

Extruder Principles and Operation

M. J. STEVENS

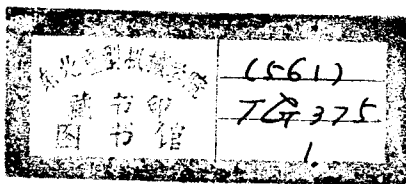


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ELSEVIER APPLIED SCIENCE PUBLISHERS
LONDON and NEW YORK

ELSEVIER APPLIED SCIENCE PUBLISHERS LTD
Crown House, Linton Road, Barking, Essex IG11 8JU, England

Sole Distributor in the USA and Canada
ELSEVIER SCIENCE PUBLISHING CO., INC.
52 Vanderbilt Avenue, New York, NY 10017, USA

British Library Cataloguing in Publication Data

Stevens, M. J.
Extruder principles and operation.
1. Polymers and polymerization—Extrusion
I. Title
668.4'13 TP1175.E9

ISBN 0-85334-336-5

WITH 92 ILLUSTRATIONS AND 21 TABLES

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PREFACE

This book is intended to fill a gap between the theoretical studies and the practical experience of the processor in the extrusion of thermoplastic polymers. The former have provided a basis for numerical design of extruders and their components, but generally give scant attention to the practical performance, especially to the conflict between production rate and product quality. In practice extruders are frequently purchased to perform a range of duties; even so the operator may have to use a machine designed for another purpose and not necessarily suitable for the polymer, process or product in hand. The operator's experience enables him to make good product in unpromising circumstances, but a large number of variables and interactions often give apparently contradictory results. The hope is that this book will provide a logical background, based on both theory and experience, which will help the industrial processor to obtain the best performance from his equipment, to recognise its limitations, and to face new problems with confidence. Mathematics is used only to the extent that it clarifies effects which cannot easily be expressed in words; if it is passed over, at least a qualitative understanding should remain. The approximate theory will not satisfy the purist, but this seems to the author less important than a clear representation of the physical mechanisms on which so much of the polymer processing industry depends.

M. J. STEVENS

ACKNOWLEDGEMENT

The author is responsible for statements and opinions expressed in this book, which are his own, but would like gratefully to acknowledge assistance over many years from Imperial Chemical Industries PLC, Petrochemicals and Plastics Division, and the staff of the Institute of Polymer Technology, Loughborough University of Technology.

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Chapter 1

INTRODUCTION

SCOPE AND LIMITATIONS

The objective of this book is to summarise the principles of single screw extrusion processes for plastics and rubbers, the practical performance and its theoretical explanation, and operating procedures to exploit this performance.

The scope of the work includes the principles and operation of the single screw extruder as a machine, as a combination with a die, and as part of a total fabrication process, including subsidiary functions such as compounding and venting. It includes the special requirements for the extruder of individual processes such as wire covering, tubular film blowing and blow moulding, but does not attempt to cover other aspects of these processes. In order that the objective may be adequately covered in a book of reasonable size, certain matters are excluded, and the reader's attention is directed to the references for further information. In particular, twin screw extruders, depending on their precise design, operate more or less as positive-displacement rather than drag pumps, leading to distinct design, constructional and operating characteristics. The principles of these machines are well described by Janssen.¹ The mechanical construction and adaptation for special purposes of single screw machines is governed partly by the process requirements described in Chapter 4, but also by standardisation, manufacturing methods and mechanical reliability. Mechanical construction is dealt with in Chapter 6 of Fisher² and Chapter 6 of Schenkel.⁷ Commercial models and unconventional types of extruder are also covered by Fisher and Schenkel, as well as by periodic reviews such as *Plastics and Rubber Weekly*.⁸ As this book is primarily con-

cerned with operation, it does not purport to be a design manual for the precise dimensional design of machine, screw or die for a specific performance. This is covered by several authors including Fenner.⁹

METHOD

The method is to summarise the properties of plastics and rubber materials suitable for extrusion, especially the flow and thermal properties of polymer melts. The relevant general equations of mass and heat flow are presented and their application to extrusion problems developed. After a brief chapter on the process requirements of the single screw extruder, to provide an objective for the following chapters, a simplified extrusion theory is developed for both mass flow and energy consumption and presented in both algebraic and graphical form to demonstrate the effects of dimensional and operational variables on output, energy balance, melt temperature and product uniformity. These effects are used to propose strategies for operation and control to eliminate faults and optimise performance of the extruder, and of the system of which it is a part. In particular the problem of scaling up an extrusion process from the development laboratory to large-scale production is studied. Although the simplified theory is approximate, its predictions are borne out in practice. It is used in preference to more exact methods since the algebraic form of the solutions permits a ready identification and understanding of the effects of separate variables on extruder performance; this tends to be obscured in the more exact methods, which usually involve digital computation.

