A comparison of the measured RTDs of Bounie and of this paper can be made with the axial dispersion model of Levenspiel, which is used by both research groups. In Fig. 8 an E-curve of Levenspiels model is accompanied by representative measurements from both extruder types. The RTD for the counter-rotating extruder resembles the dispersion model curve whereas the curve of the corotating extruder has a significantly longer tail. Bounie can simulate this longer tailing for measurements with and without reversed screw elements, by introducing a dead volume in his model. As the tailing for the counter-rotating extruder is more modest, inclusion of such a dead volume is not necessary in the present authors twin-screw extruder RTD model.

CONCLUSIONS

The screw-set geometry greatly influences the average residence time and the mass-flow pattern for a starch dough in a counter-rotating twin-screw extruder in both feed zone and compression zone. With all three screw sets the reciprocal average residence time between the detectors varies linearly with the screw speed.
The average residence time in the compression section would be increased by a reduction in the moisture content from 25% to 14% or by a reduction in the die size. With screw pair 1552 the average residence time between a point midway along the barrel and the die was about 20% greater with a 15 mm die than with a 20 mm die, but with screw pair 507 the difference in average residence times for measurements with a 20 mm and a 15 mm diameter die was not significant. A 10 mm die gave a longer mean residence time, especially when a low moisture content.
The residence time in the compression zone, consisting of continuous screws is, in the circumstances of the measurements described, independent of the specific feed rate. This is the result of two mutually opposed effects. When the specific feed rate decreases the leakage flow should increase in order to continue to fill the chambers completely. If the number of fully filled chambers then remained the same, this would result in an increase in the average residence time in the compression section. As this average residence time is in fact independent of the specific feed rate, the specific feed rate decrease must be accompanied by a reduced number of fully filled chambers.
A kneading element in the compression zone increases the volume of the completely filled part of the compression zone, and thereby the average residence time. The volume of these chambers is also enlarged by the extra gaps in the screw threads. The introduction of a kneading element in an existing screw pair offers the possibility of influencing the average residence time in the HTST part of an extruder. With a small specific feed rate (I=0.04), an increase in the average residence time in the HTST section of 600% was found. A kneading element adjacent to the compression zone makes it necessary to introduce a plug-flow time into the RTD model. This plug-flow time and the residence time increase caused by the axial mixing action in the compression zone and kneading element increases when the specific feed rate decreases. This relationship was also reported in Chapter 4 in connection with the kneading element in the feed section of screw set 506.
If the plug-flow time in the kneading element adjacent to the compression zone is converted into a plug-flow volume, this volume was found to depend on the moisture content. With a moisture content of 14%, a plug-flow volume of 40% - 55% of the kneading element was found. When the moisture content increased the plug-flow volume decreased.

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6. VISCOUS DISSIPATION IN A DROSSEL ELEMENT IN THE FEED ZONE OF A COUNTER-ROTATING, TWIN-SCREW EXTRUDER

ABSTRACT

The effects of hold-up, die diameter, rotational velocity of the screws and moisture content on the viscous dissipation in a counter-rotating, twin-screw extruder processing maize grits were studied by means of stepwise regression. The screw pair studied has a drossel element in the feed zone which acts as a high shear throttle valve. Two hypotheses could be formed from the stepwise regression equations found: The axial mixing action in the feed zone determines the viscous dissipation and the axial mixing in the feed zone is affected by backmixed steam from the transport and compression zone. These hypotheses were confirmed by experiments in which sunflower oil or water was pumped in halfway along the screws. Up to 13% (ww) oil could be mixed uniformly with the maize grits without instabilities in the extruder. Brabender amylographs showed that maize grits which had passed through the drossel element became extensively depolymerized.

NOTATION

D	die diameter (m)
E	specific viscous dissipation (Jkg^{-1})
H	hold-up (m^3)
H_c	hold-up in compression zone (m^3)
H_f	hold-up in feed zone excluding plug-flows (m^3)
H_p	plug-flow hold-up in feed zone (m^3)
M	moisture content (%ww)
Q	feed rate (kgs^{-1})
R	root of the residual sum of squares
U	rotational speed of the screws (s^{-1})
W	mechanical power (Js^{-1})
W_c	viscous dissipation in the compression zone (Js^{-1})
W_f	viscous dissipation in the feed zone (Js^{-1})
W_{max}	maximum motor power (Js^{-1})
$\dot{\gamma}$	shear rate (s^{-1})
μ	dynamic viscosity (Nsm^{-2})
μ_c	dynamic viscosity in the compression zone (Nsm^{-2})
μ_f	dynamic viscosity in the feed zone (Nsm^{-2})
ρ	specific density (kgm^{-3})

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τ average residence time (s)

INTRODUCTION

Viscous dissipation of energy is a prominent aspect of extrusion-cookers. A geometrical classification of the different extruder types - single-screw, co- or counter-rotating twin-screw - is also a classification of the mechanical of origin of the viscous dissipation. In a co-rotating extruder geometrical devices such as reversed pitch elements or kneading paddles are used to increase the amount of hold-up and shear (Martelli 1982).
A counter-rotating, twin-screw extruder has a greater pumping efficiency which results in a high degree of fill and a low level of shear combined with greater operational stability. By adding a drossel element to act as a high shear rate throttle valve, the amount of viscous dissipation can be increased to that of a corotating extruder. This results in a stable, high-shear, extrusion-cooking process. The drossel element has a smaller transport volume than the adjacent parts of the screw, which gives a high degree of fill in, and just before this element (Alber 1976).

Models which describe the viscous dissipation in corotating extruders are given by Yacu (1985), Chan et al. (1986), Levine et al. (1986) and Della Valle et al. (1986). These models were developed for one particular extrusion process and are not necessarily valid for other extrusion processes as the diversity in extruder designs, extrusion methods and extrudates is great.
This diversity makes it necessary to check for each new extrusion process which variables are significant for the processed materials. When the number of variables is large such a procedure is lengthy and the use of statistical techniques seems appropriate. An example of the application of a statistical technique in extrusion-cooking is the analysis of process response variables by multiple regression methods (Olkku and Vainionpää 1980). Yacu (1985) states that "while this approach achieves information about the specific process and product properties, it does not provide engineering understanding of the interacts between the extruder design, the material characteristics and the operating conditions of the extruder". Olkku and Vainionpää indeed approach the extruder as a black box by modelling the product properties as functions of the adjustable variables such as feed rate, screw speed, moisture content and barrel temperature.
When, instead of product properties, variables describing the operating conditions of the extruder are used, such as viscous dissipation, hold-up and viscosity, this approach may well yield the understanding meant by Yacu (1985).
In this paper stepwise regression (Mosteller and Tukey 1985) is used to describe the interactions between the torque readings, residence time distribution measurements, rotational speed of the screws, die diameter and feed rate in a conical, counter-rotating, twin-screw extruder from Chapter 3, 4 and 5 by linear equations. These equations are used to form hypotheses for further research based on all the available quantitative information.

THEORY

When a starch-rich mixture is extruded, its viscosity as measured by the Brabender viscograph will change. One of the many descriptions of this relationship was given by Yacu (1988) who extruded a wheat-based product. The temperature of the extrudate was increased by decreasing the moisture content of the extruded material from 32% (ww) to 17% (ww). The decreased moisture content increased the viscous dissipation in the extruder, while the Brabender amylograph changed from undercooked to an extensive degradation of the starch (see Fig. 1).

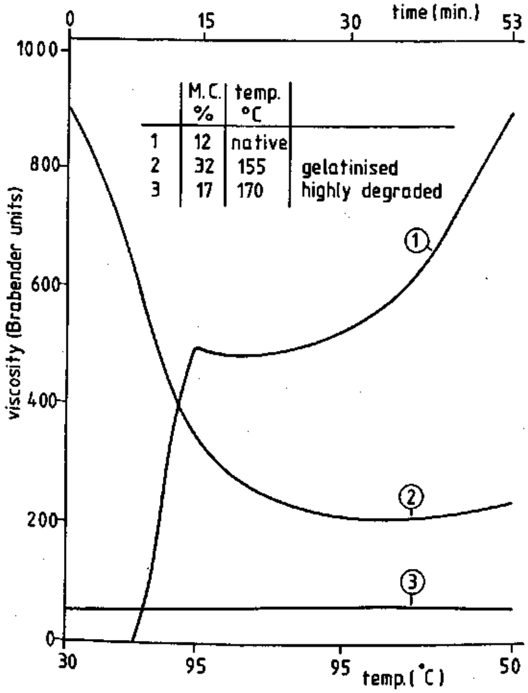

Fig. 1. Typical Brabender viscographs for a wheat based starch extrudate produced under various conditions (Yacu 1988).

Additions of small amounts of oil can cause great reductions in the viscous dissipation. If the added oil is not thoroughly mixed outside or within the extruder, oil separation from the mix takes place, resulting in two phase flow. The separated oil lubricates the screw and barrel surfaces, reducing the friction factor. In a corotating extruder this results in decreased pumping efficiency of the extruder. Gradual accumulation of material within the extruder takes place, requiring greater motor torque, either causing extruder instabilities or, in severe cases, the torque limit to be exceeded and the extruder to cut out (Yacu 1988).

The specific viscous dissipation, E, is calculated from the mechanical input power, W, as:

$$E = \frac{W}{Q} \tag{1}$$

in which Q is the feed rate. The adjustable variables in the experiments of this study are the moisture content (M), the die diameter (D) and the rotational speed of the screws (U). A further group of variables consists of three hold-up volumes calculated by the residence time distribution model described in Van Zuilichem et al. (1988). Eqn. 2 gives the hold-up volume (H) of at an average residence time τ as

$$H = \frac{\tau . Q}{\rho} \tag{2}$$

in which ρ is the specific density of the feed material at a zero porosity. The three hold-up volumes are: the compression-zone volume (H_c) caused by the average residence time in the compression zone; the plug-flow volume (H_p) which is the volume of a kneading zone filled by a plug-flow as defined in Chapter 4; and the feed-zone volume (H_f) which is the filled volume in the first part of the extruder minus the plug-flow volume.

By addition of these three hold up components the total hold-up H is found. The average residence times are converted by eqn. 2 to volumes to resemble to eqn. 3 given by Martelli (1982), which describes the viscous dissipation in a counter-rotating extruder as a function of dynamic viscosity (μ) and the shear rate exerted ($\dot{\gamma}$):

$$W = \mu . \dot{\gamma}^2 . H \tag{3}$$

Fig. 2 shows a block-diagram of the interactions which follow from eqn.s 1 to 3. W_c and W_f are the viscous dissipations respectively in the compression zone and the feed zone. It is assumed that the plug-flow hold-up in the feed zone and the hold-up in the feed zone are not influenced by the events in the compression zone and that the die diameter D only influences the hold-up in the compression zone. According to Janssen (1978) the hold-up in the compression zone is independent of the rotational speed of the screws.

The plug-flow hold-up and the hold up volume in the feed zone are, in the absence of any known model, dependent on all the variables (Q,U,M). As the maize grits used exhibit a temperature and shear thinning rheology (Van Zuilichem et al., 1980) any hold-up in a section will decrease the local viscosity and the viscosities in the following sections.

The hold-up volumes shown in Fig.2 therefore influence the local viscosities, and the viscous dissipation in the feed zone also affects the viscosity in the compression zone. The moisture content will also influence the viscosity directly (Van Zuilichem et al., 1980). This relation is not given in Fig.2, to simplify the statistical analysis.

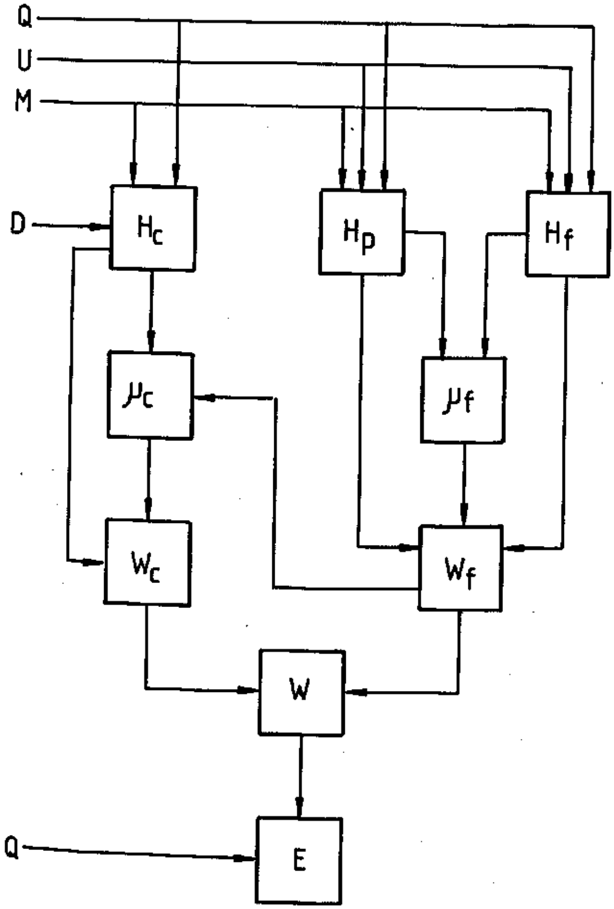

Fig. 2. Theoretical interactions between adjustable variables, viscous dissipation and average residence times in the feed and compression zone of a counter-rotating, twin-screw extruder.

When a process is studied statistically it is necessary to consider the sources of instability. In Chapter 4 it was reported that the measured average residence time was more irregular in a feed section with a drossel element than in other sections. It is possible that this indicates an instability in the feed zone. However, it does not correspond to any of the three types of instabilities in a corotating, twin-screw cooker-extruder found by Roberts and Guy (1986). They discerned die instabilities, instabilities by steam generation and process instabilities.

Die instabilities are short (<1s) periodic distortions of the extrudate. Instabilities due to steam generation will occur on a time scale of a few seconds when at some point along the extruder the pressure drops below the vapour pressure of water. A process instability, the most commonly encountered form of instability in corotating extruders, manifests itself as a large periodic variations of the viscosity and the torque. This oscillation occurs with a period equal to, or longer than, the extruder residence time, and involves a large part of the extruder. In general this oscillation can be stopped by increasing the moisture content. In Chapter 4 it was assumed that the steam generated in the compression and transport zones of a counter-rotating, twin-screw extruder affects mass-flows in the feed zone of a continuously cut screw. This could be similar to the phenomenon of instabilities by steam generation described by Roberts and Guy (1986). However, instabilities in the torque readings on a time scale comparable to the average residence time in this particular extruder length were not observed during this experimental extrusion-cooking work.

