DESIGN OF ROTOR FOR INTERNAL BATCH MIXER AND MIXING ELEMENTS FOR TWIN SCREW EXTRUDER FOR POLYOLEFIN PROCESSING

SHAFAAT AHMED SALAHUDEEN

A thesis submitted in fulfilment of the
requirements for the award of the degree of
Doctor of Philosophy (Polymer Engineering)

Faculty of Chemical and Energy Engineering
Universiti Teknologi Malaysia

FEBRUARY 2017

DEDICATION

This thesis is dedicated to my father Salahudeen, my mother Aathikka Begum for their endless support and encouragement and to all my brothers and sisters

ACKNOWLEDGEMENT

The Allah, Most Merciful and Most Beneficent. This PhD or any think without your help is impossible. I thank you for your help and I would always like to be your obedient servant.

I am most grateful to the support of my supervisor Assoc. Prof. Dr. Abdul Razak Bin Rahmat and his continuous support throughout my PhD research. With his patience and support, this journey becomes unforgettable and I am sincerely apologizing for any of my actions that made him bother during my research.

My sincere thanks to Dr. Othman Alothman and Dr. Rabeh Elleithy for their support both technically and financially and Dr. Yunusa Omar for his moral support.

My heartful thank to my friend Mohammed Ehtesham Ali Mohsin for his support and companionship and technician Khaja Nayeem Uddin for his assistance.

I heartily convey my thanks to my father, mother, sister and wife for their continuous support and encouragement during this journey.

I would like to remember this sentence always, “Things always never travel in the way you want, but patience, hard work and Allah’s help brings you to the way you want”.

ABSTRACT

Mixing is the key component of polymer processing to achieve homogeneity of final product. Previous researchers have reported poor mixing performance of internal batch mixer (IBM) and twin screw extruder (TSE) due to improper distributive and dispersive mixings. This leads to poor product properties. Hence to overcome the problem, this research aims to design a rotor and mixing element to improve mixing performance of IBM and TSE. The basic rotor design for IBM was developed on the concept of Banbury and roller rotors and this design was then optimized to attain secondary flow. Distributive mixing performance of the optimized rotor was compared with commercial rotors using ANSYS Polyflow, with results showing the new rotor was found to be better than commercial rotors. Based on these results, a prototype of optimized design rotor was developed using Computer Numerical Control machine. Using this prototype rotor, nano calcium carbonate was dispersed in high density polyethylene and its morphology was analysed via scanning electron microscopy (SEM). SEM results showed improved dispersive mixing performance of prototype rotor compared to that of commercial rotor. This prototype rotor design was later modified into two mixing elements namely, Bean-UTM for intermeshing co-rotating TSE and Blade-UTM for intermeshing counter-rotating TSE. The Bean-UTM and Blade-UTM were examined for dispersive mixing (mixing index) and distributive mixing (logarithm of length of stretch, instantaneous efficiency and time average efficiency) and then were compared with commercial TSE mixing elements. The results showed Bean-UTM has better mixing performance than kneader mixing element of Dr. Collin TSE and the Blade-UTM has better mixing performance than screw mixing element of Coperian TSE. The findings of this research will hopefully solve the issue of poor mixing in IBM and TSE.

