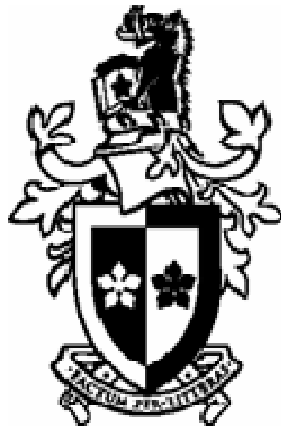


**COMPUTATIONAL SIMULATION OF
HYPERBRANCHED POLYMER MELTS
UNDER SHEAR**



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Abstract

In this work, hyperbranched polymers of different molecular weights and different molecular architectures have been simulated using a coarse-grained model and non-equilibrium molecular dynamics techniques. A number of structural parameters and the rheology of hyperbranched polymer melts under shear were analysed to explain the effect of the molecular structure and molecular weight on microscopic as well as macroscopic properties.

In order to determine the shear-induced changes in the structural properties of hyperbranched polymers, various parameters were calculated at different strain rates. The radii of gyration which characterize the size of the polymer were evaluated. The relationship between the zero shear rate mean squared radius of gyration and the molecular weight as well as the Wiener index was established. The tensor of gyration was analysed and results indicate that hyperbranched polymer molecules have a prolate ellipsoid shape under shear. As hyperbranched polymers have compact, highly branched architecture and layers of beads have increasing densities which might lead to an unusual distribution of mass, the distribution of beads was also studied. The distribution of terminal beads was investigated to understand the spatial arrangement of these groups which is very important for hyperbranched polymer applications, especially in drug delivery. Flow birefringence was characterized by taking into account both form and intrinsic birefringences which result from molecular and bond alignment respectively.

The melt rheology of hyperbranched polymer structures with different molecular weights and different number of spacers was also studied. Systems were simulated over a wide range of strain rates to capture the crossover behaviour from Newtonian to non-Newtonian regimes. Rheological properties including the shear viscosity and first and second normal stress coefficients were computed and the transition to shear thinning was observed at different strain rates for hyperbranched polymers of different sizes and topologies. The results were consistent with findings from NEMD simulations of linear and dendritic polymers. The stress-optical rule was tested and shown to be valid only in the Newtonian regime and violated in the strong flow regime where the rule does not

take into account flow-induced changes of the micro structure. The stress-optical coefficient was found to be independent of the molecular weight and topology of polymers.

Blends of hyperbranched polymers and linear polymers were also simulated and their rheological properties were investigated. Results show that even a small proportion of hyperbranched polymer in a melt of linear chains can reduce the shear viscosity of the whole system. This feature makes hyperbranched polymers a potential candidate as rheology modifiers. However there is no observed limit in the proportion of hyperbranched polymers in the samples above which the viscosity is stabilized. The viscosity drops continuously, correlating with the amount of hyperbranched polymers present.

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Declaration

I hereby declare that the thesis entitled “Computational simulation of hyperbranched polymer melts under shear”, and submitted in fulfilment of the requirements for the Degree of Doctor of Philosophy in the Faculty of Information and Communication Technologies of Swinburne University of Technology, is my own work and that it contains no material which has been accepted for the award to the candidate of any other degree or diploma, except where due reference is made in the text of the thesis. To the best of my knowledge and belief, it contains no material previously published or written by another person except where due reference is made in the text of the thesis.

Tu Cam Le

December 2009

Publications from this thesis

The following papers have been based on part of this work:

1. Tu C. Le, Billy D. Todd, Peter J. Daivis, Alfred Uhlherr (2008), “*Rheology and Structural Properties of Hyperbranched Polymers: a Non-Equilibrium Molecular Dynamics Study*”, The XVth International Congress on Rheology, published by the American Institute of Physics, **1027**, ISBN 978-0-7354-0549-3, pp433
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3. Tu C. Le, B. D. Todd, P. J. Daivis and A. Uhlherr (2009) “*Rheology of hyperbranched polymer melts undergoing planar Couette flow*”, Journal of Chemical Physics, **131**, 044902
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Notation

Abbreviations

FENE	Finitely Extensible Nonlinear Elastic potential
LJ	Lennard-Jones potential
MD	Molecular Dynamics
NEMD	Non-Equilibrium Molecular Dynamics
WCA	Weeks-Chandler-Anderson potential