EXPERIMENTAL

The twin-screw, extrusion-cooking process, the residence time distribution measurement equipment, and the feed material were as described by Van Zuilichem et al. 1988). The motor power was measured by a shunt ampere meter. The maximum motor power was 20.2 kW.
A Bran & Lübbe metering piston pump was used to pump sunflower oil with a specific density of 918 kgm^{-3} ,or water, *into the extruder halfway along the overall screw length above the axis of each* screw (see Fig. 3). The screw pair employed was the 507-type described in Chapter 4. It has a drossel element in the feed zone before the injection points (see Fig. 4) consisting of two-start screws with a channel width of 10 mm and a chamber length of 28 mm.

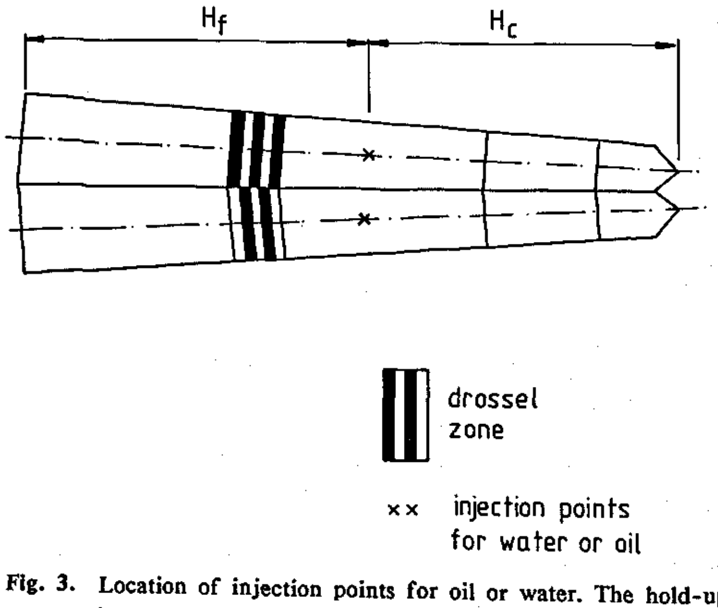

Fig. 3. Location of injection points for oil or water. The hold-up in the feed zone (H_f) and compression zone (H_c) are calculated as the hold-up before and after the injection points. The plug-flow hold-up (H_p) is substracted from (H_f).

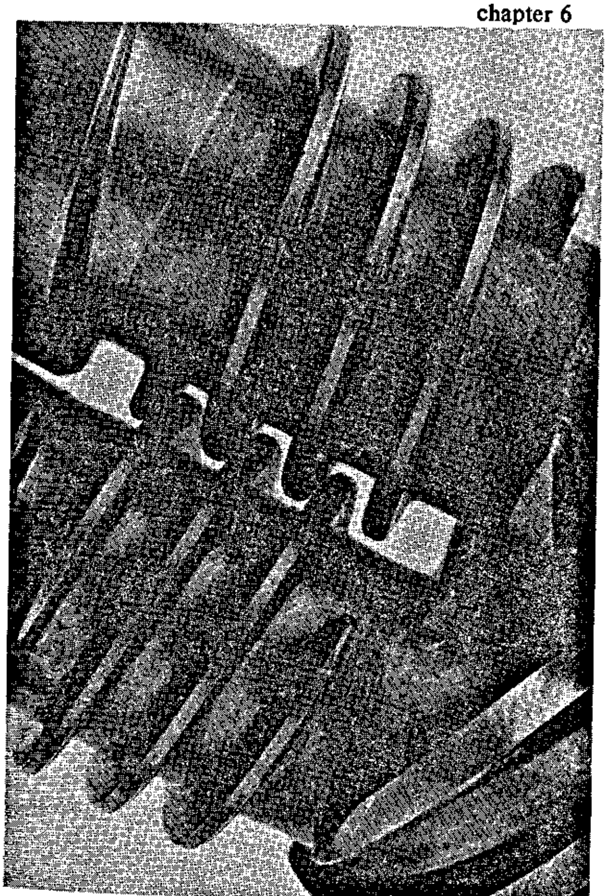

Fig. 4. Drossel element in a counter-rotating screw-pair.

Brabender amylographs

Extrudates were crushed in a grinder slurried with water to 90% moisture content and cooked in a Brabender viscoamylograph where they were heated to 95°C, held at this temperature for five minutes and finally cooled down to 65°C at a rate of 1.5°C min^{-1}. The Brabender viscoamylograph was calibrated at $25.0x10^{-5}$ mkg^{-1}.

Stepwise regression

Stepwise regression is a statistical technique for searching among a large number of possible solutions for the linear regression equation with the best possible fit (Mosteller and Tukey, 1985). Standard programs for stepwise regression operate in the following way:

Forward step: Try every variable not now in the regression, select the one with the greatest reduction in residual sum of squares, then test the significance of this reduction with the F-test, if test is favourable, add this variable to the regression combination (otherwise halt); go to backward step.

Backward step: Try removing from the regression combination every variable now in, select the one yielding the least increase in residual sum of squares, then test with the F-test; if test is favourable, delete this variable from the regression combination; go to forward step.

The significance of the variables in the regression equations in both the forward and backward steps is tested with the F-test for a critical value of 2.5 . The regression equations are characterised by the square root of the coefficient of determination, R, which is given at the right-hand side of each equation.

RESULTS

Stability

Residence time distribution measurements require a stationary process. Therefore, all measurements were performed at constant torque and pressure readings. Instabilities in output rate, output velocity, torque and pressure simular to the third type of instability described by Roberts and Guy were absent with a low moisture content (13%) feed material. When the die diameter was decreased to 8 mm, die instabilities could occur. This means that the pressure requirements of the die approximately equal the pressure built up by the extruder, which lead to die instabilities (Roberts and Guy). Die diameters >8mm were therefore used during all residence time distribution measurements.

Statistical analysis

The stepwise regression algorithm was applied to the residence time distribution measurements of screw type 507 described in Chapters 4 and 5 to examine the dependence of the energy consumption W and the viscous dissipation per unit weigth processed on the variables moisture content, M, die diameter, D, feed rate, Q, and the rotational speed of the screws, U. The results are

$$W = (170 + 4.6U + 13Q - 2.8M)\times 10^{2} \qquad (Js^{-1}) \quad R=0.96 \qquad (4)$$

and:

$$E = (214 + 8.2U - 2100Q - 3.1M)\times 10^{4} \qquad (Jkg^{-1}) \quad R=0.92 \qquad (5)$$

The units, mean, maximum and minimum values of all variables are given in Table 1. The stepwise algorithm does not select the die diameter in either eqn. 4 or eqn. 5.

Table 1
Minimum, maximum and mean values of the counter-rotating, twin-screw extrusion-cooking of maize grits.

variable	symbol	minimum	mean	maximum
rotational speed of the screws (s^{-1})	U	2.1	3.9	5.8
feed rate (kgs^{-1})	Q	0.0079	0.015	0.032
moisture content (%ww)	M	13.5	19.8	25.0
die diameter (m)	D	0.010	0.016	0.020
viscous dissipation (Js^{-1})	W	6020	6600	11200
specific viscous dissipation (Jkg^{-1})	E	280000	470000	830000
feed zone hold-up ($m^3.10^{-3}$)	H_f	0.17	0.38	0.61
compression zone hold-up ($m^3.10^{-3}$)	H_c	0.31	0.55	0.72
plug flow hold-up ($m^3.10^{-3}$)	H_p	0.08	0.20	0.31

It is therefore unlikely that the die diameter has a significant effect on the specific viscous dissipation or the total viscous dissipation. Except for the sign of the feed rate eqn. 5 is of a simular form to eqn. 4, which agrees with eqn. 1. When dependence of the energy consumptions W and E on the filled volumes of the feed zone (H_f), the compression zone (H_c) and plug-flow volume (H_p) is analysed;

$$W = (1.4 + 280H_p - 790H_f)\times10^4 \quad (Js^{-1}) \quad R=0.73 \tag{6}$$

and:

$$E = (1.5 - 200H_p - 607H_f)\times10^6 \quad (Jkg^{-1}) \quad R=0.73 \tag{7}$$

from which it appears that the filled volume in the compression zone (H_c) has no significant effect. In eqn. 8 the viscous dissipation (W) is described in a regression equation with the plug-flow hold up (H^P) as the only variable, the sign of H_p is negative.

$$W = (0.8 - 320H_p)\times10^4 \quad (Js^{-1}) \quad R=0.69 \tag{8}$$

When H_f is also considered the sign of the plug flow hold-up changes and eqn. 6 is found. Eqn. 6 and 7 suggest the geometry of the feed zone to be important for the viscous dissipation in the extruder. The feed zone volume (H_f) dependence on the moisture content, die diameter, rotational screw speed and feed rate, is described by

$$H_f = (1.9 - 0.65U + 99Q + 0.15\,M)\times10^{-4} \quad (m^3) \quad R=0.88 \tag{9}$$

The plug-flow volume is described by

$$H_p = (0.099\ M + 96\ D - 1.55)\times10^{-4} \qquad (m^3) \quad R=0.87 \qquad (10)$$

The moisture content and the die diameter (D), and not the feed rate or the rotational speed of the screws, correlate with the plug-flow volume. The influence of the die is probably as an interaction between the plug-flow volume and the compression zone volume (H_c), since the plug-flow volume is dependent on the compression zone volume,

$$H_p = 0.36\ H_c - 3\times10^{-6} \qquad (m^3) \quad R=0.77 \qquad (11)$$

when the hold up volumes of the plug-flow and feed zone are presented to the stepwise algorithm. The feed and compression zone hold-up volumes are independent. Fig.5 gives a block-diagram of the interactions found in eqn. 4 to 10 using the same design as Fig.2. In Fig.5 the the plug-flow hold-up is influenced by the hold-up in the compression zone because of the appearance of the die diameter in eqn. 10. When the plug-flow volume influences the compression zone volume, the plug-flow volume would not necessarily depend on the die diameter.

It seems a reasonable hypothesis that the compression zone volume influences the plug-flow volume. A possible mechanism for this influence is the steam blown back from the compression zone and the transport zone. The plug-flow hold-up is, according to eqn. 10, dependent on the hold-up in the compression zone, whereas the influence of the hold-up in the compression zone on the viscous dissipation is not significant. It can therefore be expected that the plug-flow hold-up (H_p) has only a slight effect on the viscous dissipation.

Viscous dissipation

From eqn. 6 and 7 and Fig. 5 it appears that the viscous dissipation is greatly affected by the filled volume in the feed zone. This was tested by pumping sunflower oil into the extruded mass halfway along the screws assuming that the oil can only influence the viscous dissipation in the compression zone (W_c) and not the viscous dissipation in the feed zone (W_f).

During this experiment the extruder was fed at a constant rate of 52 kgh^{-1} with maize grits with a moisture content of 13% (ww) and a screw speed of 30 rpm.

By adding 7.8 kgh^{-1} of oil during extrusion the fat content of the feed material becomes 13% (ww) and the water content 11% (ww). At this level the oil begins to drip out of the die outlet. The stability of the torque and pressure readings is not influenced by the addition of oil, whereas the specific viscous dissipation drops by 12% from 271 $kJkg^{-1}$ to 238 $kJkg^{-1}$, which is an indication that the greater part of the viscous dissipation takes place between the feed-inlet and the injection point of the oil.

When the oil addition is replaced by the same volume of water, which is expected to have a much smaller effect on the viscosity (Yacu, 1988), the moisture content rises to 25% and the specific viscous dissipation drops, surprisingly, to 130 $kJkg^{-1}$ (i.e. a reduction of 52%).

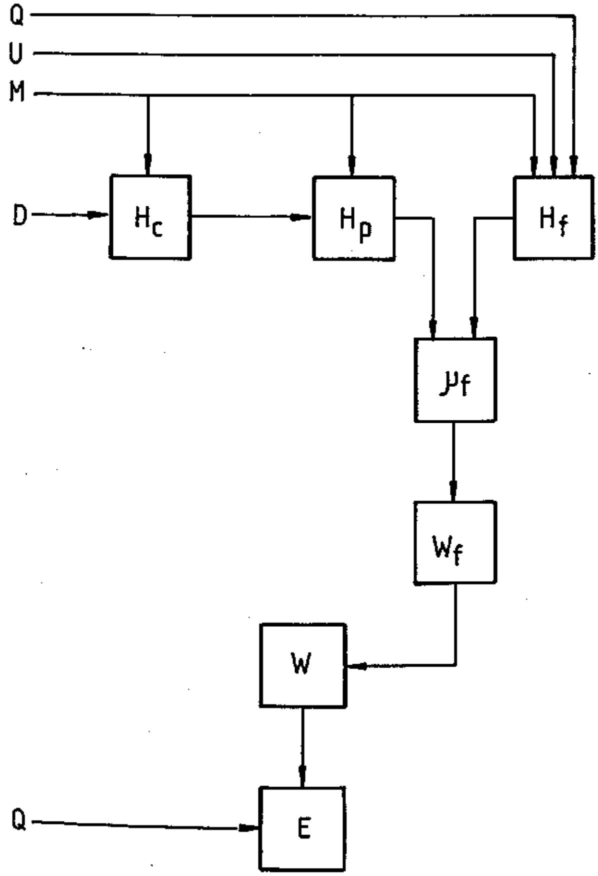

Fig. 5. Interactions found between adjustable variables and the viscous dissipation and average residence times in the feed and compression zone of a counter-rotating, twin-screw extruder.

The Brabender amylographs of samples from the above three experiments are given in Fig. 6. By comparing Fig. 1 and Fig. 6 it can be seen that all samples in Fig. 6 are extensively degraded. The sample with 13% (ww) fat has the smallest Brabender viscosity.
Brabender amylographs of material collected from the extrusion-cooking of maize grits without addition of water or oil are given in Fig. 7. The two samples are collected after a sudden stop from just behind the drossel element and just before the die. Compared with untreated maize grits both samples have very small Brabender viscosities, which indicates that the major part of the Brabender viscosity is reduced in the drossel element.
In Fig. 2 this fact is indicated by the influence of the viscous dissipation in the feed zone on the viscosity in the compression zone.

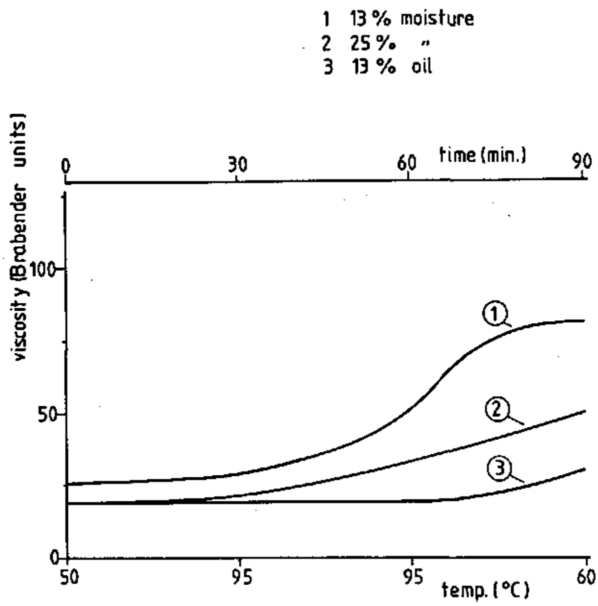

Fig. 6. Brabender viscographs for maize extrudate at 13% water content and also after adding water or vegetable oil intermediately (see Fig. 3).