ABSTRAK

Pencampuran adalah komponen utama pemprosesan polimer untuk mencapai kehomogenan produk akhir. Penyelidik terdahulu telah melaporkan prestasi pencampuran yang tidak memuaskan bagi pencampur kelompok dalaman (IBM) dan penyemperit skru berkembar (TSE) disebabkan oleh campuran taburan dan serakan yang tidak sempurna. Ini menghasilkan sifat-sifat produk yang bermutu rendah. Untuk mengatasi masalah ini, kajian dijalankan bertujuan untuk mereka bentuk rotor dan elemen pencampuran bagi meningkatkan prestasi campuran IBM dan TSE. Reka bentuk asas rotor untuk IBM telah dibangunkan berdasarkan konsep rotor *Banbury* dan penggelek dan seterusnya reka bentuk ini dioptimumkan untuk mencapai aliran sekunder. Prestasi taburan pencampuran rotor yang telah dioptimumkan dibandingkan dengan rotor komersial menggunakan *ANSYS Polyflow*, dengan keputusan menunjukkan rotor baharu lebih baik daripada rotor komersial. Berdasarkan keputusan ini, reka bentuk prototaip rotor yang telah dioptimumkan dibangunkan menggunakan mesin Kawalan Berangka Komputer. Dengan menggunakan prototaip rotor ini, kalsium karbonat nano telah diserakkan ke dalam polietilena ketumpatan tinggi dan morfologinya dianalisis menggunakan mikroskop elektron pengimbas (SEM). Keputusan SEM menunjukkan peningkatan prestasi serakan campuran prototaip rotor berbanding rotor komersial. Reka bentuk prototaip rotor kemudiannya telah diubahsuai kepada dua elemen campuran iaitu Bean-UTM untuk putaran searus antara jejaring TSE dan Blade-UTM untuk putaran berlawanan antara jejaring TSE. Bean-UTM dan Blade-UTM telah diperiksa untuk campuran serakan (indeks campuran) dan campuran taburan (logaritma daripada panjang regangan, kecekapan serta-merta dan purata kecekapan masa) dan kemudian dibandingkan dengan elemen campuran komersial TSE. Hasil kajian menunjukkan Bean-UTM mempunyai prestasi pencampuran yang lebih baik daripada elemen pencampuran kneader Dr. Collin TSE dan Blade-UTM mempunyai prestasi pencampuran yang lebih baik daripada elemen pencampuran skru Coperian TSE. Hasil kajian ini diharapkan akan dapat menyelesaikan isu pencampuran yang kurang baik di dalam IBM dan TSE.

TABLE OF CONTENT

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATION

CFD	-	Computational fluid dynamics
CPU	-	Central process unit
EVA	-	Ethyl vinyl acetate
FEM	-	Finite element method
HDPE	-	High density polyethylene
L	-	Left rotor
LDPE	-	Low density polyethylene
LLDPE	-	Linear low density polyethylene
PET	-	Polyethylene terephthalate
PS	-	Polystyrene
R	-	Right rotor
RPM	-	Rotation per minute
SME	-	Screw Mixing Element
SSE	-	Single screw extruder
TSE	-	Twin screw extruder

LIST OF SYMBOLS

β	-	Compression factor
ρ_f	-	Fluid density
c_{pf}	-	Fluid heat capacity
r_f	-	Fluid heat source
k_f	-	Fluid thermal conductivity
ρ_s	-	Density of the moving part
c_{ps}	-	Heat capacity of the moving part
r_s	-	Heat source of the moving part
k_s	-	Thermal conductivity of the moving part
Q_g	-	Viscous dissipation
Q_{out}	-	Hear-transfer rate
k	-	Heat conductivity of polymer melt
$\nabla \mathbf{T}$	-	Temperature gradient
A	-	Total surface area of the mixer
e_λ	-	Local efficiency of mixing
λ	-	Length of stretch of a material
P	-	Pressure
D	-	The rate-of-deformation tensor
f	-	Body force
T	-	Extra – stress tensor
v	-	Velocity
γ	-	Local shear rate
ρ	-	Fluid density
$H(T)$	-	Arrhenius Law
η_o	-	Zero shear-rate viscosity
η_∞	-	Infinite shear-rate viscosity
K	-	Natural time

T	-	Temperature
T_α	-	Reference Temperature
A	-	The ratio of the activation energy to the thermodynamic content
α	-	Clearnace between mixing element and mixing chamber
W		The vorticity tensor.
λ_{MZ}		Mixing index

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Background of Study

Mixing is the most important step in polymer processing industries and it determines the homogeneity of the final end product (Rauwendaal, 2001; Tatterson *et al.*, 1991). A mixing process involves two mechanisms, dispersive and distributive mixing. In general, mixing begins with a ‘distributive’ step (drops are deformed passively), followed by a ‘dispersive' one (drops break up into smaller droplets), and finally by the distribution of the droplets in the flow (Osswald and Hernandez-Ortiz, 2006).

The break-up of agglomerates or liquid cluster into small particles or droplets is termed as dispersive mixing. This has been studied by many researchers using shear and elongation stresses (Manas-zloczower and Tadmor, 1994; Rauwendaal, 1999). The distribution of compounds such as small particles or droplets into the polymer melt matrix is termed as distributive mixing (Ottino, 1989). This has been studied by many researchers using logarithm of length of stretch (Cheng and Manas-zloczower, 2004; Connelly and Kokini, 2004, 2007).

There are two types of polymeric mixers, batch mixer (internal batch mixer) and continuous mixers (single screw and twin screw extruder). Internal batch mixer is again of two types, intermeshing rotors and non-intermeshing rotors. Intermeshing rotors work in synchronizing style with similar rotational speed. While, non-intermeshing rotors work with both similar or at different rotational speeds.

