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NUMERICAL ANALYSIS OF THE EFFECT OF EXTRUSION CONDITIONS ON FLOW IN SLIT DIE RHEOMETER

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ABSTRACT

In the extrusion of starch-based materials, modifying the conditions (eg screw speed and feed rate) is used to produce a product with the desired characteristics. However, product characteristics (eg extent of cook and expansion, mechanical and rheological properties) also depend on extruder die design. This is due to the fact that such product characteristics are a function of the full flow history of the material. This paper reports a method for examining twin-screw extruded material, as it flows through a slit die attached to the extruder. The two channel slit die based on a design by Vergnes et al, (1993, Rheologica Acta, 32: 465-476) functions as an online rheometer. Rheological data of starch melt in different extrusion conditions that obtained from online slit-die rheometer experiments are the input of numerical simulation. Numerical simulation also provides an insight into velocity profile of starch melt across the channel and residence time distribution of material in the die, which is highly valuable information for die optimisation or die design, which cannot be determined through experiments.

Keywords: twin-screw extruder, slit-die rheometer, screw speed, feed rate, Polyflow

NOMENCLATURE

D	Diameter
h	Channel depth
K	Consistency factor
n	Power law index
w	Channel width
P_0	Entrance pressure
P_1	Pressure at entry of the piston valve in Channel 1
η	Viscosity
$\dot{\gamma}$	Shear rate

INTRODUCTION

Food extrusion cooking is defined as a process by which moistened, expansive, starchy, and/or proteinaceous food materials are plasticised and cooked in a tube by a combination of moisture, pressure, temperature and mechanical shear [Hauck and Huber, 1989]. There are many extrusion processing variables that can be controlled to get certain final product characteristics. Manipulation of independent variables (eg screw speed, screw configuration, die design, feed moisture content, temperature and feed rate) produces changes to one or more of the dependent variables (eg residence time, mechanical energy input to extruder, thermal energy input into the extruder) and consequently affects the rheological behaviour and the physicochemical properties of the melt [Huber, 2000]. For example, experimental studies have shown that an increase in screw speed causes an increase specific mechanical energy (SME) input resulting in the structural breakdown of the starch and hence in a lower viscosity [Chang et al, 1999], while an increase in feed rate increases shear rate but reduces the SME resulting in a higher viscosity [Chan et al, 1998]. Although these experimental observations give an overall idea about the effect of screw speed and feed rate on the material rheological behaviour and physicochemical properties, however they do not describe the material flow history in the extruder and in the extrusion die. Melt flow history information is essential to explain rheological behaviour of materials that could be valuable for products development, which is not visible in experimental work.

In extrusion process, melting material has experienced complex shearing inside extruder barrel and flow through an extruder die to be shaped to a certain form. One die design may be good to produce a certain shape of product in certain range of extrusion conditions determined by trial and error in experimental work. Nevertheless, this method consumes a lot of time and materials. Numerical simulation is one alternative to obtain such information since computational resources has been well developed. Numerical simulation also provides flexibility to change extrusion condition and die geometry with relatively lower cost compare to experimental work.

This study aims to investigate the effects of varying extrusion condition (screw speed, feed rate and feed moisture content) on velocity profile, which is related to melt rheological behaviour and residence time distribution of starch melt flowing through a twin channel slit die rheometer, (based on a design by Vergnes et al, 1993) using numerical simulation. The finite element based software package, Polyflow 3.10 (Fluent Benelux/Polyflow S.A., avenue Pasteur 4, B-1300 Wavre, Belgium) was chosen to model the flow field and particle tracking calculation. FEM is currently the preferred approach for this study due to its independence on geometry, high accuracy and flexibility, particularly when dealing with non-linear problems encounter in extrusion [Walter, 1992, Hanson and Cappella, 1998]

MATERIALS AND METHODS

The extrusion trials were performed on a granulated wheat starch (Penford Australia, North Ryde, NSW) mixture with glycerol (Chem-Supply Pty Ltd, S.A.) and water. The extrusion experiments were performed on a co-rotating intermeshing twin-screw extruder (Eurolab Prism KX16, Thermo PRISM, Staffordshire, UK), fitted with a twin-channel slit-die rheometer (Figure. 1). Details of the extruder and the slit-die rheometer are discussed elsewhere [Edi-Soetaredjo et al, 2003]. The barrel temperature was set at 100^{O}C from the feed zone to the die.