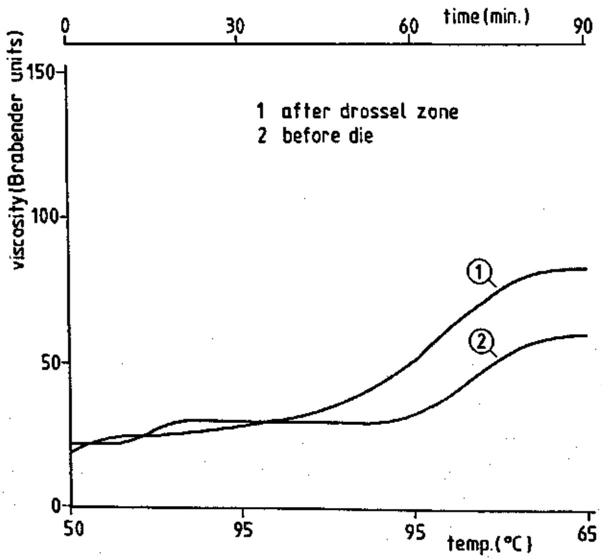

Fig. 7. Brabender viscographs for maize extrudates sampled just after the drossel element and just before the die.

DISCUSSION

Yacu (1988) claims that a mixture of oil, water and maize grits cannot be extruded when fed through the feed-inlet as the amount of viscous dissipation in the extruder becomes too small for a normal extrusion-cooking process. The arrangement shown in Fig. 3 is an alternative method of adding oil to an extruder. When water or oil are added in this way, it was found that the reduction in the viscous dissipation in the extruder due to oil is less than that due to water addition.
The large reduction in the torque following water addition is probably caused by evaporation of water in the transport zone of the screw which flows back to the cooler feed zone where condensation takes place. In this way the downstream addition of water can affect the viscous dissipation in the feed zone.
This is not possible with oil as it does not evaporate under the prevailing conditions. The Brabender amylographs in Fig. 7 also indicate that the major part of the viscosity reduction in the extrusion-cooking process takes place in the drossel element. The backflowing of steam to the feed zone is a possible explanation of the interaction found between the plug-flow volume in the feed zone and the filled volume in the compression zone. Such a mechanism was also suggested in Chapter 4 for a screw without a drossel element.

The variability of the average residence time in the drossel element, as found in Chapter 4 and mentioned under 'Theory', cannot be seen as an instability. If the degree of axial mixing in the drossel element is variable then, according to eqn. 6 and 7, the torque readings would vary also. As the viscous dissipation is constant, a reason for this variability based on interactions between the compression zone and the drossel element seems an interesting subject for further research.

CONCLUSIONS

When oil is pumped into this particular counter-rotating, twin-screw extruder at a point after the feed zone, up to approximately 13% (ww) oil can be mixed uniformly with the extrudate. At this level the oil begins to separate from the extruded mass and drips from the die outlet. This mixing system can be considered for development of new products.
The Brabender amylograph of material sampled, after a sudden stop, from just beyond the drossel element has a cold, hot and final viscosity all below 100 Brabender units. This shows that maize grits which pass the drossel element are extensively depolymerised or degraded. The mass-flows and torque requirements in a twin-screw extruder can be analysed by stepwise regression to produce equations, which are valid only for this unique screw configuration and for the extrusion conditions employed. These equations should not be extrapolated.
The leakage flows in the feed-zone decrease the torque requirements, which can be explained by the temparature and by the shear-thinning rheology of the processed material (Van Zuilichem et al. 1980).
The viscous dissipation in the extruder with a drossel element is, according to the regression equations, mainly dependent on the hold-up in the feed zone. This is confirmed by the Brabender amylographs which show that the temperature and viscous dissipation in the drossel element

hydrolyses the maize grits. The Brabender viscosities of material beyond the drossel element are too low to produce a viscous dissipation comparable to that in the feed zone. Further confirmation emerges from the experiment in which oil is added to the extruded mass beyond the drossel element. An oil addition of 13% (ww) did not greatly reduce the viscous dissipation in the extruder; the oil addition can affect only the relatively small viscous dissipation in the compression zone.

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7. MODELLING OF A COROTATING, TWIN-SCREW, EXTRUDER FED WITH MAIZE GRITS

ABSTRACT

The residence time distribution (RTD) of an APV-Baker MPF-50 type corotating, twin-screw extruder is measured by a radiotracer technique. Measurements are made with various barrel temperature profiles, feed rates, screw speeds and positions of the barrel valve. The accuracy for the measurement of the average residence time and the curve width indicators used are within 1%. The measurements are analysed by stepwise regression and compared with a simulation model. A small but systematic deviation between model and measurements can be explained as a stagnation in the kneading elements. The occurrence of this deviation is calculated and discussed with the help of measurements with model liquids in a full-size transparant perspex model. The deviation can be modelled by separate flow systems with different mixing properties or by the introduction of dead volumes. The numerical model can be used as a 'standard' RTD model for both co- and counter-rotating, twin-screw extruders.

NOTATION

a	tangent of the tail of the logarithmic RTD (s^{-1})
B	barrel valve position (rad.)
D	degree of fill
E	specific viscous dissipation (Jkg^{-1})
G	coefficient for the mixing of leakage flows and chamber content
H	hold-up volume (m^3)
I	specific feed rate
i	counting variable
k	number of counts
k	average number of counts
K	total number of counts in an RTD
M_i	moment of the RTD (s^i)
m	number of variables in a regression equation
N	number of CSTRs
n	number of measurements
Na	apparent number of CSTRs
P	plug flow time (s)
p	percentage of the filled volume above the minimal fill that is occupied by plug flow

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Pe	ratio of transport by convection and by diffusion (Peclet number)
Pr	probability
R	square root of the coefficient of determination
R'	R corrected for n and m
Q	feed rate (kgs^{-1})
Q_{max}	maximal feed rate (kgs^{-1})
W	mechanical power (Js^{-1})
T	temperature profile "low"=0, "high"=1
t	time (s)
t_x	time in which x per cent of the tracer has passed the detector (s)
U	rotational speed of the screws (s^{-1})
V(i)	volume of the i-th chamber (m^3)
V_{tot}	reactor volume (m^3)
z	number of thread starts on one screw
Z	reduction percentage of a
Y	end time of RTD measurement or the time in which a bend can be found in the logarithmic RTD (s)
λ	Poisson distribution parameter
ρ	specific density (kgm^{-3})
σ	variance
τ	average residence time (s)

INTRODUCTION

When an extrusion process is scaled up or transferred from one extruder geometry to another, it is difficult to compare the mass flows in both extrusion processes. Direct measurement of mass flows in a working extruder is possible for model studies with plastics and rubber (Kalyon and Sangani 1989) but not with the heat sensitive biopolymers in food.
The residence time distribution can be measured ,but it is the result of all mass flows present in the reactor. The transformation of an RTD of a corotating, twin-screw extruder to the mass flows present requires a RTD model based on a thorough description of the possible mass flows. Accurate RTD measurements of an extrusion process are a prerequisite.

In Chapters 4, 5 and 6 a numerical RTD model was used to describe the mass flow in a counter-rotating, twin-screw extruder. The model simulates the axial movements of screw chambers in a twin-screw extruder. The amount of leakage flows necessary to fill the extruder to a given extent are calculated. A mixing coefficient describes the mixing of chamber contents and leakage flows. When this model was used for a counter-rotating, twin-screw extruder with a kneading zone it was necessary to introduce a plug flow time in the kneading zones as a second model parameter (Jager et al., 1988).
This model is used here for a corotating extruder to forecast the responses of the RTD to changes

in feed rate, screw speed and hold up volume. By comparing the measurements and forecasts of the curve spread it is possible to describe the changes in flow regime by the changes in the two model parameters, the mixing coefficient and the plug flow time. Changes in feed rate and screw speed can be compared when they are converted to changes in the specific feed rate, I, which is defined as:

$$I = \frac{Q}{2z.V(1).U.\rho} = \frac{Q}{Q_{max}} \qquad (1)$$

in which Q is the mass flow entering the extruder, ρ is the density of the feed material for a zero porosity, z is the number of thread starts on one screw, V(1) is the chamber volume of the first chamber, U is the rotational velocity of the screws and Q_{max} is the theoretical maximum mass flow. When the average residence time τ is known the hold up, H can be calculated as:

$$H = 2z.V(1).U.I.\tau = D.V_{tot} \qquad (2)$$

in which D is the degree of fill and V_{tot} is the reactor volume of the extruder. The main part of the hold-up in a corotating extruder can be found in the kneading zones (Kirby et al. 1988). Altomare and Anelich (1988) and Kao and Allison (1985) found that the introduction of kneading zones in a screw geometry consisting of only screw elements increases the curve width of the RTD.

RTD measurements of Mosso et al. (1981) and Altomare and Ghossi (1986) in corotating, twin-screw extruders show an increase in the hold up volume at an increasing specific feed rate, while Komolprasert and Ofoli (1990) find the opposite.
Altomare and Anelich (1988) found that all geometrical elements which increase the hold up also increase the plug flow as described by the model of Wolf and White (1976) while Bounie (1986) found that the introduction of a reversed pitch screw element in a corotating, twin-screw extruder increases the RTD curve width.
These observations show conflicting results, demonstrating the complexity of the axial mixing in twin-screw extrusion-cookers. Hold-up and average residence time are a function of at least the processed material, moisture content, feed rate, screw speed, barrel temperature and screw geometry. There is also no description available of a 'standard' RTD for a corotating, twin-screw extruder.

In Chapter 4 and 5 it was found for a counter-rotating, twin-screw extruder that plug flow occurs in kneading elements. Kalyon and Sangani (1989) measured the mass flow of a plasticized thermoplastic elastomer in reversing and forwarding kneading elements in a corotating, twin-screw extruder. They found that reversing kneading elements gave a more plug flow like mass flow than the forwarding element. This conclusion can also be found in the measurements of Altomare and Ghossi (1988).

Van Zuilichem et al. (1989) found a minor increase in the curve width of a corotating, twin-screw extruder when the barrel-valve was closed. The barrel-valve can increase the hold-up in an extruder in the same way as a die, but at a location within the barrel. With a simulation model given in this paper it is possible to calculate how the mass flow changes by changing the position of the barrel-valve.

The RTD model applied is that used in Chapter 5 for the description of the RTD in the compression zone of a counter-rotating, twin-screw extruder. The model consists of a row of continuously stirred tank reactors (CSTRs) which move from feed inlet to die in a simulated extruder. The degrees of fill in all axial positions of this simulated extruder can be adjusted to each level above the minimum.
This minimum degree of fill corresponds to a minimum flow, hereafter called the transport flow. When leakage flows and plug flows occur the degree of fill increases. Each flow can be associated with a part of the degree of fill. The plug flow part is substracted from the measured degree of fill. Its influence on the RTD is corrected by addition of a plug flow time to the simulated residence times.

In order to simulate the RTD, first the levels of the leakage flows for each axial position of the simulated extruder have to be found. Therefore the model is continuously fed with an amount equal to the specific feed rate (I) for each rotation of the screw. The leakage flow part of the degree of fill is simulated by slowly increasing the leakage flows until the installed degree of fill is reached. Then the RTD is calculated as the result of a Dirac pulse which travels through this model consisting of moving CSTRs and leakage flows. In Fig. 1 it can be seen that the direction of the leakage flows is opposite to the direction of CSTR transport.

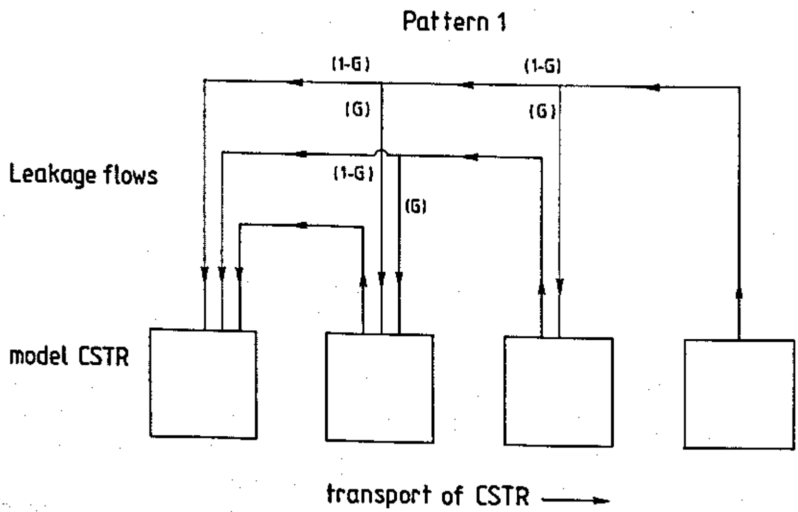

Fig. 1. Mixing pattern of leakage flow and chamber content in the numerical model.

Janssen (1976) described leakage flows which do not mix completely with the chamber content, which will increase the curve width of the RTD. The pattern of the leakage flows between the chambers in Fig. 1 describes one possible relation for the mixing of the leakage flows and the chamber content in the RTD model.
When a leakage flow enters a CSTR a part proportional to the chamber mixing coefficient (G) mixes with the chamber content. The remainder goes to the next CSTR for which the procedure is repeated. When leakage flows enter a CSTR from which no leakage flow is emitted all flows entering this CSTR do mix. This pattern of backmixing was also used in Chapter 5.

Van Zuilichem et al. (1988) analysed a counter-rotating, twin-screw extruder by a model with a different backmixing for the leakage flow for the feed- and the compression zone. The axial mixing in these two zones could be distinguished by using two detectors. In this study only one detector could be mounted on the extruder and consequently backmixing in the RTD model is assumed to be equal for all zones in the extruder.

In the numerical model the part of the hold up volume in the kneading elements which is occupied by plug flow is defined by p, the percentage of the degree of fill above the minimum degree of fill which is not occupied by leakage flow.
Both the plug flow and the mixing coefficient affect the curve width of the RTD. Eqn. 3 from Chapter 4 gives the apparent number of continuously stirred tank reactors (CSTRs) (N_a) when N CSTRs are present at an average residence time τ which is increased by a plug flow time (P).

$$N_a = N \frac{(\tau+P)^2}{\tau^2} \qquad (3)$$

Eqn. 3 describes the effect of the plug flow time on the curve width of the RTD model. Without this correction the simulated RTDs of a counter-rotating, twin-screw extruder with a kneading element in Chapters 4 and 5 were too small. The effect of the mixing coefficient on the curve width can only be simulated as it is dependent of the geometry and the degree of fill in the extruder.