However, most of the polymer industries use different rotational non-intermeshing type (Dick and Annicelli, 2001). Therefore, for batch mixer, this research work will focus on the use of non-intermeshing type internal batch mixer with different rotational speeds.

Numerous experimental and numerical research studies have been published related to internal batch mixer (Bai *et al.*, 2011; Flaherty, 1988; Hutchinson *et al.*, 1999; Jongen, 2000; Salahudeen *et al.*, 2011). Notably, Salahudeen *et al.*(2011) studied the batch mixer using numerical simulation and verified the data experimentally. Salahudeen *et al.* (2011) identified the poor mixing region in commercial mixer such as cam, banbury and roller batch mixer. They explained that this poor mixing region decreased the overall distributive mixing efficiency of internal batch mixer. Also they reported the generation of secondary flow between the rotor edge and mixing chamber by banbury rotor. They predicted that this secondary flow was created due to some design features of banbury rotor. Interestingly, overall dispersive mixing performance of banbury rotor was better than cam rotor and roller rotor. As for distributive mixing, roller rotor performance was considered better than cam rotor and banbury rotor.

Therefore, in order to improve the distributive and dispersive mixing performance of internal batch mixer, this study will focus on developing a new rotor design with the features of banbury rotor and roller rotor for internal batch mixer. Additionally, the reason for generation of secondary flow will be analyzed in this research.

As for continuous mixer, single screw extruder is not considered for this research work. The mixing capacity of a single screw extruder is considered weak. On industrial scale; twin screw extruders (TSE) are used for compounding and mixing purpose (Clextral, 2015; Connelly and Kokini, 2007; Rathod and Kokini, 2013). Therefore, twin screw extruders were used for this research. Similar to batch mixer, TSE has two types, intermeshing and non-intermeshing. Based on screw rotation it has two types, co-rotating and counter rotating TSE. On industrial scale; intermeshing co-rotating TSE and intermeshing counter-rotating TSE are commonly used (Manas-Zloczower, 2009). As for TSE, this research work covered intermeshing co-rotating TSE and intermeshing counter-rotating TSE.

Numerous experimental and numerical research studies have been published related to twin screw extruders (Bakalis and Karwe, 1999; Barrera et al., 2008; Bertrand et al., 2003; Bigio and Wang, 1996; Cheng and Manas-zloczower, 2004; Connelly and Kokini, 2007; Fard and Anderson, 2013b; Fard et al., 2012; Ishikawa et al., 2000; Sämann, 2008; Vyakaranam et al., 2012a; Zhang et al., 2009). Notably, Fard *et al.* (2012) and Fard and Anderson (2013) studied the mixing in twin screw extruders using kneader mixing element (co-rotating TSE) and Screw mixing element (SME) (counter rotating TSE). Fard *et al.* (2012) identified the poor mixing zones in the twin screw extruders. Fard and Anderson (2013) provided solution for poor mixing with an increase in the gap size between the mixing elements and between the mixing element and the barrel. The radial mixing (cross-sectional mixing) was improved due to the increase in amount of back flow. However, it decreased the axial mixing due to decrease in positive transport. In order to improve the axial mixing and overall mixing performance of TSE, this study focused on to develop new mixing element to replace kneader mixing element and SME for TSE. In this research, base design of new mixing element was adopted from the new rotor design of internal batch mixer. Similar approach was used to develop kneader mixing element for TSE from the base design of cam roller geometry of internal batch mixer by Kiani and Burbank (2000).

1.2 Problem Statement

This research covered two important pieces of polymer mixing equipment i.e. internal batch mixer and twin screw extruders. In internal batch mixer, Salahudeen et al. (2011) identified the poor mixing region in commercial mixers such as cam, banbury and roller batch mixer. This poor mixing region overall decreased the distributive mixing efficiency of internal batch mixer. Comparatively, they identified roller rotor has better distributive mixing performance than cam rotor and banbury rotor. They identifed that banbury rotor has better dispersive mixing performance compared to cam and roller rotor. Interestingly, they noticed secondary flow at the rotor edge of banbury rotor and it helped to improve the dispersive mixing performance of banabury rotor. They predicted that improved dispersive mixing was due to this secondary flow as shown in Figure 1.1.