Latin alphabet

b	<i>spacer</i> – number of beads in a linear unit of a dendritic polymer
B	degree of branching
d_{ij}	number of bonds separating site/bead i and j of a molecule
D	number of fully branched units in a hyperbranched molecule
\mathbf{D}	rate of strain tensor
f	functionality of the branch groups of a dendritic polymer
f_c	functionality of the core of a dendritic polymer
\mathbf{F}_i	force acting on molecule i
$\mathbf{F}_{i\alpha}$	force acting on bead α in molecule i
$\mathbf{F}_{i\alpha j\beta}$	intermolecular force on bead α in molecule i due to bead β in molecule j
g	generation number of a dendrimer
$g_A(r)$	atomic radial distribution function
$g_{CM}(r)$	distribution of beads from the centre of mass
$g_{core}(r)$	distribution of beads from the core
$g_{inter}(r)$	interpenetration function
$g_{term}(r)$	radial distribution of terminal group
\mathbf{I}	tensor of inertia, unit tensor
k	spring constant of the FENE potential
k_B	Boltzmann constant
K	consistency index in the Cross model

l_{bond}	bond length
L	number of partially reacted units in a hyperbranched molecule
L_y	size of the simulation box along the y axis
L_1, L_2, L_3	mean eigenvalues of the tensor of gyration
L'_1, L'_2, L'_3	eigenvalues of the mean tensor of gyration
m	mass of a single bead
m_C	power law exponent in the Cross model fitted for shear viscosity data
m_p	power law exponent in the Carreau-Yasuda model fitted to isotropic pressure data
m_ρ	power law exponent in the Carreau-Yasuda model fitted to reduced bead density
M	mass of a molecule
N	number of molecules
N_s	number of beads composing a single molecule
N_t	total number of beads composing the system
N_1	first normal stress difference
N_2	second normal stress difference
p	isotropic pressure
p_η	power law exponent in the Carreau-Yasuda model fitted for shear viscosity data
p_{R_g}	power law exponent in the Carreau-Yasuda model fitted to radius of gyration data
\mathbf{P}	pressure tensor
\mathbf{P}^A	atomic pressure tensor
\mathbf{P}^M	molecular pressure tensor
P_{xy}	xy element of the pressure tensor
\mathbf{p}_i	momentum of the centre of mass of molecule i
$\mathbf{p}_{i\alpha}$	momentum of bead α in molecule i
Q	damping factor in the NpT algorithm

\mathbf{r}_i	position of the centre of mass molecule i
\mathbf{r}_α	position of bead α
$\mathbf{r}_{i\alpha}$	position of bead α in molecule i
\mathbf{r}_{CM}	position of the centre of mass
\mathbf{r}_{i1}	position of the core of molecule i
r_{ij}	distance between centres of mass of molecule i and molecule j
R_0	finite extensibility of the FENE spring
\mathbf{R}_g^2	tensor of gyration
$\langle R_g^2 \rangle$	mean squared radius of gyration
$\langle R_g^2 \rangle_0$	zero shear rate mean squared radius of gyration
R_g	radius of gyration
\mathbf{S}_m	molecular alignment tensor
\mathbf{S}_b	bond alignment tensor
S_m	molecular order parameter
S_b	bond order parameter
$S_{m,i}$	eigenvalue of the molecular alignment tensor
$S_{b,i}$	eigenvalue of the bond alignment tensor
S_{xx}	xx component of the alignment tensor
Δt	integration time step
T	temperature
$u_x(t)$	x component of the streaming velocity vector
\mathbf{u}_i	unit vector denoting the orientation of molecule i
\mathbf{v}_i	unit vector denoting the orientation of bond i
U	interaction potential energy
U_{ij}^{FENE}	FENE interaction energy between beads i and j
U_{ij}^{LJ}	LJ interaction energy between beads i and j
U_{ij}^{WCA}	WCA interaction energy between beads i and j
V	volume of the simulation box

W	Wiener index
Wi	Weissenberg number

Greek alphabet

α	power law exponent for first normal stress coefficients
β	power law exponent for second normal stress coefficients
$\dot{\gamma}$	shear rate
$\dot{\gamma}_c$	shear rate of the onset of shear thinning
ε	LJ energy parameter
$\dot{\varepsilon}_{xx}$	compression rate along x axis
η	shear viscosity in the steady shear
η_0	zero shear viscosity
η_∞	infinite shear viscosity
$[\eta]$	intrinsic viscosity
κ	characteristic strain rate in the flow
λ	characteristic time of the fluid
λ_η	time constant in the Carreau-Yasuda model fitted for shear viscosity data
λ_p	time constant in the Carreau-Yasuda model fitted for isotropic pressure data
λ_ρ	time constant in the Carreau-Yasuda model fitted for reduced bead density data
λ_{R_g}	time constant in the Carreau-Yasuda model fitted for radius of gyration data
ρ	bead concentration/density
σ	stress tensor
σ	LJ length parameter
ζ	thermostatting coefficient
τ_0	longest relaxation time
χ_m	molecular alignment angle

χ_b	bond alignment angle
ψ_1	first normal stress coefficient
ψ_2	second normal stress coefficient