Janssen et al. (1978) found that, for polypropylene in a counter-rotating, twin-screw extruder, the tail of a logarithmic RTD shows a bend which increases the Peclet number. This deviation increases when the gap between the flight of one screw and the channel of the other screw, also called calender gap, decreases or with lower pressure gradients over the fully filled part of the extruder. The percentage of tracer left when this bend occurs is between 10% and 1%. In the measurements of Todd (1975) this non-linearity also occurs. According to Janssen (1976) its magnitude increases with the angle of the screws.

Westerterp et al. (1984) and Shinnar (1987) identify the source of such a tailing as a bypass or a dead volume in the reactor. Bounie (1986) also needs a dead volume in order to model his RTD

measurements in a corotating extruder. The locations of these dead volumes on the screws have not been identified.
Boissonnat et al. (1988) finds in a corotating twin-screw extruder evidence for a flow with two differentiated strands of material which can be described by two parallel cascades of perfect mixers. About 70 % of the tracer takes the quickest cascade. The remaining tracer has a considerable longer residence time.
Westerterp et al. (1984) identify such curves as caused by channelling or short-cutting. When the F-curves of Janssen et al. (1978) and Boissonnat et al. (1988) are drawn logarithmical both curves are similar in appearance (see Fig. 2) and may have similar cause.

Janssen (1976) describes a leakage flow which travels backwards in this part of the extruder at a comparatively high backpressure on the screws and with a small calendar gap. It is not known if this flow has to be associated with the bend in the logarithmic RTD.
According to Shinnar and Naor (1967), the RTD of a cascade of CSTRs with internal reflux will not show this bend. However that conclusion can not be applied directly to twin-screw extruders in which the direction of the axial leakage flow is opposite to the direction of the total mass flow. A mass flow pattern as described by Janssen (1976) can be simulated with the numerical model having a leakage flow pattern as shown in Fig. 3.
In Chapter 4 such a leakage flow pattern was used to simulate the mass flow in the feed zone of a counter-rotating, twin-screw extruder.

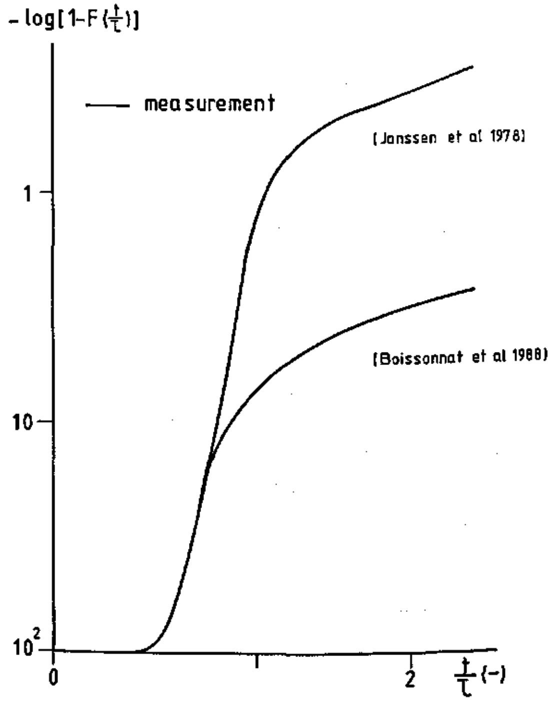

Fig. 2. Schematic logarithmic RTD curves of Janssen et al. (1978) and Boissonnat et al. (1988).

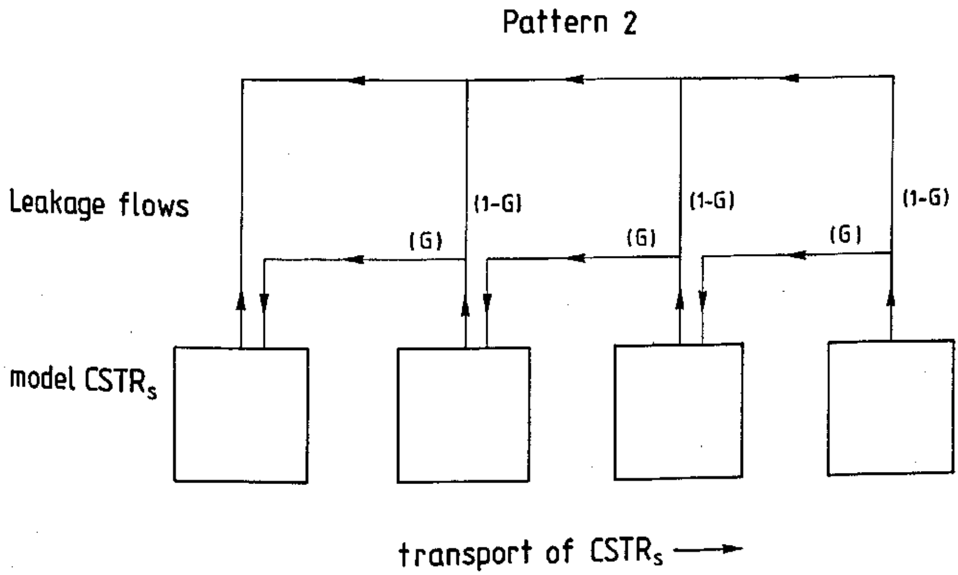

Fig. 3. Alternative mixing pattern of leakage flow and chamber content in the numerical model.

THEORY

Todd (1975) describes the curve spread of measurements in a perspex model of a counter-rotating, twin-screw extruder with the ratio of the times in which 16% and 84% of the tracer have passed the detector. He calculates the Peclet number by assuming that the axial dispersion model of Levenspiel (1972) is valid for his measurements. This procedure for the characterisation of the curve width can not be applied without hesitation to the RTDs of corotating, twin-screw extruders as they have a combination of peak width and tailing (see Fig. 4) that does not fit to curves of the axial dispersion model. The times in which 16% and 84% of the tracer pass give only an indication of the spread around the peak (see Fig. 4) and neglect the shape of the tail. Therefore they could be unrepresentative of the whole curve spread.

The difference in curve shape is probably caused by the symmetry of the axial dispersion in the axial dispersion model, which is different from the backwards directed leakage flows in an extruder and in the numerical model. As a result the RTD curves of an extruder and of the numerical model are more asymmetrical than the RTD curves of the axial dispersion model. The ratio of the time in which 92% of the tracer has passed and the average residence is used here as an indication for the shape of the tail.

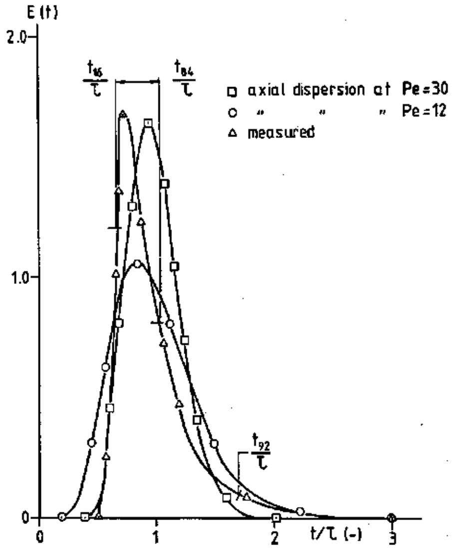

Fig. 4. Time intervals in RTD characteristic for the curve spread.

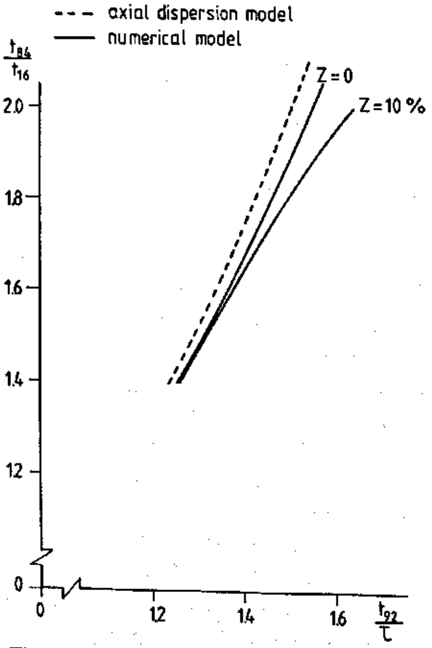

Fig. 5. Combinations of curve width indicators for the axial dispersion model and the numerical model.

The numerical model gives a single relation of both curve width indicators (see Fig. 5) Small deviations (<0.01 units) from this line occur for extreme values of the plug-flow and mixing coefficients but these deviations are too small to use for the description of the RTDs. Therefore it is sufficient for the numerical model to have one indicator for the curve width. This means that the influences of the percentage of plug flow and the mixing coefficient on the curve shape can not be distinguished and it is necessary to choose a fixed value for one of these coefficients.

By using two indicators for the curve shape it is possible to check the validity of the numerical model. When in Fig. 5 the measurements are mainly found on the left side of the line of the numerical model the axial dispersion model should be used. When the logarithmic plot of the integrated RTD show a bend the curve width indicator of the tail will be increased while the curve width indicator of the peak remains almost equal.
In Fig. 5 this will give deviations on the right side of the line predicted by the numerical model. This deviation increases with the curve width as can be seen by the line which shows the reduction of the logarithmic slope (Z) of the numerical model with Z=10% after $t=1.5\tau$. These deviations should be further studied, preferably at wide RTDs.

The Peclet numbers of simulated RTDs for some values of the curve width indicators are given in Fig. 6. The axial dispersion model used by Todd (1975) gives Peclet numbers that are approximately 10% larger than that of the numerical model. The effect of the bend on the Peclet number is given in Fig. 7. On the horizontal axis the reduction in the slope of the logarithmical curve after the bend is shown. The mathematical background is described in appendix A.

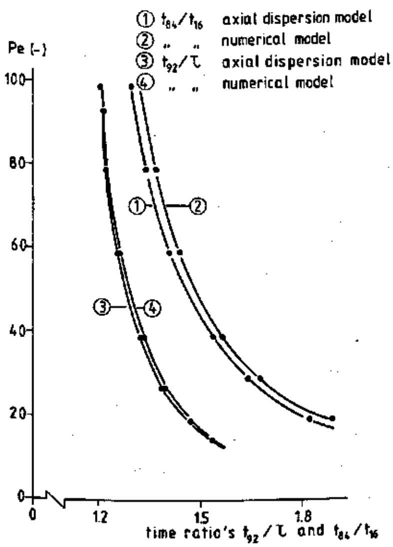

Fig. 6. Peclet numbers of the curve width indicators for the axial dispersion and the numerical model.

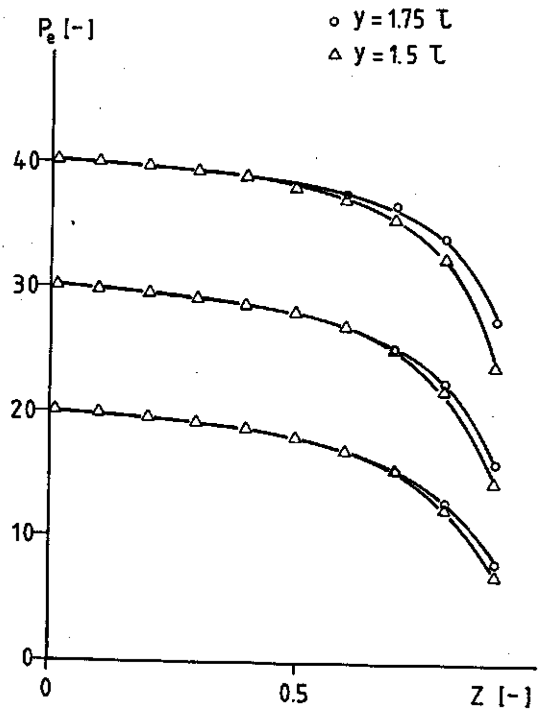

Fig. 7. Peclet number as influenced by the bend in the logarithmic RTD.

The RTD is measured by coincidence detection of annihilation radiation as described in Chapter 1. This measurement equipment is not sensitive to errors caused by the sight-angle of the detector and background radiation. Nevertheless, there are small errors in the measurements caused by the truncation error at the end of the RTD and by the low concentration of tracer in the tail of the curve. The deviations can be calculated by a Monte Carlo simulation. The number of counts measured is small compared to the tracer ^{64}Cu present. Therefore it is possible to describe the probability (Pr) of the counts measured (k) in a short time interval with a Poisson distribution:

$$Pr(k) = \frac{\exp(-\lambda)\lambda^k}{k!} \tag{4}$$

in which:

$$\bar{k} = \lambda = K \int_t^{t+\Delta t} E(t)\, dt = \sigma . k^2$$

Here K is the total number of counts in a RTD and λ is the Poisson parameter. The Poisson

distribution can be used without knowledge of the exact ratio of ^{64}Cu present and counted. The RTDs of the numerical model are simulated 200 times with a probability as expressed by eqn. 4. The time intervals are similar to those used during the RTD measurements.
The deviations found can be divided into systematic and stochastic errors. The systematic deviations can not only be used to correct for the truncation error of the average residence time, as described by TODD (1975) but also to correct for the truncation error of the curve shape indicators.

EXPERIMENTAL

The extruder used is a MPF-50 APV-Baker corotating, twin-screw extruder With a 15 kW engine and two 4 mm diameter die-outlets. The length/diameter ratio is 15 to 1. The total reactor volume is 1.02 $10^{-3} m^3$. Maize grits are extruded with a moisture content of 23% (ww) of which the chemical composition and size distribution are given in Table 1. RTD's are measured with three screw speeds (218, 326, 432 RPM) and two mass flows, 40 kgh^{-1} and 51 kgh^{-1}. The maximum screw speed is 500 RPM.

Table 1
Chemical composition and size distribution of processed maize grits

Chemical composition (%ww)		Size distribution size (mm)	fraction (%)
carbohydrates	73.3	< 0.7	14
water	9.9	0.7 - 1.0	80
protein	5.7	> 1.0	6
lipids	0.8		
minerals	0.3		
	100.0		100

A screw configuration with ten sections (see Fig. 8) is used. It contains five different elements: transport screw, single lead screw, self wiping single lead screw, barrel valve discs, and kneading paddles. The barrel valve is located at the end of the sixth zone. For each section the length, pitch and the barrel temperature for two temperature profiles are given in Table 2. The kneading paddles are all placed in angles at 30° with a positive conveying action.

The RTD is measured as described by Van Zuilichem et al. (1988). A coincidence detector measures the ^{64}Cu activity at the die outlet. Maize grits soaked in $CuCl_2$ and dried to a moisture content of approximately 12% are used as tracer. The detectors have a slit type detection opening of 44x10mm. The minimum distance between the collimator and the hot extrudate is 63 mm. With the coincidence detector the average residence times and curve shapes are not influenced by the measuring equipment (see Chapter 3).