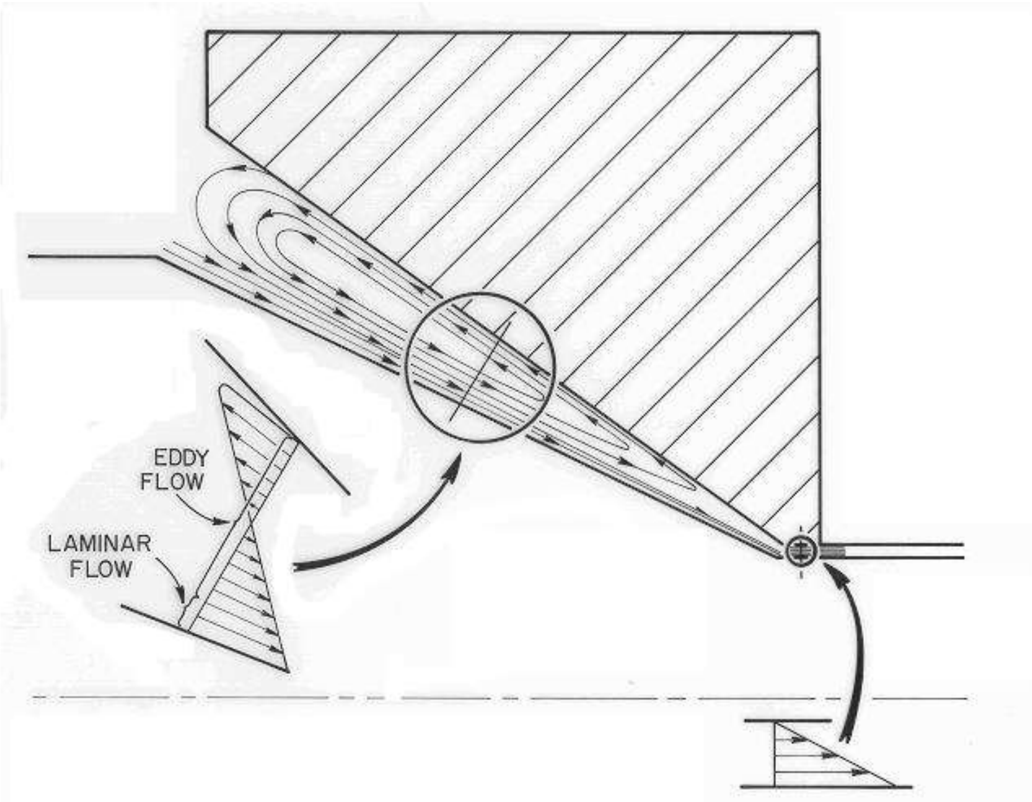

Figure 1.1 Schematic illustration of secondary flow (Eddy flow) in the velocity profile (Avitzur, 1983).

In order to improve the distributive and dispersive mixing performance of internal batch mixer (Salahudeen et al., 2011), this study considered to develop new rotor design with the combined features of roller rotor (distributive mixing) and banbury rotor (dispersive mixing) for internal batch mixer. The reason behind the generation of secondary flow in banbury rotor was unknown. In order to unveil the secret, design procedure to develop secondary flow between rotor edge and mixing chamber was studied. The result of the secondary flow study was implemented directly on the new rotor as well as in further studies on twin screw extruders. Design procedure to develop secondary flow in internal batch mixer and twin screw extruder is an one of the major contribution of this research. This design procedure can be used in any types of polymer mixing equipments.

In twin screw extruder, Fard *et al.* (2012) and Fard and Anderson (2013) studied the mixing in twin screw extruders using kneader mixing element (co-rotating TSE) and Screw mixing element (SME) (counter rotating TSE). Fard *et al.* (2012) identified the poor mixing zones and Fard and Anderson (2013) provided solution to remove the poor mixing regions. However, this solution increased the radial mixing, but decreased the axial mixing. In order to improve the axial mixing, the focus of this research was to develop a new mixing element for TSE. In this research, new rotor design of internal batch mixer was adopted as a basic design for new mixing element of intermeshing co-rotating TSE and intermeshing counter rotating TSE. Please note that results of the design procedure to develop secondary flow was implemented on new mixing elements.

The questions that needed to be answered in this research are:

i. What is the general design parameter to develop secondary flow in internal batch mixer and TSE?
ii. What is the best feasible rotor design for internal batch mixer based on distributive and dispersive mixing performance?
iii. What is the effect of new TSE mixing element, developed based on the design of new rotor for internal batch mixer with kneader mixing element in intermeshing co-rotating TSE.
iv. What is the effect of new TSE mixing element, developed based on the design of new rotor for internal batch mixer with screw mixing element in intermeshing counter rotating TSE.