The experimental design considered the following variables: screw speed (30 to 100 rpm), feed moisture content (20% and 22%) and feed rate (Table 1). The feed rate was varied to obtain 90% of the maximum extruder torque to imitate industrial practice. The rheological behaviour of the starch melt was obtained by varying the local shear rate in the measuring section in the slit channels [Vergnes et al, 1993].

Table 1: Experimental conditions and resulting variables

Moisture Content (%)	Screw Speed (rpm)	Feed Rate (kg/h)	SME (Wh/kg)	Power law	
				K	N
20	30	0.13	418	8204	0.55
20	60	0.20	594	5449	0.35
20	100	0.23	774	6495	0.28
22	30	0.11	481	6253	0.69
22	60	0.16	677	8506	0.40
22	100	0.19	801	4890	0.38

MODEL DESCRIPTION

A three-dimensional (3-D) mesh representing the die geometry was built using Gambit 2.0 (Fluent Inc., Lebanon, N.H., U.S.A) (Figure 2a). Because of the symmetry of the slit-die, the flow could be calculated on one quarter of the real geometry, which has 6282 elements that consisted of cube, tetrahedron, pyramid and prism (Figure 2b). There were three steps of calculation for each combination of experimental conditions: (1) calculation of the flow field; (2) calculating trajectories of a set of material points in the flow and (3) a statistical analysis of the set of trajectories calculated to obtain the correlation between time and viscosity.

Flow Simulation

In this steady state flow simulation, the fluid was considered as an isothermal non-Newtonian viscous fluid. In order to represent the shear rate dependent viscosity, a power-law model was used.

$$\eta = K(\dot{\gamma})^{n-1}$$

The viscosity of starch melt shows significant shear thinning behaviour (Figure 3). The values of the consistency factor, K, and the power-law index, n, were determined experimentally (Table 1), as discussed elsewhere [Edi-Soetaredjo et al, 2003]. Because the power-law index is lower than 0.75, Picard interpolation was used in the calculation because it provides better convergence behaviour [Fluent, 2001].
The material density applied in the model (1380 kg/m^3) was measured experimentally using a GNOMIX PVT (Gnomix in Boulder, Colorado, USA).

To set up the finite element calculation, five boundary conditions were defined (Figure 2C):

Boundary 1: Inlet: flow rate in this modelling was a quarter of the total flow rate.
Boundary 2: Die wall: all components of the velocity were set to zero (no slip condition).
Boundary 3: Horizontal plane of symmetry: normal velocity= 0 and tangential force= 0.
Boundary 4: Vertical plane of symmetry: normal velocity=0 and tangential force= 0.
Boundary 5: Outlet: normal force= 0 and tangential velocity= 0.

This calculation assumed that fluid did not penetrate though the symmetrical plane and the wall. Relative variable convergence was 1.10^{-4} and flow calculations converged after 8 – 21 iterations.

Particles Tracking

The second step was particle-tracking calculation (known as mixing simulation in Polyflow). For the mixing simulation the same mesh and boundaries condition as the flow simulation was taken and the result of the flow simulation used.

To determine residence time distribution of particles, a thousand particles were placed in the inflow of the flow domain (distributed along boundary 1); then the trajectory of each particle throughout the slit die calculated. In order to optimise the time calculation, the maximum particle-tracking lifetime was set to 100,000 seconds. If the calculation of a particle lifetime in the flow domain exceeded the maximum particle-tracking lifetime, the simulation programme would automatically stop the calculation of that particle and continue calculations of other particles. Calculation result shows that approximately 30% of particles were lost due to the time cut off point. Possibly, infinitesimal points sticked on the die wall during cross-sectional area changes

Statistical analysis

Statistical analyses of the mixing simulation results were performed in Polystat (included in the Polyflow software package). Residence time distributions were calculated in this session.