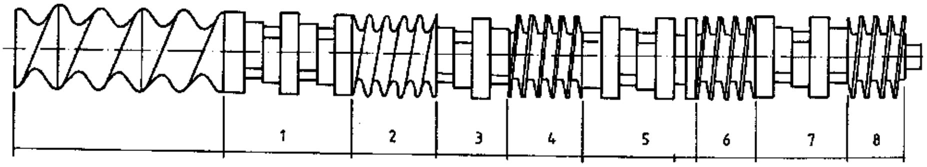

Fig. 8. Screw geometry.

Table 2
Screw configuration and temperature profile.

Screw configuration			temperature profile	
section number	geometrical section	length (m)	'low' (°C)	'high' (°C)
1	transport section	0.250	21	21
2	7 kneading paddles	0.088	30	51
3	self wiping section	0.050	60	93
4	4 kneading paddles	0.050	60	93
5	single lead screw	0.050	90	121
6	6 kneading paddles	0.075	90	121
7	barrel valve plugs	0.025	90	121
8	single lead screw	0.050	120	150
9	5 kneading paddles	0.062	120	150
10	single lead screw	0.050	120	150

As these RTD measurements give limited information on the mass flow in the different screw sections, a translucent full size model has been made of the twin-screw extruder. The barrel is made of perspex and the screws have bearings on both sides to protect the barrel from the abrasive action of the screws. The screw configuration is identical to that of Table 2, except for the pitch of the kneading paddles in the last kneading element before the die, which is reversed. This model extruder is fed with glycerine with a specific density of 1420 kgm^{-3}. A solution of methylene blue in water can be injected at the beginning of section 6,7 and 8 in Fig. 8. The colored glycerine is caught at the die in test-tubes. Afterwards the RTD is measured with a LKB spectrophotometer at 699 nM using cuvettes with equal extinction.

RTD calculations

The average residence time and the curve width indicators are calculated from the uncorrected E-curve. They are corrected with a systematical error as calculated by the Monte Carlo procedure. The uncorrected average residence time is calculated using equations A2 and A3 of appendix A. The times in which 16%, 84% and 92% of the counts in the uncorrected E-curves were calculated by linear interpolation of two measured points with an interval time of half a second.
The curves shown are corrected for the systematical error of the number of counts as calculated by the Monte Carlo procedure.

Stepwise regression

Data from the experiments are analysed by stepwise regression, which is a statistical technique to search, among a large number of possible solutions for the linear regression equation with the best possible fit (Mosteller and Tukey, 1977). The significance of the variables are tested with the F-test for a critical value of 2.0 . The regression equations are characterized by square root of the coefficient of determination, R. which is corrected to R', for the number of measurements (n) and variables in the equation (m) as defined by Freund and Minton (1979):

$$R'^2 = \frac{1-(1-R_2)(n-1)}{n-m-1} \tag{5}$$

When variables give no improvement of R' they are considered to be of secondary importance and are discarded from the equation.

RESULTS

Accuracy of measurements

The Monte Carlo simulations of the measurements show that the accuracy is a function of the total number of counts in the RTD, the average residence time and curve width.
Systematic and non-systematic deviations of the measured average residence time and curve width

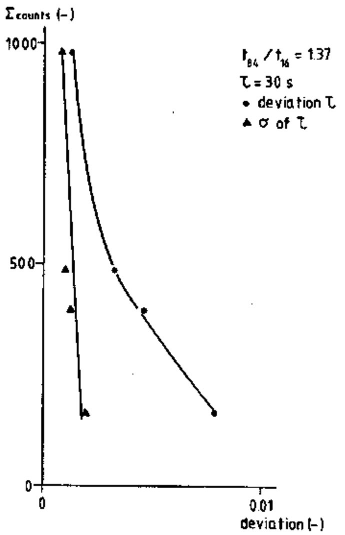

Fig. 9. Systematical and non-systematical deviations of the average resisdence time in 200 runs of a Monte Carlo analysis of the RTD for changes in the total number of counts.

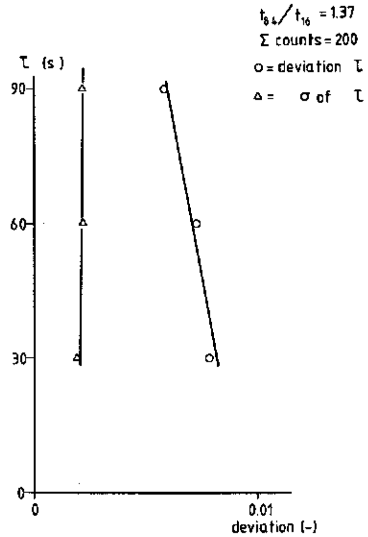

Fig. 10. Results of the Monte Carlo analysis for deviations in the average residence time of a corotating, twin-screw extruder dependent of the average residence time.

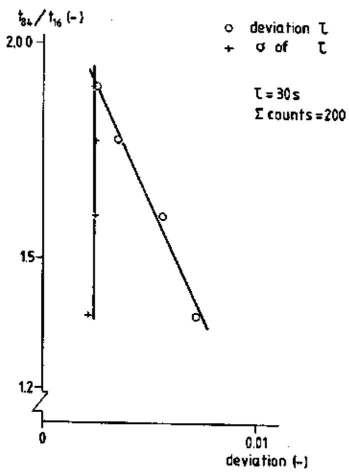

Fig. 11. Results of the Monte Carlo analysis of the average residence time at different values of the curve width.

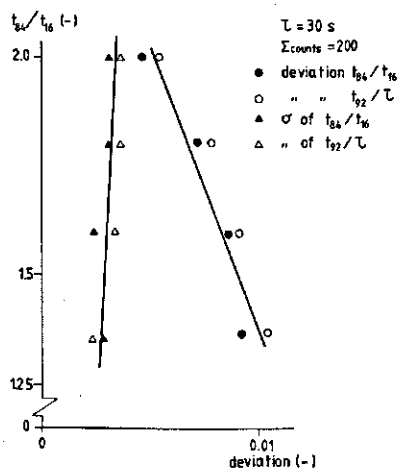

Fig. 12. Systematical and non-systematical deviations of the curve width indicator in 200 runs of a Monte Carlo analysis of the RTD of a corotating, twin-screw extruder dependent of the curve width.

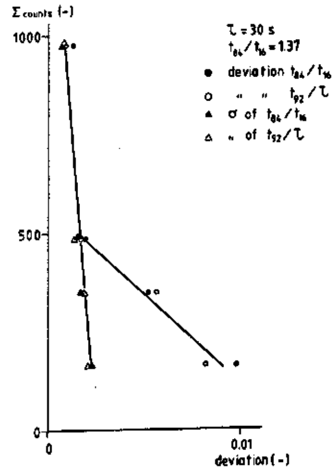

Fig. 13. Deviations of the curve width indicators calculated with a Monte Carlo analysis for RTDs with a a total number of counts between 200 and 1000.

indicators are given in Fig. 9 to 13. The systematic deviations in the average residence time are smaller than 0.01 and are similar in size to the truncation error described by Todd (1975). The non-systematical deviations are also smaller than 0.01.

In Table 3 the corrected average residence times and curve width of the measured RTDs are presented. For two similar experiments indicated with a '#' the average residence time could be reproduced twice with the same value. The Peclet number varied for these two measurements between 19 and 20 (see Table 3 and Fig. 6).
This variation found in the curve shape of the duplicate measurements is greater than the non-systematical deviations calculated by the Monte Carlo analysis and caused by small non-systematic deviations in the extrusion-cooking process.

Statistical analysis

For six variables a regression equation is constructed with stepwise regression. The units and ranges of all variables in the regression analysis are given in Table 4. The variables offered to the stepwise algorithm for each equation are given in Table 5. The viscous dissipation (W) can be described by:

$$W=-1000+15.8\ 10^{5}\ \ H+380\ U\ +14.2\ 10^{4}\ Q \qquad (Js^{-1}) \quad R'=0.90 \quad (6)$$

With only the hold-up in this equation its sign is negative as was found in Chapter 6 for a counter-rotating, twin-screw extruder. The specific viscous dissipation (E) is described by:

$$E=378\ 10^{3}\ -105\ 10^{4}\ I+44.4\ 10^{3}\ \ B \qquad (Jkg^{-1}) \quad R'=0.93 \quad (7)$$

Table 3

RTD measurements of a corotating, twin-screw extruder. Q is the feed rate, T is the temperature profile * , B is the position of the barrel valve ** , U is the screw speed, D is the degree of fill and τ is the average residence time

Q	T	B	U	τ	D	t_{92}/τ	t_{84}/t_{16}	
(kgs^{-1})	(-)	(rad.)	(RPM)	(s)	(-)	(-)	(-)	
0.011	low	-0.26	218	58.2	.53	1.41	1.64	
0.011	low	0.26	218	67.2	.61	1.41	1.68	
0.011	low	0.78	218	61.3	.55	1.36	1.62	
0.011	low	1.30	218	71.3	.65	1.48	1.68	
0.014	low	0.26	218	38.4	.44	1.34	1.61	
0.014	low	0.78	218	40.5	.47	1.35	1.49	
0.014	low	1.30	218	45.8	.53	1.41	1.52	
0.011	low	0	326	40.8	.37	1.48	1.86	
0.011	low	0.26	326	40.7	.37	1.60	1.82	
0.011	low	0.78	326	41.1	.37	1.55	1.81	
0.011	low	1.30	326	50.2	.45	1.45	1.73	
0.011	low	-0.26	432	35.3	.32	1.57	1.86	
0.011	low	0.26	432	37.0	.33	1.48	1.82	
0.011	low	0.78	432	40.4	.37	1.54	1.87	
0.011	low	1.30	432	42.2	.38	1.47	1.90	#
0.011	low	1.30	432	42.2	.38	1.46	1.84	#
0.014	low	0.26	326	31.7	.37	1.42	1.69	
0.014	low	0.78	326	35.6	.41	1.41	1.57	
0.014	low	1.30	326	41.2	.48	1.52	1.96	
0.014	low	-0.26	432	27.9	.32	1.47	1.80	
0.011	high	-0.26	326	37.7	.34	1.44	1.67	
0.011	high	0.26	326	38.2	.35	1.45	1.66	
0.011	high	1.30	326	45.0	.41	1.40	1.64	
0.014	high	-0.26	326	31.7	.37	1.42	1.71	
0.014	high	0.26	326	32.4	.37	1.48	1.69	
0.014	high	0.78	326	34.3	.40	1.39	1.63	
0.014	high	1.30	326	37.1	.43	1.44	1.65	
0.011	high	-0.26	218	42.5	.38	1.48	1.73	
0.011	high	0.26	218	44.3	.40	1.41	1.62	

Table 3 continued

*	The "high" and "low" temperature profile of the barrel are given in table 4.
**	The barrel valve is closed at 1.31 rad. and fully open at -0.26 rad.
#	Repeated measurement.

Table 4

Units, average, maximum and minimum values of selected variables. The barrel temperature is '1' for the 'high' temperature profile in Table 2 and '0' for the 'low' temperature profile.

		minimum	average	maximum	units
Temperature before barrel valve	(T_1)	91.0	112.9	140.0	°C
Temperature after barrel valve	(T_2)	44.5	70.6	94.8	°C
Barrel temperature used	(T)	0	0.7	1	-
Pressure at die outlet	(P)	11.7	24.3	36.5	10^5Nm^{-2}
Feed rate	(Q)	0.011	0.012	0.014	kgs^{-1}
Specific feed rate	(I)	0.072	0.122	0.181	-
Screw speed	(U)	3.63	4.93	7.2	s^{-1}
Specific viscous dissipation	(E)	200000	275000	380000	Jkg^{-1}
Viscous dissipation	(W)	2400	3330	4650	W
Average residence time	(τ)	27.9	46.3	87.1	s
Average number of screw rotations	(R)	140	220	350	-
Hold-up	(H)	.00033	.00046	.00081	m^3
t_{92}/τ	(92)	1.33	1.45	1.59	-
t_{84}/t_{16}	(84)	1.48	1.71	1.95	-
Barrel valve position	(B)	-0.26	0.59	1.31	(rad)

Table 5
The horizontal variables are preselected to test for the stepwise regression equations of the vertical variables.

		T	Q	I	U	E	W	τ	H	92	84	B
Barrel temperature used	(T)	0	0	0	0	0	0	0	0	0	0	0
Feed rate	(Q)	0	0	0	0	0	0	0	0	0	0	0
Specific feed rate	(I)	0	0	0	0	0	0	0	0	0	0	0
Screw speed	(U)	0	0	0	0	0	0	0	0	0	0	0
Specific viscous dissipation	(E)	1	1	1	1	0	0	1	1	0	0	1
Viscous dissipation	(W)	1	1	1	1	0	0	1	1	0	0	1
Average residence time	(τ)	1	1	1	1	1	1	0	0	0	0	1
Hold-up	(H)	1	1	1	1	1	1	0	0	0	0	1
t_{92}/τ	(92)	1	1	1	1	1	1	1	1	0	0	1
t_{84}/t_{16}	(84)	1	1	1	1	1	1	1	1	0	0	1
Barrel valve position	(B)	0	0	0	0	0	0	0	0	0	0	0

1: selected
0: not selected

The barrel valve position (B) which influence the specific viscous dissipation by up to 60 $kJkg^{-1}$ (see Fig. 14). The barrel-valve position did not appear in eqn. 6 for the viscous dissipation. However eqn. 6 contains the hold-up, H, which is dependent of the barrel-valve position as:

$$H=(75+3.6\ B-\ 5.7U-9.5\ T)10^{-5} \qquad (m^3) \qquad R'=0.88 \qquad (8)$$

The average residence time is dependent of the same variables as the hold-up with the feed rate as an additional variable:

$$\tau=126\ +3.86\ B\ -5.84\ U\ -4130\ Q\ -9.65\ T \qquad (s) \qquad R'=0.85 \qquad (9)$$

The number of variables in eqn. 9 indicates that the average residence time is the result of a complex process. However, both indicators of the curve shape are dependent on only two variables; the specific feed rate and the hold-up volume as given by eqn. 10 and 11.

$$\frac{t_{92}}{\tau}=1.52+137\ H\ -1.17\ I \qquad (-) \qquad R'=0.97 \qquad (10)$$

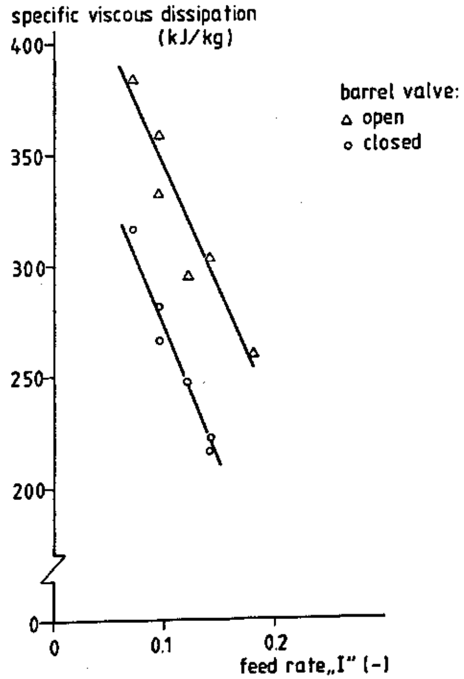

Fig. 14. Specific viscous dissipation 'E' versus the specific feed rate 'I'.

$$\frac{t_{84}}{t_{16}} = 1.94 + 193\ H - 2.59\ I \qquad (-) \qquad R' = 0.96 \qquad (11)$$

When except for the hold-up volume the same variables are offered to the stepwise regression algorithm eqn. 12 and 13 are found.

$$\frac{t_{92}}{\tau} = 1.56 \quad - 0.92\ I \qquad (-) \qquad R' = 0.95 \qquad (12)$$

$$\frac{t_{84}}{t_{16}} = 2.53 - 0.057\ T \quad - 1.95\ B - 2.26\ I \qquad (-) \qquad R' = 0.95 \qquad (13)$$

In eqn. 12 the specific feed rate is now a function of the single variable, I, while in eqn. 13 the hold-up volume is replaced by the barrel temperature and the barrel-valve postion. The last two variables can also be found in eqn. 8 which describes the hold-up volume.