1.3 Objectives of Study

The objective of this research was to develop a suitable rotor design for internal batch mixer with improved dispersive and distributive mixing performance than commercial rotor such as cam rotor, roller rotor and banbury rotor. Additionally, mixing elements for intermeshing co-rotating TSE and intermeshing counter-rotating

TSE was developed using new rotor design of internal batch mixer. Therefore, the specific objectives can further be classified as:

i. To develop the general design procedure for secondary flow in internal batch mixer and TSE.
ii. To determine the best feasible rotor design for internal batch mixer based on distributive and dispersive mixing performance experimentally and numerically.
iii. To simulate the effect of new TSE mixing element developed based on the design of new rotor for internal batch mixer with Kneader mixing element in intermeshing co-rotating TSE using ANSYS Polyflow.
iv. To simulate the effect of new TSE mixing element developed based on the design of new rotor for internal batch mixer with screw mixing element in intermeshing counter rotating TSE using ANSYS Polyflow.

1.4 Scope of Study

Materials used for this work are High density polyethylene (HDPE- injection molding grade), red master batch (Injection molding grade) and Nano Calcium carbonate (approximately 20 nm).

The following equipment and softwares were used for the model design purpose. Equipments such as internal batch mixer (Haake Polylab, Germany) with different rotors; cam, banbury and roller rotors, kneader mixing element for intermeshing co-rotating TSE from COLLIN Twin-screw Extruder, Germany, Screw mixing element (SME) for Intermeshing counter-rotating TSE from COPERION Twin-screw Extruder, Germany were used. Softwares such as- ANSYS POLYFLOW and supportive applications - ANSYS DESIGN MODELER, ANSYS MESHING, ANSYS POLYDATA, ANSYS POLYMAT, ANSYS POLYSTAT, ANSYS CFX and ANSYS POLYCURVE were used. ANSYS DESIGN MODELER was used to create a base geometry for the simulation. ANSYS MESHING was used to create meshes on the geometry. ANSYS POLYDATA was used to perform simulation task on the meshed geometry. ANSYS POLYMAT was used to generate material data from the experimental rheological data. ANSYS POLYCURVE was used to draw XY curve plots. ANSYS POLYSTAT was used to generate raw data and curves from the result files of POLYDATA. ANSYS CFX was used to graphically visualize the result files of POLYDATA.

The rheological data was generated experimentally using AR-G2 Rheometer (TA Instrument). For simulation, this shear –viscosity data was used as a polymer (melt domain) material data.

Experimental methods - Injection molding grade HDPE was melted in internal batch mixer, followed by injection of red master batch for specific period of time at 20 sec and 60 sec. The constant temperature of 190° C was maintained. The result was recorded via digital camera.

Experimental methods – Injection molding grade HDPE was melted in internal batch mixer, followed by injection of 2% of nano calcium carbonate for 5 min. The result was analyzed using scanning electron microscopy (SEM).

Simulation methods – For internal batch mixer, constant speed ratio of 9 rpm (left rotor) / 6 rpm (right rotor) and constant temperature of 190° C were used. As for intermeshing co-rotating TSE and intermeshing counter-rotating TSE, constant speed of 9 rpm was maintained. ANSYS supporting software’s such as ANSYS POLYMAT, ANSYS POLYCURVE and ANSYS CFX were used for result analysis.

REFERENCES

Ansys. (2007a). *Polyflow - User's Manual, Version 3.12.0.* Place del'Universite 16, B-1348 Louvain-la-Neuve, Belgium: Ansys.

Ansys. (2007b). *Polyflow - Mixing User's Manual, Version 3.12.0.* Place del'Uni¬versite 16, B-1348 Louvain-la-Neuve, Belgium.: Ansys.

Avitzur, B. (1983). Handbook of metal-forming processes. New York :: Wiley.

Bai, Y., Sundararaj, U., and Nandakumar, K. (2011). Nonisothermal Modeling of Heat Transfer Inside An Internal Batch Mixer. *AIChE Journal, 57*(10), 2657-2669.

Bakalis, S., and Karwe, M. V. (1999). Measuring of Velocity Distributions in the Nip Region of a Co-Rotating Twin-Screw Extruder. *Trans IChemE, 77*(Part C).

Banbury, F. H. (1916). USA Patent No. 1,200,070 U.S. Patent.