As a complement to the analysis of steady-state operation, recommendations for start-up, shut-down, dismantling and cleaning are given, based on practical experience.

The total commercial process of extrusion of plastics and rubbers covers the conversion of a raw polymer, usually in the form of powder or pellets, into a saleable finished or semi-finished product. This will include matters of management and plant organisation common to many other materials and processes. It will also include polymer handling and storage, product specification and quality control, plant layout, installation and maintenance, product finishing, assembly, packaging and distribution which are general to many plastics processes and only indirectly concerned with the actual operation of extrusion. The intention in this volume is to provide the specific requirements of

extrusion, and their explanations, which form the technical background to the total process and its peripheral aspects.

In its simplest terms, extrusion consists of forcing a polymer in liquid form (usually molten) under pressure through a die to produce a continuous section or profile. This may then be sized, drawn down, corrugated, etc., to modify and control the shape and dimensions of the section and in some cases the properties (mechanical, optical, etc.). In the case of thermoplastics, the product or 'extrudate' must be cooled to retain its shape, while rubbers are chemically cross-linked ('cured') to achieve properties such as elasticity and resistance to chemicals and heat. In some processes, e.g. blow moulding, injection moulding and in-line vacuum forming, the extrudate may be shaped into a discontinuous or intermittent form before cooling or curing. Other subsidiary processes, such as printing, slitting and on-line testing, may precede coiling or cutting into handleable lengths. The detail of these operations after the die (collectively 'post-forming') is highly specific to the material and product, much of it confidential to each company, so space precludes exhaustive study here. However, it is just as important as the extruder to the 'quality', dimensions and surface finish of the product; an understanding of the effects of, say, the ratio of haul-off rate to extruder output is essential to economic production. The effects of changes after the die are usually visible, if not self-evident, but one cannot see what is going on inside the extruder, and this book aims to provide the basic mechanisms which help to explain the performance of the screw and die, and hence their interactions with post-forming operations. The book also introduces strategies for operation (Chapter 7) and control (Chapter 8), as well as some practical experience on selection of screws, start-up, cleaning and fault-finding (Chapters 8 and 9).

An important subject for development engineers is the prediction of the performance of full-scale production plant from that of a small laboratory process, since by its nature heavy moving machinery is expensive to modify or replace and, owing to special materials and manufacture, changes cause lengthy and costly production delays; this is given special attention. Literature references are given at the end of the book, numbered in order of first appearance. Mathematical equations are also numbered in order of appearance, but separately for each chapter. SI units are used throughout, with Imperial units in brackets where appropriate. Unless stated otherwise, numerical constants are dimensionless, and therefore the same in any consistent system of units.

Chapter 2

FLOW BEHAVIOUR RELEVANT TO EXTRUSION

In this chapter the principles and basic equations relating to fluid flow of polymers will be stated, with emphasis on those which are relevant to melt extrusion. In general, for proofs and other applications, reference should be made to standard works on rheology such as that by Brydson.¹¹ Design of extruder dies has received special attention^{13,14} and will be mentioned further only where it is affected by extruder performance.

2.1. VISCOSITY

When a liquid is subjected to stress, it deforms continuously as long as the stress is applied, unlike a perfect solid which deforms a fixed amount, independent of time. On removal of stress, the liquid remains in its deformed state, whereas an elastic solid recovers its original dimensions instantaneously and completely (Fig. 2.1). Thus the stiffness or modulus, which is the relation between stress and deformation (strain), is unique for a solid, but for a liquid is dependent on time and so does not define a property of the material. However, under a constant stress, the *rate* of deformation with time is constant and the ratio is the viscosity. In direct stress σ (tension, compression), the strain ϵ is defined as extension/original length (Fig. 2.2) and the ratio stress/strain as the modulus of elasticity E , which is constant for a Hookean solid. For a liquid, the strain rate is:

$$d\epsilon/dt = \dot{\epsilon} = \frac{1}{L} \cdot \frac{dL}{dt} \quad (2.1)$$

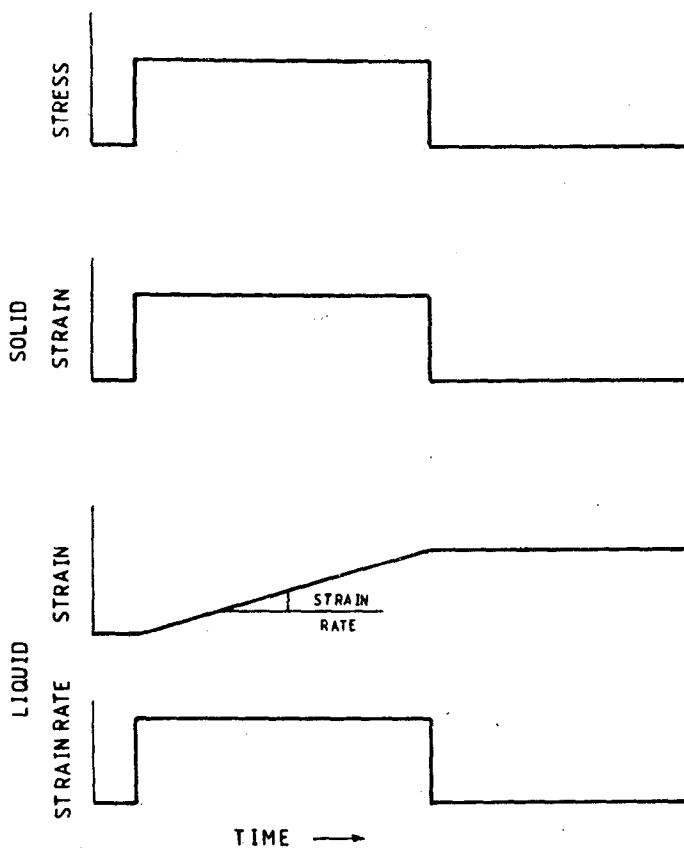


FIG. 2.1. Deformation under stress.

and the extensional viscosity:

$$\frac{\sigma}{\dot{\epsilon}} = \lambda \quad (2.2)$$

In shear, stress τ causes a deformation dx in the direction of the stress, but shear strain is defined (Fig. 2.3) as:

$$\frac{dx}{dy} = \tan \gamma \approx \gamma \quad (2.3)$$

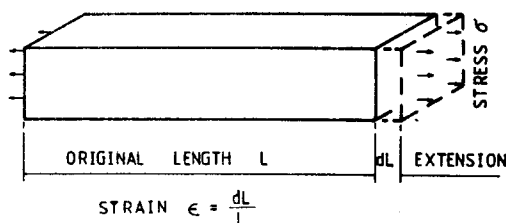


FIG. 2.2. Extensional strain.

for small strains. Shear modulus G (modulus of rigidity) is τ/γ . For a liquid, the strain rate is:

$$\frac{d\gamma}{dt} = \dot{\gamma} = \frac{d}{dt} \left(\frac{dx}{dy} \right) = \frac{d}{dy} \left(\frac{dx}{dt} \right) = \frac{dw}{dy} \quad (2.4)$$

where $w = dx/dt$ is the velocity. The shear viscosity is:

$$\frac{\tau}{\dot{\gamma}} = \eta \quad (2.5)$$

Strain is a pure ratio and therefore dimensionless. Thus the units of stress and modulus are both N/m^2 . Strain rate has dimensions 1/time, expressed as ' s^{-1} ', and so the unit of viscosity is Ns/m^2 . In a Newtonian fluid, the relation between shear stress and shear strain rate is linear (Fig. 2.4), i.e. the viscosity is constant, independent of the values

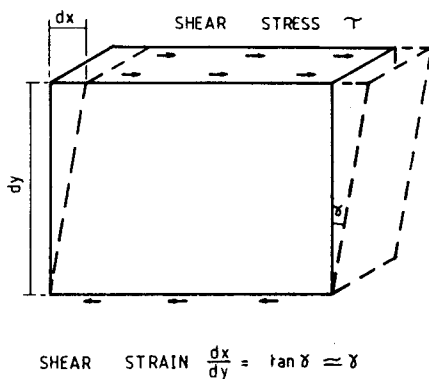


FIG. 2.3. Shear strain.