Plug flow in the kneading element and mixing coefficient

In the 'theory' section it was found to be impossible to distinguish between the effects of the percentage of plug flow in the kneading zone and the coefficient of mixing of chamber contents and leakage flow. Therefore for practical purposes these two coefficients are regarded as one combined coefficient. All RTDs are simulated with a coefficient for mixing of leakage flow and chamber content with a fixed value of 0.5.
Now the percentage of plug flow acts as the only parameter of the model. However, the same RTDs can be obtained by a fixed plug flow coefficient while the chamber mixing coefficient varies.

Table 6
Simulation of a change in the barrel valve position.

						simulated	measured	
nr.	B	Q	I	τ	H	Pe	Pe	p
	(rad.)	(kgs^{-1})	(-)	(s)	(m^3)	(-)	(-)	(%)
1	0.26	0.014	0.12	31.8	.00038	23.2	23.2	40
2	0.30	0.014	0.12	35.8	.00042	19.0	22.4	40
3	0.30	0.014	0.12	35.8	.00042	22.4	22.4	49

According to eqn. 8 the hold-up can be changed amongst others by the position of the barrel valve, which, according to eqn. 10 and 11 will affect the curve shape. The effect of a small change in the barrel-valve position on the Peclet number can be calculated from equations 8,11 and Fig. 6. The influence of the same increase in hold-up on the Peclet number can be calculated by the model assuming that the flow regime or model coefficients do not change. According to Table 6 the response of the model to changes in the hold up agrees only qualitatively with the measurements.
Quantitatively the model over-reacts in comparison with the calculated Peclet number from the statistical equations. This can be explained by a dependence of one of the two model coefficients on either the hold up or the barrel-valve position. A better model performance for the Peclet numbers in Table 6 can be obtained by using the percentage of plug flow in the kneading zones (p) as a variable. The percentage of plug flow increases when the barrel valve is closed and the hold up is increased.

In Fig. 15 iso-Peclet lines are given calculated with a given plug flow and mixing coefficient. They are less steep as those drawn from eqn. 11 and Fig. 6. On the line for which the measured

Peclet numbers equal the modelled value the flow regime in the extruder seems to be comparable. Fig. 16 gives some lines for different values of the plug flow coefficient in the kneading zone while the mixing coefficient is 0.5. In this figure can be seen the two dimensional dependence of the percentage of plug flow on the hold up and the specific feed rate.

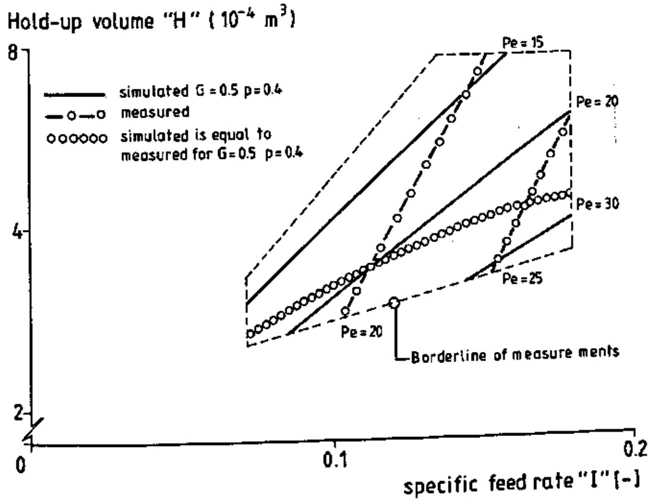

Fig. 15. Measured and modelled iso-Peclet lines.

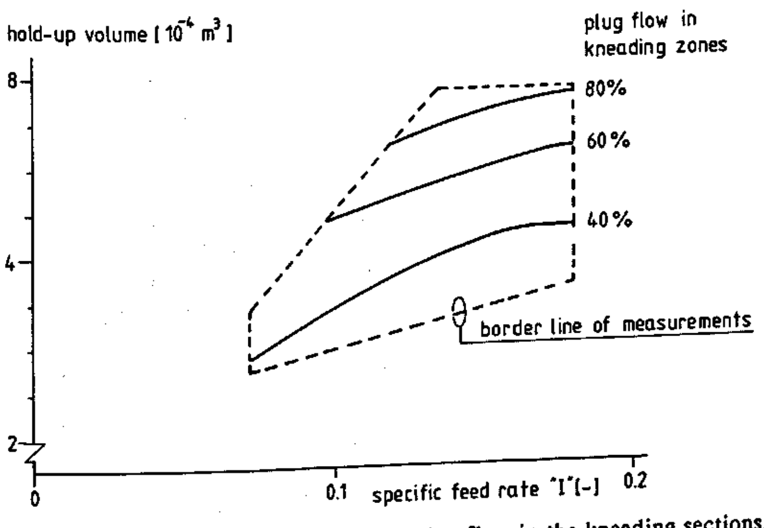

Fig. 16. Lines with equal percentage of plug flow in the kneading sections.

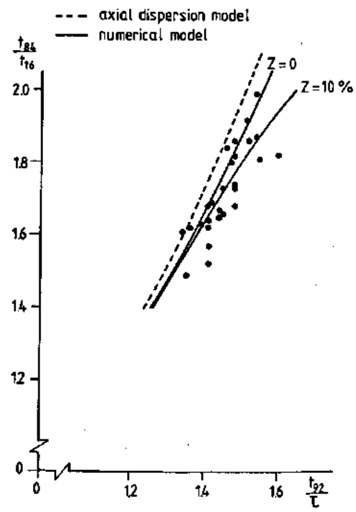

Fig. 17. Measured and modelled curve width indicators.

Curve shape

In Fig. 17 the curve width indicators of the measurements are given. Most of the measurements can be found on the line predicted by the numerical model or on the right side of it. The distance between the line of the numerical model and some of the measurements on its right side is greater than the accuracy of the measurement. These deviations can be explained by a bend in the logarithmic F-curve as described by Janssen et al. (1978). The fit of the numerical model and the measurements can be seen in Fig. 18. However the validity of the numerical model follows from fig. 17. For the RTD of Fig. 18 all agreeable combinations of mixing coefficient and percentage of plug flow in the kneading zones are given in Fig. 19. This figure shows how the degree of fill can be divided in three parts each associated with one flow type of the RTD model. As the kneading elements are not completely filled, the summation of these three contributions is less than 100%.

When the RTD is given in a logarithmic plot the bend predicted by Fig. 17 is visible as shown in Fig. 20. On the vertical axis of Fig. 20 the percentage of the filled volume which is still present in the extruder at the beginning of the bend can be found. This volume ranges from less than 1% to approximately 10% of the filled volume in the extruder. The percentage of the extruder which is filled with this longtreated material ranges from 6% to less than 0.6% as can be calculated with eqn. 2.

RTDs of glycerine

Glycerine is extruded with a specific feed rate of 0.024 at 20 RPM in a transparant twin-screw

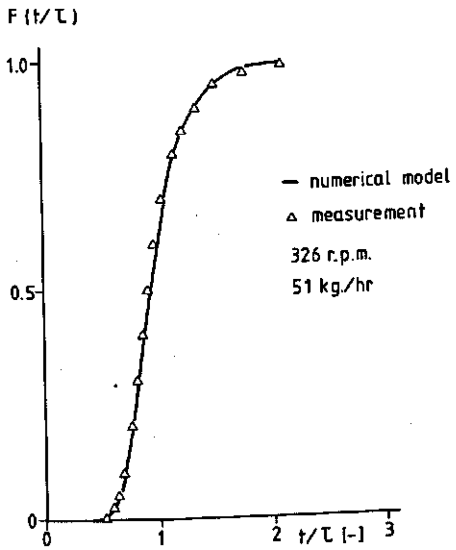

Fig. 18. Comparison of model and measurement for the extrusion cooking of maize grits.

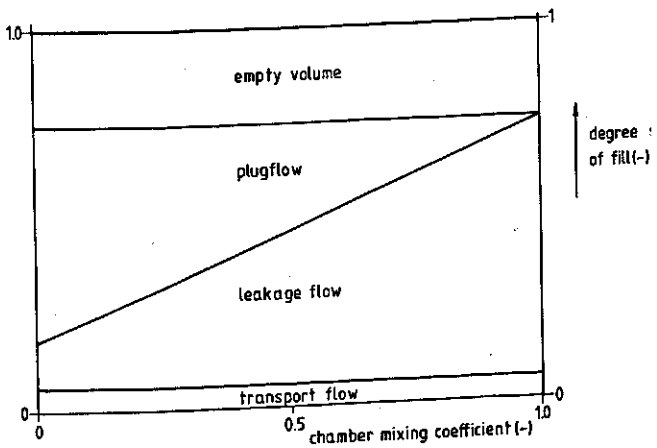

Fig. 19. Combinations of chamber mixing and plug flow coefficients in the kneading zones which simulate the measured ratio of time in which 92% of tracer passed the detector and the average residence time.

extruder. The tracer is injected on three points: the first chamber of the last screw element before the die, the beginning of the adjacent reversed kneading section and at the feed port. Of the four kneading sections only the last one is reversed; the first three are forwarding. By having three injection points it is possible to give different values of the two model parameters to each section.

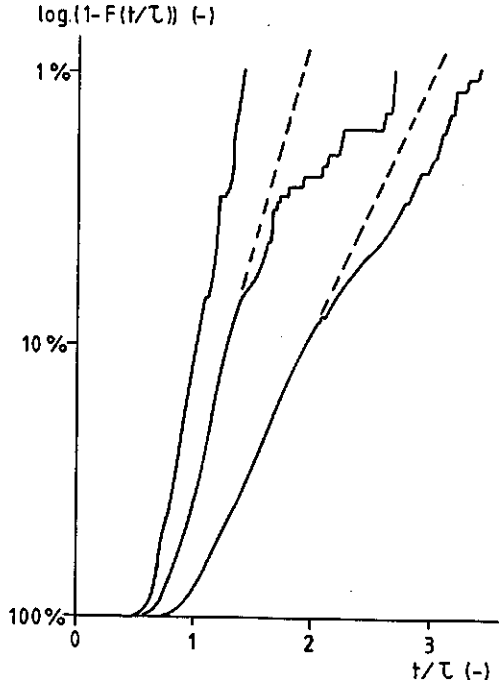

Fig. 20. Logarithmic RTD curves for the extrusion cooking of maize grits.

The F-curve of the last screw element is given in Fig. 21. During the measurement no backmixing to the adjacent kneading section was observed. This RTD can be simulated with a complete mixing of chamber content and leakage flow. The degree of fill (0.0772) and chamber mixing coefficient (1.00) are used for all model simulations with screw elements in the glycerine measurements. The logarithmical RTD (Fig. 22) shows a bend when about 1% of the tracer is still left in the extruder.

The RTD of the whole reversed kneading element including the last screw section can be simulated with a chamber mixing coefficient of 0.018 and no plug flow (see Fig. 23).For the kneading element this first value is smaller than expected from visual observation. When the chamber mixing coefficient is raised the plug flow component in the kneading section should also be raised in order to keep the curve width constant. The logarithmical RTD in Fig. 24 shows a large deviation from the simulated curve. The RTD for the whole extruder has only a small deviation (see Fig. 25). The forwarding kneading sections can be simulated when in the RTD model 40% of the degree of fill above the minimum represents a plug flow and when the leakage flows and the chamber content do mix completely. The deviation of modelled and measured F-curve in Fig. 25 is due mainly to the deviation in the reversed kneading section.

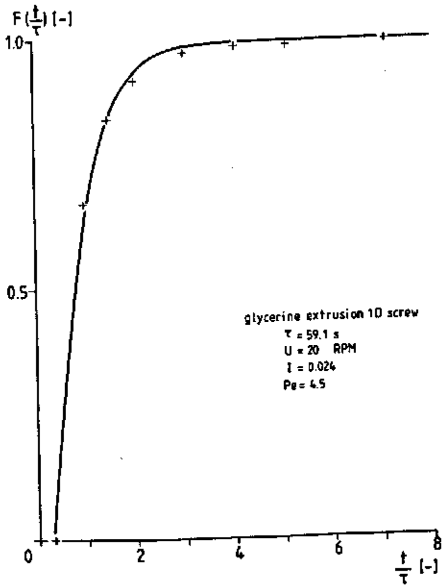

Fig. 21. F-curve of glycerine in the last screw element of a twin-screw extruder. The model is represented by a line and the measurements by a '+'.

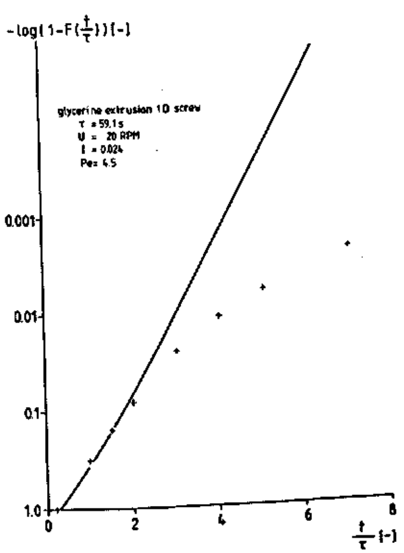

Fig. 22. Logarithmic RTD of glycerine in the last screw element of a twin-screw extruder. The model is represented by a line and the measurements by a '+'.

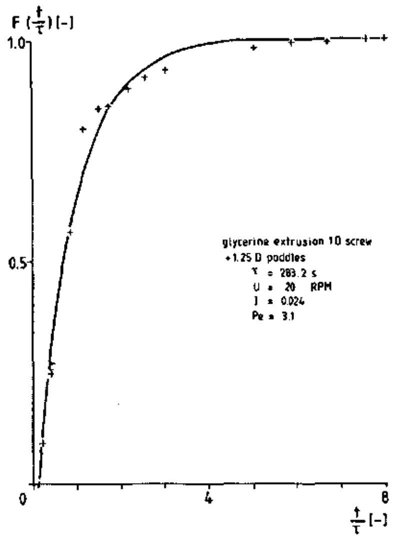

Fig. 23. F-curve of glycerine in the last screw element and kneading section of a twin-screw extruder. The model is represented by a line and the measurements by a '+'.