Barrera, M. A., Vega, J. F., and Martínez-Salazar, J. (2008). Three-Dimensional Modelling of Flow Curves in Co-rotating Twin-Screw Extruder Elements. *Journal of Materials Processing Technology*, *197*(1–3), 221-224.

Berk, Z. (2009). *Food Process Engineering and Technology*: Elsevier Science.

Bertrand, F., Tanguy, P. A., and Thibault, F. (1997). A Three-Dimensional Fictitious Domain Method for Incompressible Fluid Flow Problems. *International Journal of Numerical Methods in Fluids, 25*, 719-736.

Bertrand, F., Thibault, F., Delmare, L., and Tanguy, P. A. (2003). Adaptive Finite Element Simulations of Fluid Flow in Twin-screw Extruders. *Computers and Chemical Engineering, 27*, 491-500.

Bigio, D., and Wang, K. (1996). Scale-up Rules for Mixing in a Non-intermeshing Twin-screw Extruder. *Polymer Engineering and Science, 36*(23), 2832 – 2839.

Bigio, D. I., Boyd, J. D., Erwin, L., and Gailus, D. W. (1985). Mixing Studies in the Single Screw Extruder. *Polymer Engineering & Science, 25*(5), 305-310.

Bird, R. B., Stewart, W. E., and Lightfoot, E. N. (2004). *Transport Phenomena* (second ed.). New York: John Wiley & Sons.

Cheng, H., and Manas-zloczower, I. (2004). Distributive Mixing in Conveying Elements of a ZSK-53 Co-rotating Twin Screw Extruder. *Polymer Engineering Science, 38*, 626–635.

Cheng, J. J., and Manas-Zloczower, I. (1990). Flow Field Characterization in a Banbury Mixer. *International Polymer Processing, 3*, 178-183.

Clextral. (2015). Benefits of twin screw extrusion. from http://www.clextral.com/technologies-and-lines/technologies-et-procedes/benefits-of-twin-screw-extrusion/

Connelly, R. K., and Kokini, J. L. (2003). 2-D Numerical Simulation of Differential Viscoelastic Fluids in a Single Screw Continuous Mixer: Application of Viscoelastic Finite Element Methods. *Advances in Polymer Technology, 22*(1), 22-41.

Connelly, R. K., and Kokini, J. L. (2004). The Effect of Shear Thinning And Differential Viscoelasticity on Mixing in a Model 2d Mixer As Determined Using Fem With Particle Tracking. *J. Non-Newtonian Fluid Mech, 123*, 1-17.

Connelly, R. K., and Kokini, J. L. (2007). Examination of the Mixing Ability of Single and Twin Screw Mixers Using 2d Finite Element Method Simulation with Particle Tracking. *Journal of Food Engineering 79,* 956-969.

Cooke, R. T. (1934). UK Patent No. 431,012. British Patent.

Coperion. (2016). ZSK twin screw extruder

Dick, J. S., and Annicelli, R. A. (2001). *Rubber Technology: Compounding and Testing for Performance*: Hanser Publishers.

Dr.Collin. (2012). Laboratory Twin-Screw Kneader ZK 25. In Collin (Ed.). Ebersberg: Plastima.

Elemans, P. H. M. (2016). Polymer Twin-Screw Extrusion: Melting, Mixing and Screw Design. In *Reference Module in Materials Science and Materials Engineering*: Elsevier.

Fard, A. S., and Anderson, P. D. (2013a). Simulation of distributive mixing inside mixing elements of co-rotating twin-screw extruders. *Computers & Fluids, 87*, 79-91.

Fard, A. S., and Anderson, P. D. (2013b). Simulation of Distributive Mixing Inside Mixing Elements of Co-rotating Twin-screw Extruders. *Computers & Fluids*, - (Accpeted).

Fard, A. S., Hulsen, M. A., Meijer, H. E. H., Famili, N. M. H., and Anderson, P. D. (2012). Tools to Simulate Distributive Mixing in Twin-Screw Extruders. *Macromolecular Theory and Simulations, 21*(4), 217-240.

Flaherty, W. F. (1988). The Acquisition and Application of Data Obtained During the Mixing Cycle of an Internal Batch Mixer. *RubberWorld, 198*(4), 14-18.

Fuad, H. Z., Mohd. Ishak, Azman Hassan. (2010). Polypropylene/calcium carbonate nanocomposites – effects of processing techniques and maleated polypropylene compatibiliser. *Express Polymer Letter, 4*(10), 611-620.