RESULTS AND DISCUSSION

Figure 4 and 5 show velocity profiles of starch melt across x-axis in three sections slit-die rheometer, cylindrical channel (z= 12 mm), conical channel (z= 35 mm) and slit channel (z= 47 mm). Figure 4A and 5A show starch melt velocity profile from one side of slit-die wall to the horizontal symmetry of cylindrical channel, whereas Figure 4B-C and 5B-C show velocity profile of starch melt from one side of slit die wall to the other wall side in conical channel and slit channel, respectively. It is clearly shown that an increase in screw speed and feed rate increases melt velocity of starch melt. Melt velocity gradient close to slit die wall increased with an increase in screw speed and feed rate in all slit-die rheometer sections (Figure 4 and 5). Simulation results show that the increase of velocity due to an increase in screw speed from 30 rpm to 60rpm was greater than the increase in velocity due to increase of screw speed from 60 rpm to 100 rpm. This trend was more pronounced for 20% MC than 22% MC.

Velocity profiles obtained from the numerical simulations demonstrated that in the area closed to die wall, starch melt experienced higher shear rate gradient compare to that of the middle of the channel, which caused viscosity range of melt was broader in the area closed to die wall and almost uniform in the middle of die. However, this was not observed in the conical channel (Figure 4B and 5B) since the change in geometry influenced starch melt velocity profile, which consequently influenced melt viscosity.

Table 1 shows that the power law index decreased with increasing SME, indicating that changing screw speed and feed rate simultaneously affected starch melt viscosity, which is consistent with previous observation [Ilo et al, 1996]. (Ceweq, I'm not sure whether this is what you are trying to say). Modelling results show that viscosity range broadened with increasing SME since the mechanical energy intensity provided to the material during the shearing of the molten phase induced the macromolecular degradation of the material and consequently influence the viscosity of the molten starch [Vergnes and Villemeire, 1987].

Figure 6 shows the range of residence times of particles as a function of screw speed. The curves demonstrate that the mean residence time of the particles decreased as the screw speed increased and the moisture content decreased. The bulk of particles began to leave the slit die after 170 s, 185 s and 270 s for 100 rpm, 60 rpm and 30 rpm, respectively, at 20 %MC; and after 190 s, 230 s and 310 s for 100 rpm, 60 rpm and 30 rpm, respectively, at 22%MC. The spread of residence time inside the slit die became broader as the screw speed decreased, which indicated the axial mixing decreased.

Figure 7 shows the area in the slit die channel that had the largest residence time. The transition area from cylindrical channel to conical channel seems to be a dead zone since residence times in this area are up to 54,000 s at 30 rpm and up to 40,000 s at 100 rpm. The residence time in this zone decreased as the screw speed increased.

These simulations results show that increasing SME in the extrusion process influenced the die performance since the molten starch flowing through the channel already had a flow history from the extruder. Increasing SME increased the shear rate and resulted in a lower viscosity, since starch melt showed shear thinning behaviour. These conditions also affected the spread of residence time. Residence time distribution of the starch melt inside the slit die became narrower as the SME increased.

CONCLUSION

Finite element modelling result performed in Polyflow 3.10 found increasing SME cause the range of viscosities broaden and the residence time distribution to narrow. The flow simulation results show the possibility of a dead zone in the angle between two sections of the die.

FUTURE WORK

There is a problem found in experimental work of low moisture content starchy product that slit-die rheometer channels got narrower because of high viscosity starch melt when it is working in low shear rate. This particular simulation analysis can be used to optimise slit-die rheometer design.

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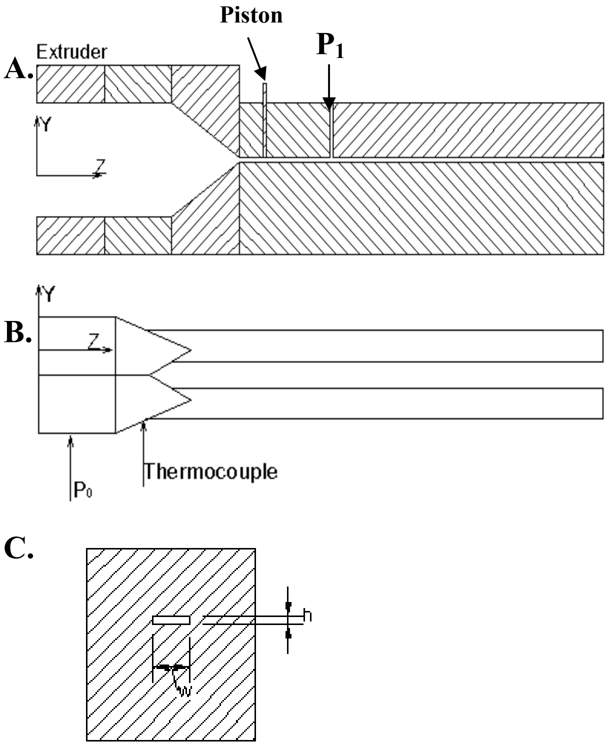