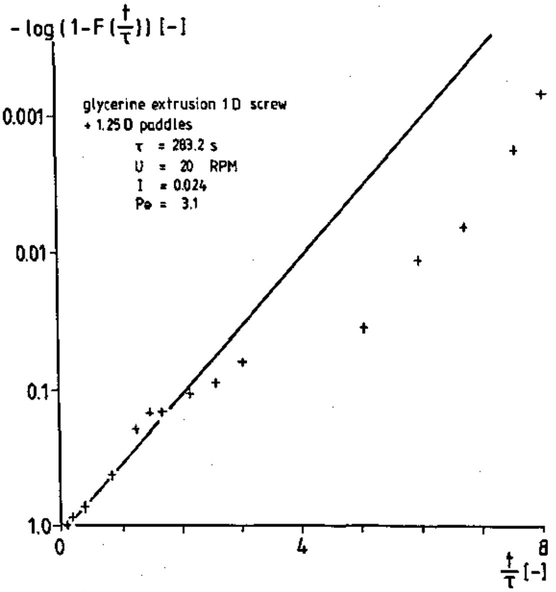

Fig. 24. Logarithmic RTD of glycerine in the last screw element and kneading section of a twin-screw extruder. The model is represented by a line and the measurements by a '+'.

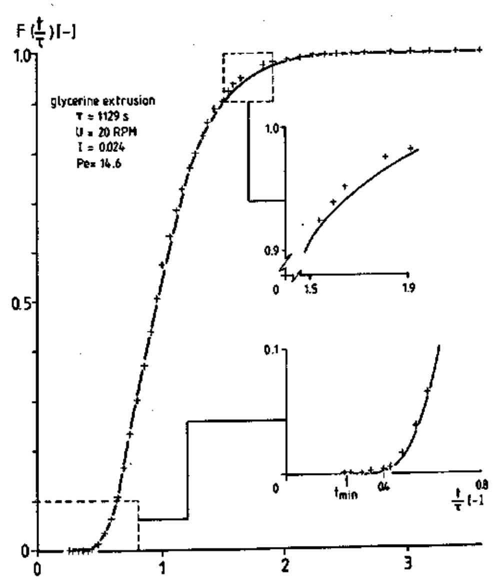

Fig. 25. F-curve of glycerine of a twin-screw extruder. The model is represented by a line and the measurements by a '+'.

DISCUSSION

In Fig. 26 two measured extinction curves with a degree of fill of 56% and 46% are compared with a curve of Altomare and Ghossi with a degree of fill of 46%. The shape of the E-curves with a 46% degree of fill is comparable for $t>\tau$.

It is possible that the bend found in the logarithmical RTD is caused by the material properties of the tracer. This hypothesis is unlikely as this bend is found with different tracer systems and as in some cases it is even found when more than 10% of the tracer is still left in the reactor. The RTDs discussed, the measurements of Boissonnat et al. (1988) in a corotating, twin-screw extruder, Janssen et al. (1978) and Todd (1975) in counter-rotating, twin-screw extruders have similar logarithmical RTDs which points to a similarity in mechanism with different tracer systems.

When both curve width indicators in Table 3 are converted to Peclet numbers with help of Fig. 6 a considerable deviation (up to 30%) of these two Peclet numbers can be found. This deviation which occurs as Fig. 6 does not take the bend in the logarithmical RTD into account. The bend does not influence the t_{84}/t_{16} ratio as it is found after both characteristic times and this ratio is independent of an increase in the average residence time caused by this bend. The t_{92}/τ is affected not only by the t_{92} time but also by the average residence time.

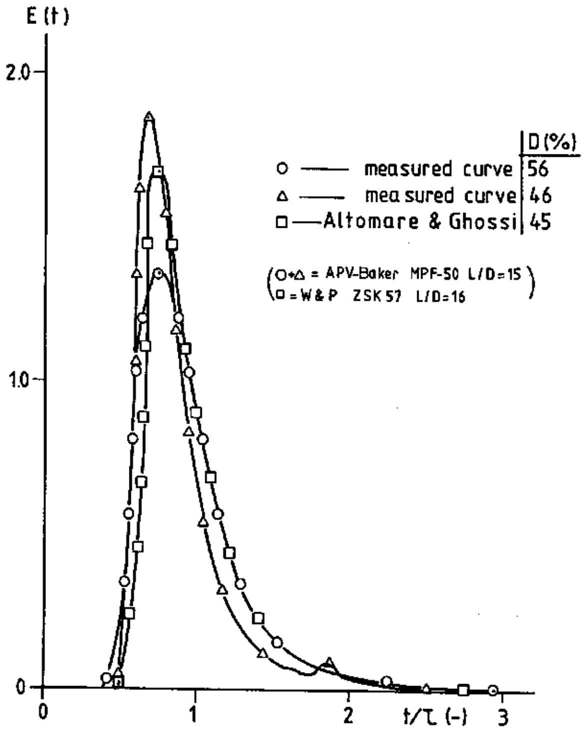

Fig. 26. RTD curves of corotating extruders.

Fig. 7 calculated from appendix A gives the influence of the bend in the logarithmical RTD on the Peclet number for a decrease in the slope in the tail. This decrease for the measurements with maize grits has in Fig. 20 a maximum value of around 50%. According to Fig. 7 the maximum decrease in the Peclet number should then be 10%. When this is compared with the 30% difference between the Peclet numbers from both curve width indicators it can be concluded that by using Fig. 6 the effect of the bend on the Peclet number for the t_{92}/τ curve width indicator is over estimated. However it is possible to use the difference between Peclet numbers from the two curve width indicators and Fig. 6 to quantify the size of the bend. The difference in Peclet number is expressed as:

$$1 + 2\,\frac{Pe_1 - Pe_2}{Pe_1 + Pe_2} \tag{14}$$

In which Pe_1 is derived from the t_{92}/τ ratio and Pe_2 from t_{84}/t_{16} . According to Fig. 7 and appendix A (Pe_1-Pe_2) should be possitive. two negative values are found at measurements for which (t_{84}/t_{16} <1.6) and the total number of counts is smaller than 300. At these measurements the small difference in these two Peclet numbers can not be calculated accurately. The dimensionless group defined by eqn. 14 is used with a stepwise regression analysis for all variables given in Table 2 except for the curve width indicators. Measurements for which t_{84}/t_{16}< 1.6 are not used in this analysis. The equation found is a correlation between the dimensionless group and the rotational speed of the screws ,U:

$$1 + 2 \frac{Pe_1 - Pe_2}{Pe_1 + Pe_2} = 1.28 - 0.024\ U \qquad R'=0.92 \qquad (15)$$

In the simulation model of Chapter 4 described in Fig. 3, a small amount of leakage flow travelled unmixed backwards through the extruder. Despite several adaptations of this pattern of back-mixing it was not possible to simulate a bend, which is consistent with the analysis of Shinnar and Naor (1967). The measured bend can be simulated by a dead volume in some chambers of the numerical model Bounie (1986) or by dividing a part of the model into two parallel submodels with different values for the percentage of plug flow and, or the mixing coefficient. Boissonat et al. (1988) use a model with two parallel strands.
A choice between these two descriptions can not be made on basis of the RTDs or the visual observations of the mixing of a coulored tracer and glycerine in the translucent extruder. The tracer left after $t >> \tau$ during the glycerine experiments in the forwarding kneading element, was distributed in all parts of the element. A specific location of the tracer could not be seen. This makes it is unlikely that there is a dead volume with a constant location, volume and tracer exchange properties.
As the tracer in the kneading element is constantly mixed it is also impossible to distinguish the separated volumes which are required by two parallel flows. Both one dimensional approaches of the RTD model can describe the deviations between the numerical model and the measured RTDs but do not describe fully the three dimensional visual observations. However, in both the dead volume and the two parallel flow model the radial distributive mixing of the the tracer is not uniform (Westerterp et al. 1984), which suggests that the bend in the logarithmical RTD represents this type of mixing. When the percentage of tracer left after the bend decreases, while the shape of the curve before this bend does not change significantly, the radial distributive mixing improves.

A model of a kneading element can be considered as a combination of three dimensional internal circulations patterns with variable average residence times and different rates for the exchange of volumes between those patterns. When an amount of tracer is introduced into this system, it shows a circulation pattern with large exchange rates, which is equivalent to a good distributive mixing. After a certain time when most of the tracer has left the kneading element the remaining tracer will be found mostly in circulation patterns with small exchange rates and therefore a poor distributive mixing.
In such a system the distributive mixing of the tracer is time dependant. The time dependant

change in the distributive mixing is represented by the change of the slope of the logarithmical RTD before and after the bend. This can be illustrated by two numerical RTD simulations shown in Fig. 27. The simulations have equal average residence times and the amount of plug flow, but the values of the chamber mixing coefficient G is smaller in the simulation with the less steep RTD. When, during a simulation, the value of the mixing coefficient is changed from that of the steepest curve to that of the less steep curve in Fig. 27 the slope of the former curve decreases to that of the latter. Therefore the size of the change in slope of the logarithmical RTD is commensurate with the heterogenity of the exchange rates of the three dimensional circulation patterns described. When this system can be considered as being heterogenious the circulation pattern with the smallest exchange rates will be limiting for the distributive mixing. Therefore the size of the change in slope of the logarithmical RTD is commensurate with the distributive mixing.

The slope of the logarithmical RTD itself is proportional to the axial mixing. There is a relation between this axial mixing and the distributive mixing in the kneading element and it may be

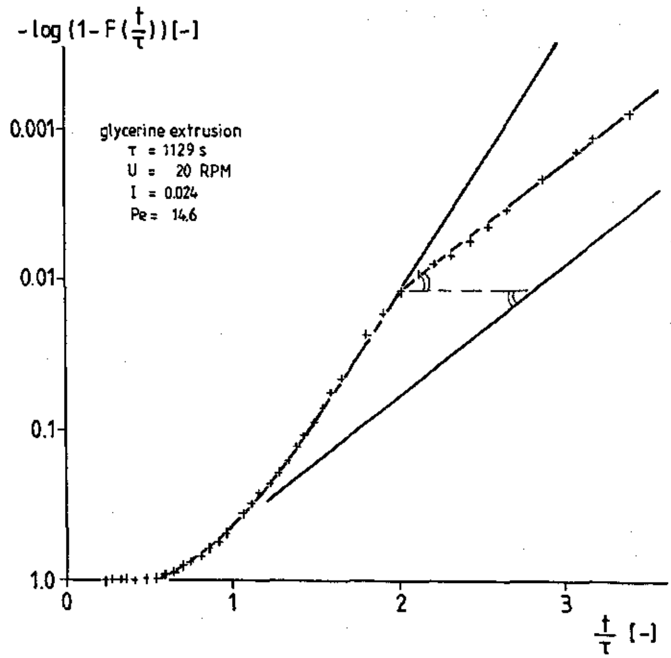

Fig. 27. Simulation of the non-linearity in the logarithmical F-curve.

expected that there is a relation between the distributive mixing and the radial distributive mixing. However for the presented measurements with an axial plug flow this relation still has to be proved. Therefore the slope of the logarithmical RTD is not used to characterize the radial distributive mixing in the extruder.

The dimensionless group defined in eqn. 14 is now affected in two ways by the distributive mixing. This dimensionless group will decrease when the percentage of tracer after the bend decreases or when the heterogenity of the exchange rates of the circulation patterns decrease (which will improve the distributive mixing). According to eqn. 15 the distributive mixing improves when the shear rate is raised.

CONCLUSIONS

When the axial dispersion model of Levenspiel is fitted to the peak height or peak width of the RTD of twin-screw extruders it underestimates the curve height in the tail of the RTD. The numerical model simulates the measured curve more accurately than the axial dispersion model despite the fact that it was not possible to distinguish both the chamber mixing coefficient and the percentage of plug flow in the kneading zone. Consequently the model has in practice only one parameter.

The curve width is mainly dependent on the specific feed rate and the hold up. When the barrel valve is closed the hold up increases, and a small increase in the curve width was found by (Van Zuilichem et al 1989). This can be explained quantitatively by a more plug flow like behaviour of the material present in the kneading zones when the hold up is increased by the closing of the barrel valve.

The measured deviations of this model can be described as a reduction of the logarithmic slope in the tail of the RTD. This behaviour is reported in both co and counter-rotating, twin-screw extruders. The RTD of the examined corotating, twin-screw extruder is closer to the counter-rotating, twin-screw extruder studied by Janssen (1978) than the corotating, twin-screw extruder investigated by Boissonnat (1988). The effect of the bend on the Peclet number is, in most cases, small.

The proposed model can not predict the average residence time as this is dependent of the physical properties of the extruded materials, which are not incorporated in the model. It can be used as a 'standard' RTD model which explains how changes in the RTD reflect changes in the mass flow in a wide range of twin-screw extrusion processes, including non-food applications.

APPENDIX A

Calculation of the effect of a bend in the tail of the RTD on the Peclet number

The average residence time (τ) and the curve width expressed as the number of CSTRs (N) can be defined with the zero, first and second time moment (M_0,M_1,M_2) of the measured extinction C(t) as:

$$M_i = \int_0^\infty t^i . C(t) dt \tag{A1}$$

$$\tau = \frac{M_1}{M_0} \tag{A2}$$

$$N = \frac{M_1^2}{M_0 . M_2 - M_1^2} \tag{A3}$$

The Peclet number, the ratio of the average axial convective transport and the transport by dispersion is:

$$Pe = \frac{<v> . l}{D_e} \tag{A4}$$

in which l is the extruder length, <v> the average axial velocity, and D_e the axial dispersion coefficient, defined by Levenspiel (1972), in a dispersed plug flow model, as:

$$\frac{\delta(t)}{\delta t} = D_e \frac{\delta^2 E(t)}{\delta X^2} \tag{A5}$$

in which X gives the axial location in the extruder. The numer of CSTRs can be derived from eqn. A5 as:

$$\frac{1}{N} = 2 \frac{(Pe - 1 + exp.(-Pe))}{Pe^2} \tag{A6}$$

As all RTD measurements are ended after a time period (Y) there is a truncation error for each moment. Todd (1975) assumes an exponential curve for the RTD to calculate this error for the zero moment:

$$C(t) = C(Y)\exp(-at) \qquad \text{for } t>Y \tag{A7}$$

while

$$\log(1-F(t)) = -a(t-Y)-\log(M(0)a/C(Y)) \quad \text{for } t>Y \tag{A8}$$

This aproach can also be used to calculate the effect of a change in the logarithmic slope ,a, in the tail of the curve. The truncation error of the zero moment is according to Todd:

$$\frac{C(Y)}{a} \tag{A9}$$

The correction terms for the second and third moments are respectively:

$$\frac{(a.Y + 1)\ C(Y)}{a^2} \tag{A10}$$

$$\frac{(a^2.Y^2 + 2a.Y+2)\ C(Y)}{a^3} \tag{A11}$$

The effect of a bend on the Peclet number can be calculated by determination of M_0,M_1 and M_2 with equations A1,A2,A3 and A6 and to correct them for changes in the logarithmic slope ,a, after time ,Y, with equations A9,A10 and A11. The corrected Peclet number is smaller when a is reduced.