Garmabi, H., and Kamal, M. R. (1999). Improved Barrier and Mechanical Properties of Laminar Polymer Blends. *Journal of Plastic. Film Sheeting, 15*(2), 120–130.

Ghoreishy, M. H. R. a. N., V. (1997). Modeling the transient flow of rubberr compunds in the dispersive section of an internal mixer with slip-stick boundary conditions. *16*(1), 45-68.

Harnby, N., Edwards, M. F., and Nienow, A. W. (1992). *Mixing in the Process Industries* (second ed.). Oxford: Butterworth/Heinemann Ltd.

Hétu, J. F., and Ilinca, F. (2013). Immersed boundary finite elements for 3D flow simulations in twin-screw extruders. *Computers & Fluids, 87,* 2-11.

Hrymak, A. N., Bravo, V. L., Khalfalla, Y., and Benyounis, K. Y. (2016). Polymer Melt Mixing in Twin Screw Extruders. In *Reference Module in Materials Science and Materials Engineering*: Elsevier.

Hutchinson, B., Rios, A. C., and Osswald, T. A. (1999). Modeling the Distributive Mixing in an Internal Batch Mixer. *Int. J. Polym. Proc 16*(315).

Ishikawa, T., Kihara, S.-I., and Funatsu, K. (2000). 3-D Numerical Simulations of Nonisothermal Flow in Co-rotating Twin Screw Extruders. *Polymer Engineering & Science*, *40*(2), 357-364.

Jongen, T. (2000). Characterization of Batch Mixers Using Numerical Flow Simulations. *AIChE Journal*, *46*(11), 2140-2150.

Kiani, A., and Burbank, F. R. (2000). Mixing element for screw extruder: Google Patents.

Kohlgrüber, K. (2008). *Co-Rotating Twin-Screw Extruders*: Hanser.

Kwon, T. H., Joo, J. W., and Kim, S. J. (1994). Kinematics And Deformation Characteristics As A Mixing Measure In The Screw Extrusion Process. *Polymer Engineering & Science, 34*(3), 174-189.

Manas-Zloczower, I. (2009). *Mixing and Compounding of Polymers: Theory and Practice*: Carl Hanser GmbH.

Manas-zloczower, I., and Tadmor, Z. (1994). *Mixing and Compounding of Polymers - Theory and Practice*. New York: Carl Hanser Verlag.

Millauer, C. (1978). Kneading and mixing machine: Google Patents.

Muzzio, F. J., Alexander, A., Goodridge, C., Shen, E., Shinbrot, T., Manjunath, K., Dhodapkar, S., Jacob, K. (2004). Solids Mixing. In E. L. Paul, V. A. Atiemo-Obeng and S. M. Kresta (Eds.), *Handbook of Industrial Mixing: Science and Practice*. Hoboken, NJ, USA: John Wiley & Sons, Inc.

Nassehi, V., and Ghoreishy, M. H. R. (2001). Modeling of mixing in internal mixers with long blade tips. *Advances in polymer technology, 20*(2), 132-145.

Osswald, T., and Hernandez-Ortiz, P. (2006). *Polymer Processing – Modeling and Simulation*. Ohio: Hanser Gardner Publication.

Ottino, J. M. (1989). *The Kinematics of Mixing: Stretching, Chaos and Transport.* Cambridge: Cambridge University Press.

Padmanabhan, B. (2008). Understanding the Extruder Processing Zone: the heart of a twin screw extruder. *Plastics, Additives and Compounding, 10*(2), 30-35.

Pinto, G., and Tadmor, Z. (1970). Mixing And Residence Time Distribution In Melt Screw Extruders. *Polymer Engineering & Science, 10*(5), 279-288.

Qiu, G., Zhang, P., Pan, J., Xie, Y., and Zhoa, S. (2003). Mechanical Properties and Morphology of Polypropylene Toughened with Metallocine Polymerized Polyethylene Elastomers. *Polymer Plastics Technology and Engineering 42*(1), 33–44.

Qu, F., Jiang, Z., and Lu, H. (2015). Effect of Mesh on Springback in 3D Finite Element Analysis of Flexible Microrolling. *Journal of Applied Mathematics, 2015*, 7.

Ralf, S., Martin, B., Thomas, P., and Stephan, H. (2012). Droplet based microfluidics. *Reports on Progress in Physics*, *75*(1), 016601.