Figure 1: Schematic diagram of slit die rheometer: A: side view; B: top view; C: front view of one of the slit dies. (h= 0.0015 m and w= 0.0075)

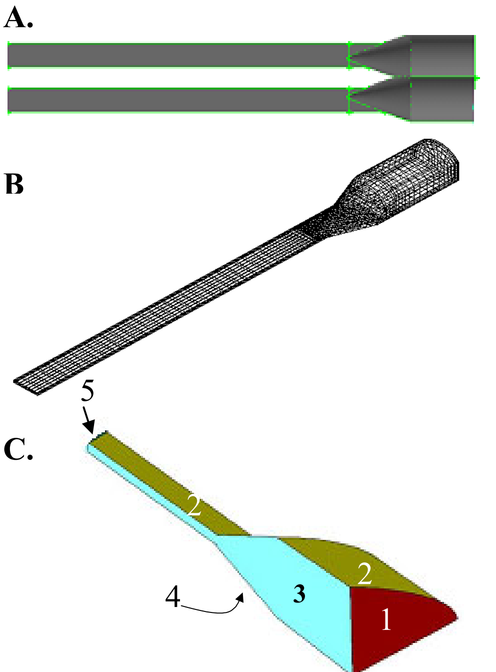

Figure 2: A: Slit-die rheometer geometry; B: mesh of a quarter of slit-die rheometer; C: boundary conditions position.

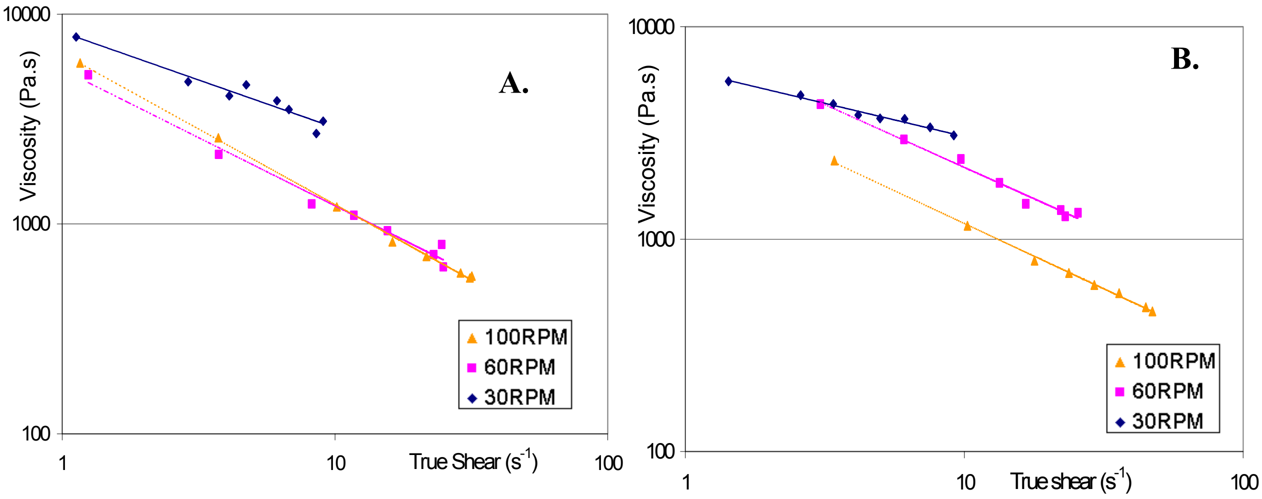

Figure 3: Flow curve for starch melt as a function of screw speed. A: 20% moisture content; B: 22% moisture content.