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8. DISCUSSION AND RECOMMENDATIONS

The developed RTD model is able to describe a relation between a possible pattern of axial mass flow and the RTD of a twin-screw extruder. For the confirmation of this relation it is necessary to measure the mass flows in a twin-screw extruder. Direct measurement of the three dimensional mass flows is, even for model experiments extremely laborious. Kalyon and Sangani (1988) describe a method to measure the mass flow for a thermoplastic elastomer (TPE). A running extruder filled with coloured TPE was suddenly brought to a dead stop. The barrel was cooled until the TPE became solid. Wedges of the white TPE were cut out and replaced by black coloured TPE. The barrel was closed and heated. After temperature equilibration the shafts were rotated for a desired number of rotations, followed by cooling, opening of the barrel and removal of the samples.
The application of this method to biopolymers seems impossible. Also the described equalisation of the temperature can be a source of artificial disturbances. Therefore it is doubtfull whether this method is sufficiently accurate and representative for the confirmation of a certain pattern of backmixing of leakages flows, or of a residence time dependant change in the flow properties in a twin-screw extruder. When such measurement techniques are not available the measurement of RTD is an acceptable substitute for a first check of predictive models of the axial mass flow in twin-screw extruders. However confirmation of other properties, such as: pressure generation, heat flow and mixing lengths remain necessary.

The RTD model is used to describe the mass flow in both a co- and a counter-rotating, twin-screw extruder. Therefore it is able to compare the axial mixing in different extruder types. The quality of such a comparison in the scale-up of twin-screw extruders is dependent of the accuracy and the number of measurement points.
The description of a single-screw extruder with this model seems less advisable. Therefore the radial separated laminar layers with different velocities of the single-screw extruder (Pinto and Tadmor 1970) are too different from the radial mixed C-shaped chambers of the twin-screw extruder.
The RTD of a single-screw extruder for shear thinning fluids has been described by Bigg and Middleman (1974). This model could however not be confirmed for maize-grits with a shear thinning rheology (Van Zuilichem et al. 1988).
The cokneader extruder with barrel-pins and an axial oscillating single-screw is a more likely mixer to be modelled by the here presented RTD model. The radial mixing of the barrel-pins destroys the radial separation of layers which is typical for a single-screw extruder, while the oscillating motion of the screw can be modelled as the conveying of chambers in a twin-screw extruder with a large amount of leakage flow. The pin-barrel extruder has a middle position between the single-screw extruder and the cokneader.

In Chapter 2 it was concluded that the reactions of the RTD for changes in screw speed at a constant specific feed rate were divers while the effects of important material properties were not investigated. Also the hold up volume increased in most cases for an increase of the specific feed rate. The exceptions of this 'rule of thumb' were mainly found for non-food applications. A relation between the material properties of the extrudate and the mass flows required in the RTD model to produce similar changes in the RTDs could possibly give more information on the working mechanism of the twin-screw extruder.

The coincidence detection system used could work with a modest amount of radiotracer. During the experiments the level of radiation around the extruder was four to six times that of the background radiation. Still the use of a radiotracer in the production plants of the food industries seems to introduce not acceptable hazards. Therefore the development of on-line measuring systems based on other tracers is necessary for the use of RTD measurements in the food industry. In Chapter 2 some possible systems are mentioned.

In Chapter 5 it was concluded that it is not necessary to include a dead volume in the RTD model, or an other source of stagnancy, in order to describe the RTD of a counter-rotating, twin-screw extruder. Opposed to this conclusion the logarithmical F-curve of the same experiment in Chapter 2 (see Fig. 3, Chapter 2) shows a small bifurcation. This contrast can be enlightened by Fig. 5 of Chapter 7. According to this figure the influence of a bifurcation is very hard to detect in an RTD with a small curve width. However, these bifurcations could have been found in the RTDs of Chapters 4 and 5, when the same curve fit method with two curve width indicators was applied as developed in Chapter 7. A second assumption in the Chapters 4 and 5 is that the curve shape of the measured RTD was approximately equal to that of a plug-flow with axial dispersion model. This approximation is only acceptable for narrow RTDs.

Härröds (1987) describes that the axial mixing in rotated scraped heat exchangers influences the axial temperature distribution. The leakage flows in twin-screw extruders can be expected to have a similar effect. Figure 1 shows the axial temperature profile in a kneading element with and without axial backmixing. The temperatures are calculated as described by Van Zuilichem et al. (1990) while the mass flow is described with the RTD model of Chapter 7 for the material maize grits.
It can be seen in Figure 1 that the backmixing of extrudate increases the temperature at the beginning of the kneading element. This decreases the temperature gradient at the wall and the heat flow from barrel to extrudate, as can be seen by the lower end temperature of the backmixed simulation in Figure 1. Therefore a correction on the heat flow model of Van Zuilichem et al. (1990) for the axial mixing in continuous cut elements seems necessary.
When a continuous cut screw element is changed in a kneading element the Peclet number increases. This indicates that such a correction term for kneading elements should be smaller than that for a continuous cut element.

A study on the interactions between mass and heat flow (Jager and Van der Laan 1992) suggest that the heat exchange coefficient from barrel to bulk in the kneading elements of a corotating twin-screw extruder is dependent of the local percentage of plug flow. When this radial heat mixing action is representative for the radial distributive mixing it can be concluded that the distributive mixing in the kneading elements is proportional to the Peclet number of mass flow corrected for all axial plug-flow present. The Peclet number in the here presented RTD model is not calculated as a ratio of two mass flows, but as a comparison of the curve width in relation to that of a plug-flow and axial dispersion model. When the Peclet number is calculated as the ratio of leakages flows and total mass flow in the model the Peclet number is sufficiently corrected for axial plug-flows.

The developed RTD model gives a possibility to compare the RTDs in different twin-screw extruders and reduce them to a number of mass flow related variables. Which describe the axial degree of fill in the RTD model, the mixing of chamber content and leakage flows, the percentage of plug flow in the kneading elements and eventually the change in the chamber mixing coefficient by stagnant-like behaviour. As studies on distributive mixing and heat flow simplify the mass flow generally to a plug-flow, the use of this RTD model can increase the understanding of the processes involved.

This will increase the number of measured variables and possible interactions. Typical parameters are: the rotational speed of the screws, feed rate, screw and barrel geometry, temperatures and feed material properties, while pressures, temperatures, viscous dissipation, mixing lengths, RTD variables and extrudate properties are examples of the measurable variables. A test with a Box-Wilson experimental design can describe the statistical relation between the process parameters and the measured results. However the interactions among the process conditions are more interesting for a better understanding of the processes involved. Also quality properties of the extrudate can not be analysed by this method as a function of the process conditions as they can not be varied freely in the Box-Wilson experimental set up. Therefore this method is less effective in order to understand the working mechanism of the extruder involved. The approach described in Chapter 6 can result in a statistical likely hypothesis. Self-evidently logical explanations for each hypothesis have to be checked by independent experiments.

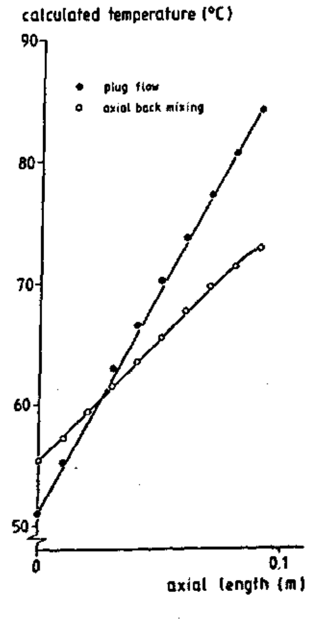

Fig. 1. Axial temperature profile in a kneading element for 0 and 100% plug-flow.

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SUMMARY

For the twin-screw extruders used in the food industry at short time high temperature processes the knowledge of their reactor properties is incomplete for mass- and heat flow. Therefore each process change such as: scale-up or product development requires a great number of measurements before an acceptable product quality can be made with a stable process. The number of measurements is considerable by the great number of possible variables in the extrusion process and the interactions between process conditions such as: temperatures, viscous dissipation and distributive mixing.
From these constraints the objective of this thesis is expressed as the measurement and characterisation of the mass flow in a twin-screw extruder, possibly without laborious methods. As the direct measurement of these mass flows is quite time consuming, it is chosen to describe the relation between the mass flow and the residence time distribution. This relation is described in a residence time model which translates the axial mass flow in a twin-screw extruder into a residence time distribution. At the start of this project an appropriate measuring method for the average residence time was already available from a collaboration with ITAL. Its accuracy was calculated during this project.
The influence of the adjustable variables of the twin-screw extruder on the degree of fill and the shape of the residence time distribution is dependent of the properties of the extruded material as well as of the extruders geometry. A standard behaviour of the residence time distribution has been found for biopolymers. For non-food applications a considerable number of exceptions can be found in the literature. The mechanisms behind these exceptions are not appointed in the literature.
In this work a method is given to search for statistical interesting hypotheses which describe possible relations between the multitude of possible variables in extrusion research. By this method a steam reflux was found in a counter-rotating, twin-screw extruder.
The developed residence time distribution model describes the extruder as a machine in which chambers are formed and conveyed by the revolutions of the screws. During there residence in the extruder these chambers lose leakage flows which give a substantial part of the axial mixing. The mixing of these leakage flows and the contents of the chamber is described.
The model can be used for co- and counter-rotating, twin-screw extruders in food and non-food applications. The residence time distribution of the compression zone of a counter-rotating, twin-screw extruder can be simulated with a complete mixing of the leakage flows and chamber content. Incomplete mixing has been used for most of the measurements on a corotating, twin-screw extruder and on the feed zone of a counter-rotating type.
In all comparable logarithmical F-curves from the literature a bend was found. This bend can increase the fraction with the longest residence time considerably, while the characteristic variables for the curve width are hardly changed. This phenomenon can be simulated by the developed model with a time dependent change in mixing properties.

SAMENVATTING

Bij de in de levensmiddelenindustrie gebruikte dubbelschroefextruders voor korte verblijftijd bij hoge-temperatuurprocessen is de kennis van de reactoreigenschappen zeer onvolledig voor zowel warmte- als massastromingen. Dit resulteert bij schaalvergroting, produktontwikkeling en andere veranderingen aan bestaande extrusieprocessen, in een groot aantal benodigde proeven voordat een stabiel proces en een kwalitatief volwaardig produkt ontstaat. De grootte van dit aantal proeven word veroorzaakt door de veelheid van mogelijke variabelen in het extrusieproces, en door de onderlinge afhankelijkheid van belangrijke procescondities als temperatuur, visceuze dissipatie en distributieve menging.

Uit deze probleemstelling kan het doel van dit promotieonderzoek geformuleerd worden als het meten en beschrijven van de massastromingen in een dubbelschroefextruder, met, bij voorkeur, niet arbeidsintensieve technieken. Daar een directe meting van de massastromingen zeer arbeidsintensief is, werd gekozen voor een benadering waarbij de relatie tussen verblijftijdspreiding en massastromingen werd gezocht. Voor het beschrijven van deze relatie is een model ontwikkeld dat de axiale massastromingen van een dubbelschroefextruder vertaalt in een verblijftijdspreidingscurve. Een geschikte meetmethode voor verblijftijdspreiding was voor aanvang van het onderzoek al ontwikkeld in samenwerking met het ITAL. Tijdens het onderzoek is de meetnauwkeurigheid van deze detectiemethode berekend.

De invloed van de instelbare variabelen van de dubbelschroefextruder op de vulgraad en de vorm van de verblijftijdspreiding blijkt afhankelijk te zijn van zowel eigenschappen van het geëxtrudeerde materiaal als van de geometrie van de extruder. Er is een standaardpatroon van de reacties van de verblijftijdspreidingscurve bij biopolymeren beschreven. In de literatuur worden echter veel uitzonderingen op dit patroon beschreven voor non-food toepassingen. Verklarende mechanismen voor deze uitzonderingen zijn onbekend. De thesis geeft een methode voor het zoeken naar statistisch interessante hypothesen, die mogelijke verbanden tussen de veelheid aan variabelen in extrusieonderzoek beschrijven. In een tegendraaiende dubbelschroefextruder is met deze methode een terugstroming van stoom gevonden.

Het ontwikkelde verblijftijdspreidingsmodel beschrijft de extruder als een machine waarin, door het draaien van de schroeven, kamers gevormd en getransporteerd worden. Tijdens hun verblijf in de extruder verliezen de kamers lekstromen die de belangrijkste bijdrage zijn aan de axiale menging. De menging van deze lekstromen en de inhoud van de kamers wordt beschreven. Het model kan gebruikt worden bij zowel mee- als tegendraaiende dubbelschroef extruders voor levensmiddelen- en niet levensmiddelen toepassingen. De verblijftijdspreiding van de compressiezone van een tegendraaiende dubbelschroefextruder kan gesimuleerd worden door een volledige menging van lekstromen en kamerinhoud. Een onvolledige menging is gebruikt bij de metingen aan een meedraaiende dubbelschroefextruder en aan de voedingszone van een tegendraaiend type. In alle vergelijkbare logaritmische F-curven uit de literatuur werd een bocht gevonden. Deze bocht kan de fractie met de langste verblijftijd aanzienlijk vergroten terwijl de kengetallen voor de verblijftijdspreiding nauwelijks veranderen. Door de menging in het verblijftijdspreidingsmodel tijdsafhankelijk te maken kan dit verschijnsel gesimuleerd worden met het ontwikkelde verblijftijdspreidingsmodel.

CURRICULUM VITAE

De auteur van dit proefschrift werd te Rotterdam geboren op 31 oktober 1956. In 1975 behaalde hij het diploma atheneum aan de scholengemeenschap Albert Einstein te Rotterdam. Een studie levensmiddelentechnologie aan de Landbouwhogeschool Wageningen werd in 1984 afgesloten met het diploma landbouwkundig ingenieur. Tussen 1984 en 1986 werd consultancy onderzoek uitgevoerd bij enkele levensmiddelenbedrijven. Het in dit proefschrift beschreven promotieonderzoek werd in de periode van 1986 tot 1990 voltooid. Van 1988 tot 1991 is hij research medewerker geweest bij van Melle Internationaal. In 1991 trad hij in dienst bij de firma Langenberg-Fassin ten bate van de produkt en proces ontwikkeling.