Rathod, M. L., and Kokini, J. L. (2013). Effect of mixer geometry and operating conditions on mixing efficiency of a non-Newtonian fluid in a twin screw mixer. *Journal of Food Engineering*, *118*(3), 256-265.

Rauwendaal, C. (1987). Scale-up of Single Screw Extruders. *Polymer Engineering & Science*, *27*(14), 1059-1068.

Rauwendaal, C. (1999). New Dispersive Mixers Based on Elongational Flow. *Plastics, Additives and Compounding, 1*(4), 21-23.

Rauwendaal, C. (2001). *Polymer Extrusion* (Fourth ed.). Cincinnati: Hanser publications.

Rauwendaal, C. (2002). New Directions for Extrusion: Compounding with Single Screw Extruders. *Plastics, Additives and Compounding, 4*(6), 24-27.

Rauwendaal, C. (2012). The Role of Screw Design in Efficient Extrusion of Medical Devices. *Plastics Technology*.

Rauwendaal, C. (2014a). 8 - Extruder Screw Design. In C. Rauwendaal (Ed.), *Polymer Extrusion (Fifth Edition)* (pp. 509-652): Hanser.

Rauwendaal, C. (2014b). 10 - Twin Screw Extruders. In C. Rauwendaal (Ed.), *Polymer Extrusion (Fifth Edition)* (pp. 697-761): Hanser.

Rauwendaal, C. J., Gramann, P. J., Davis, B. A., and Osswald, T. A. (2000). Screw extruder with improved dispersive mixing elements: Google Patents.

SABIC® HDPE - Injection Molding M300054, (2013).

Salahudeen, S. A., Elleithy, R., AlOthman, O., and AlZahrani, S. M. (2011). Comparative Study of Internal Batch Mixer Such as Cam, Banbury and Roller: Numerical Simulation and Experimental Verification *Chemical Engineering Science, 66*(12), 2502-2511

Sämann, H.-J. (2008). Screw Elements for Co-rotating, Closely Intermeshing, Twin-Screw Extruders. In K. Kohlgrüber (Ed.), *Co-rotating Twin-screw Extruder* (pp. 215-235): Hanser.

Shengwei, M. (2011). Top 5 misunderstandings on (good) mesh.

Tatterson, G. B., Brodkey., R. S., and Calabrese, R. V. (1991). Move Mixing Technology into the 21st Century. *Chemical Engineering Progress, 87*(6), 45-48.

Thermo-Scientific. (2012). Haake Rheomix* QC for the Haake PolyLab* QC System.

Vyakaranam, K. V., Ashokan, B. K., and Kokini, J. L. (2012a). Evaluation of Effect of Paddle Element Stagger Angle on the Local Velocity Profiles in a Twin-Screw Continuous Mixer with Viscous Flow Using Finite Element Method Simulations. *Journal of Food Engineering, 108*, 585-599.

Vyakaranam, K. V., Ashokan, B. K., and Kokini, J. L. (2012b). Evaluation Of Effect Of Paddle Element Stagger Angle On The Local Velocity Profiles In A Twin-

Screw Continuous Mixer With Viscous Flow Using Finite Element Method Simulations. *Journal of Food Engineering, 108*(4), 585-599.

Wagner Jr, J. R., Mount Iii, E. M., and Giles Jr, H. F. (2014). 11 - Twin Screw Extruder Equipment. In J. R. W. M. M. F. Giles (Ed.), *Extrusion (Second Edition)* (pp. 125-148). Oxford: William Andrew Publishing.

Wiedmann, W. M., and Schmid, H. M. (1982). Optimization of Rubber Mixing in Internal Mixers. *Rubber Chemistry and Technology, 55*(2), 363-381.

Yang, H.-H., Wong, T. H., and Manas-Zloczower, I. (1994). Flow Field Analysis of a Banbury Mixer. In I. Manas-Zloczower and Z. Tadmor (Eds.), *Mixing and Compounding of Polymers: Theory and Practice* (pp. 187-223). New York: Carl Hanser Verlag.

Yobas, L., Martens, S., Ong, W.-L., and Ranganathan, N. (2006). High-performance flow-focusing geometry for spontaneous generation of monodispersed droplets. *Lab on a Chip, 6*(8), 1073-1079.

Zhang, X.-M., Feng, L.-F., Chen, W.-X., and Hu, G.-H. (2009). Numerical Simulation And Experimental Validation Of Mixing Performance Of Kneading Discs In A Twin Screw Extruder. *Polymer Engineering & Science, 49*(9), 1772-1783.