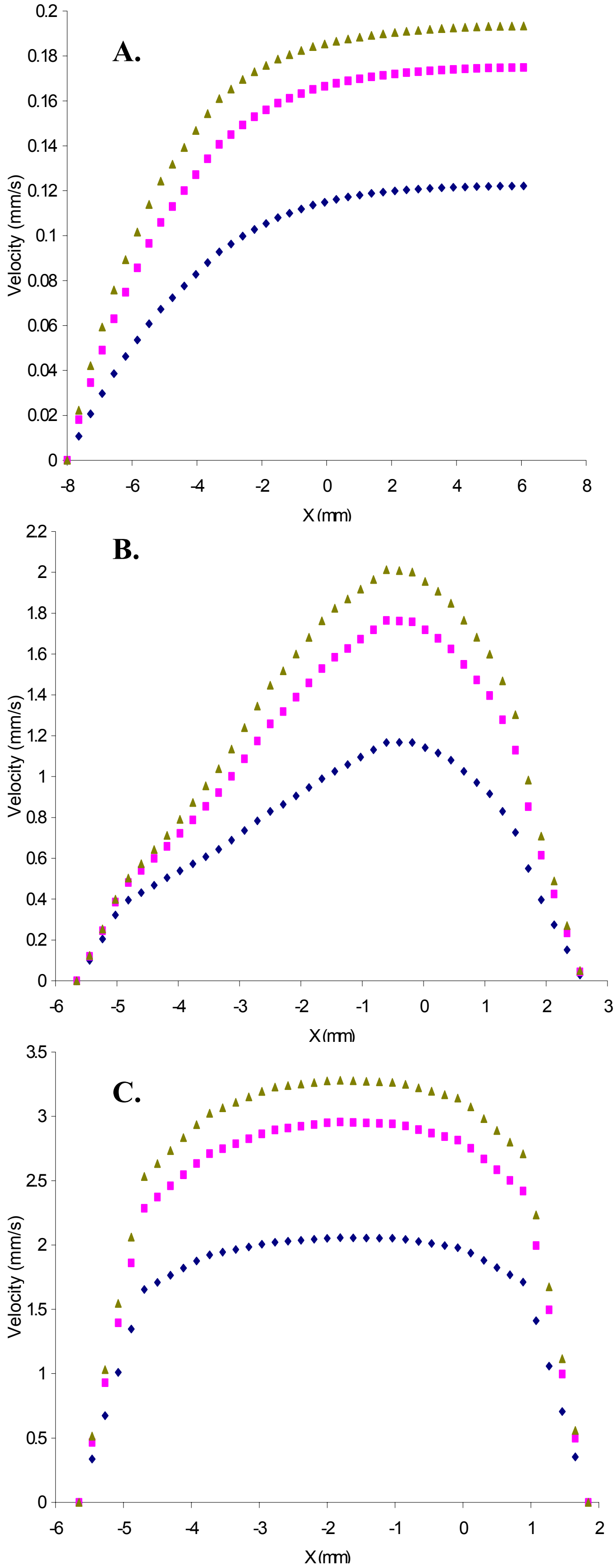

Figure 4: Velocity profile across x-axis at some points of z-axis as a function of screw speed for 20%MC. A (X, 0, 12); B (X, 0, 35) and C (X, 0, 47). ▲:100 rpm; ■: 60 rpm and ◆: 30 rpm