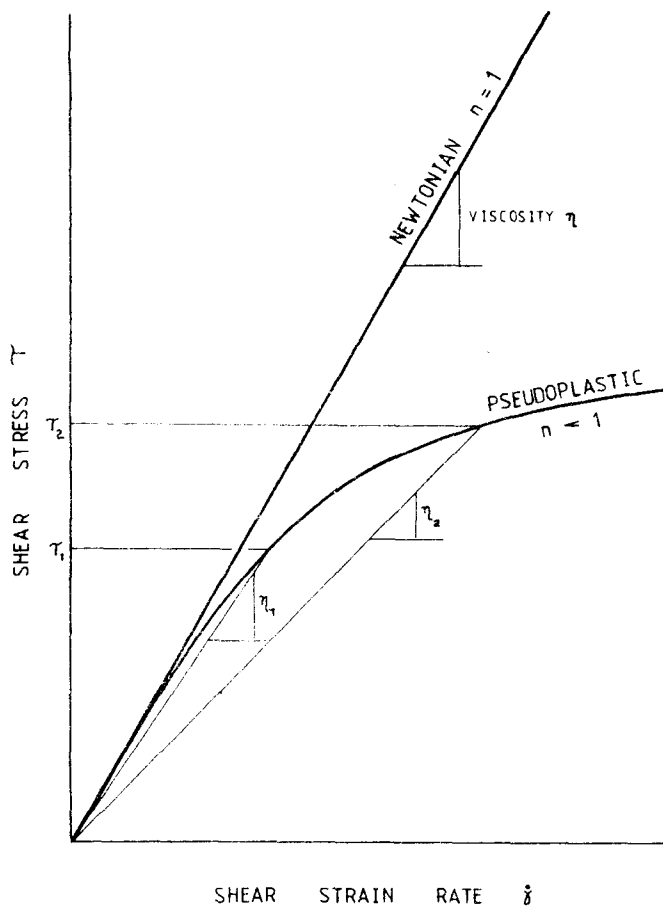


FIG. 2.4. Shear viscosity.

of stress and strain (shear) rate, but dependent on temperature. Many molten polymers are to a lesser or greater extent non-Newtonian, i.e. shear rate is no longer proportional to shear stress, the viscosity usually decreasing with increasing shear stress or shear rate, when they are said to be 'pseudoplastic' (Fig. 2.4). The definition of viscosity (eqn (2.5)) is still used, but this is now a function of shear stress or shear

rate as well as temperature. An approximation which is frequently used expresses shear stress as a simple power of shear rate:

$$\tau = K(\dot{\gamma})^n \quad (2.6)$$

where K is a constant for a specified material and temperature. Combining eqn (2.6) with (2.5) gives:

$$\eta \propto (\dot{\gamma})^{n-1} \propto (\tau)^{(n-1)/n} \quad (2.7)$$

where for a pseudoplastic fluid, $n < 1$, and evidently Newtonian behaviour is equivalent to $n = 1$. Both of these approximations facilitate mathematical analysis, but it must be realised that the 'power-law' has little physical basis; it is a convenient approximation over a limited range of shear rates.

The index n is known as the 'pseudoplasticity index', and as values decrease from unity towards zero it indicates further departure from the Newtonian relation, i.e. shear stress rises more slowly with shear rate. Figure 2.4 indicates that at very high shear rates, shear stress tends to a limiting value and viscosity continuously decreases, giving a curve similar to Fig. 2.5 (log/log scales). If viscosity is plotted against shear rate, the curve has a negative slope of $n - 1$ (eqn (2.7)) on log/log scales, with a maximum value of -1 (45°) when $n = 0$. In both cases Newtonian flow is represented by a horizontal line.

Viscosity (at fixed shear rate for pseudoplastic flow) decreases with increase of temperature; the best approximation is probably an Arrhenius relation:

$$\eta = A \exp(E/RT) \quad (2.8)$$

where A and E are constants, the latter being the activation energy for flow in J/mol, R is the gas constant in J/mol K and T the absolute temperature in degrees Kelvin. Other approximations used over limited ranges of temperature are:

$$\eta = B \exp(-bT) \quad (2.9)$$

and

$$\eta = \eta_0 [1 - \beta(T - T_0)] \quad (2.10)$$

Equation (2.8) would imply that curves of $\log \eta$ v. $\log \dot{\gamma}$ were parallel, i.e. that the effect of temperature was independent of shear rate. For many real polymers this is not the case and either n must be varied with temperature or E must be a function of shear rate; this leads to