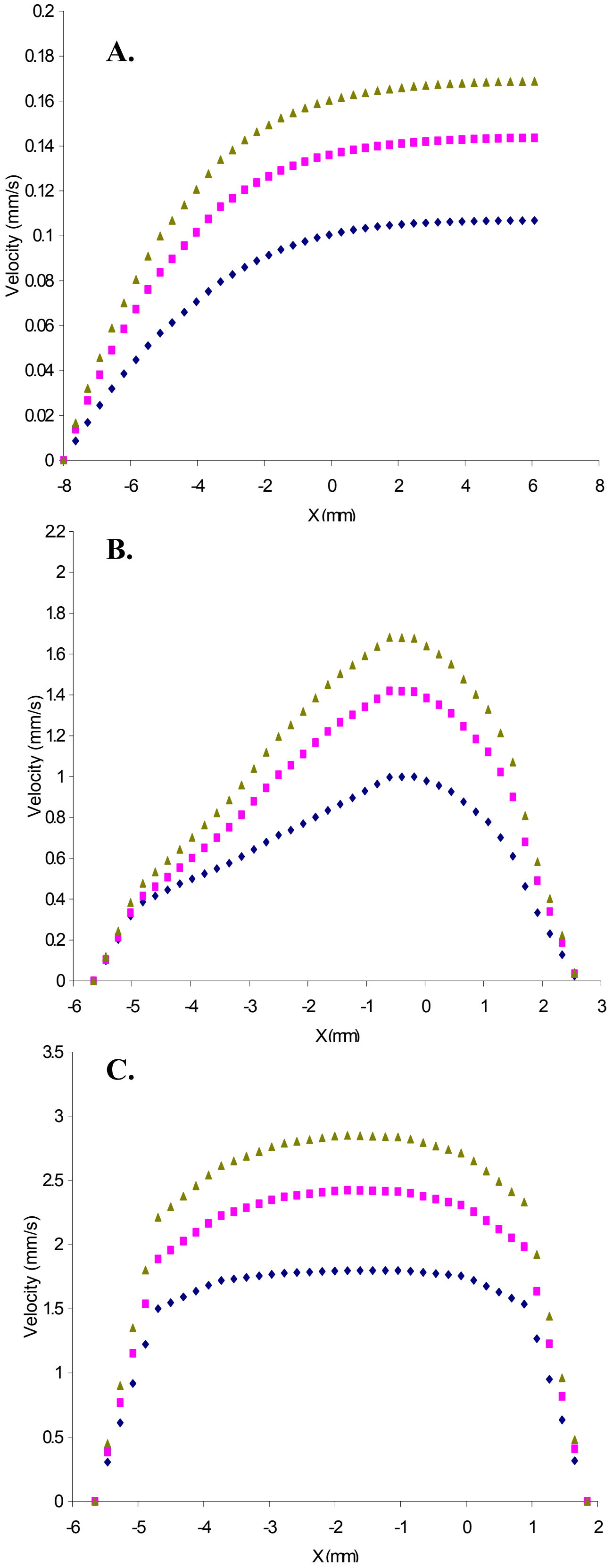

Figure 5: Velocity profile across x-axis at some points of z-axis as a function of screw speed for 22%MC. A (X, 0, 12); B (X, 0, 35) and C (X, 0, 47). ▲:100 rpm; ■: 60 rpm and ◆: 30 rpm

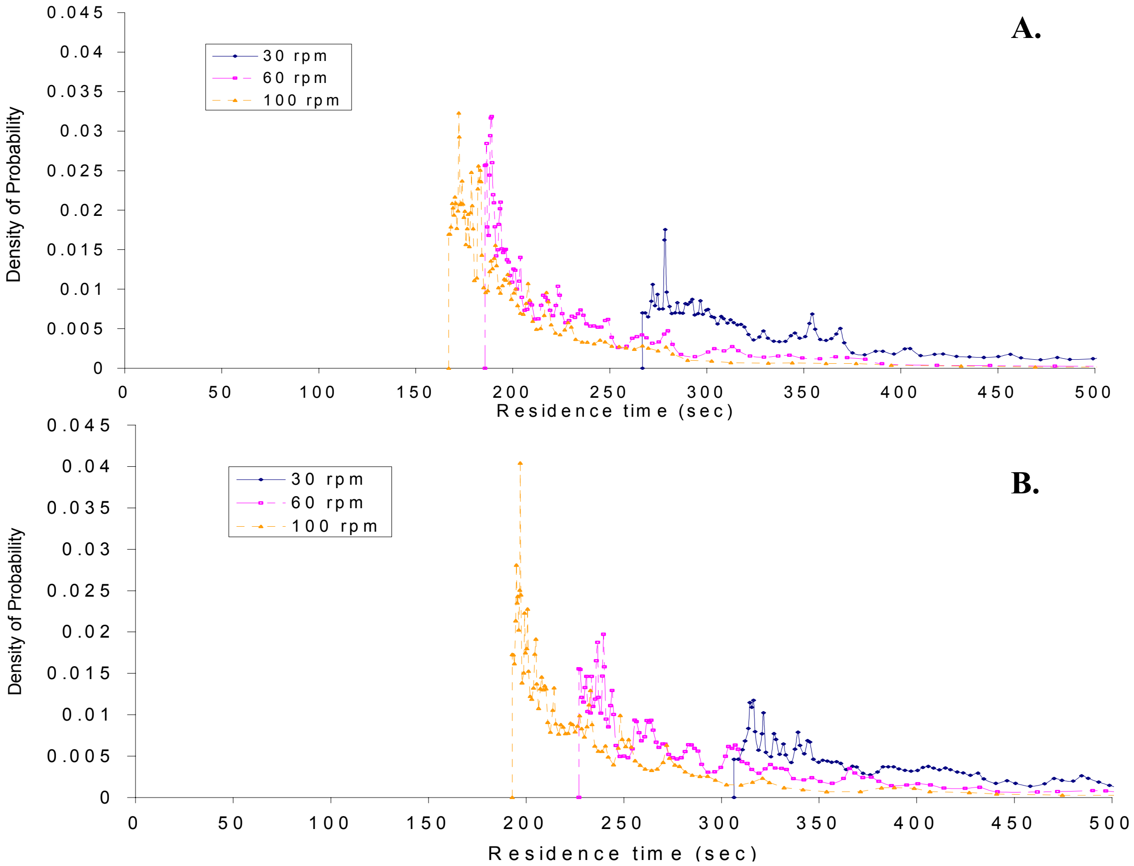

Figure 6: Residence time distribution as a function of screw speed. A: 20% moisture content; B: 22% moisture content.

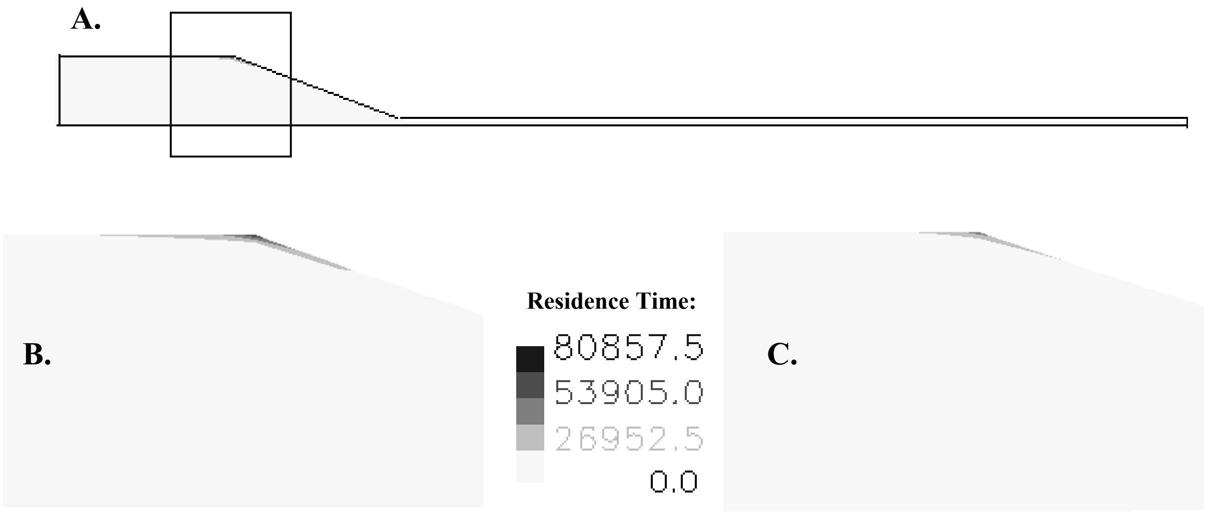

Figure 7: A. Flow simulation results show the highest residence time on the transition area between cylindrical channel to conical channel; B. Zoom of the highest residence time zone for the lowest experiment condition, 30 rpm 20%MC; C. Zoom of the highest residence time zone for the highest experiment condition, 100 rpm 22%MC. The plane slice was taken at x=0