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CONTINUOUS FLOW OF SOLID-LIQUID FOOD MIXTURES DURING OHMIC HEATING: FLUID INTERSTITIAL VELOCITIES, SOLID AREA FRACTION, ORIENTATION AND ROTATION

DISSERTATION

Presented in Partial Fulfillment of the Requirements for the Degree Doctor of Philosophy in the Graduate School of The Ohio State University

By

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*****

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To my parents, your example is my inspiration
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TABLE OF CONTENTS

ACKNOWLEDGMENTS ....................................................................................................... iii

VITA ............................................................................................................................................... v

LIST OF TABLES ................................................................................................................... ix

LIST OF FIGURES ................................................................................................................... xi

CHAPTER

I. INTRODUCTION ............................................................................................................... 1

II. INVESTIGATION OF SOLID-LIQUID INTERSTITIAL FLOW IN THREE DIMENSIONS USING PARTICLE TRACKING VELOCIMETRY ......................................................... 6

   Abstract ............................................................................................................ 6
   Introduction ..................................................................................................... 7
   Materials and Methods .................................................................................. 8
   Results and Discussion ................................................................................... 22
   Conclusions and Recommendations ............................................................ 30
   Nomenclature .................................................................................................... 31
   References ......................................................................................................... 32

III. RELATIVE VELOCITY BETWEEN SOLID PARTICLE AND LIQUID IN THREE DIMENSIONS IN CONTINUOUS FLOW USING PARTICLE TRACKING VELOCIMETRY ................................................. 34

   Abstract ............................................................................................................ 34
   Introduction ..................................................................................................... 35
   Materials and Methods .................................................................................. 37
   Results and Discussion ................................................................................... 41
   Conclusions and Recommendations ............................................................ 57
LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>Characteristic parameters used in AGW interpolation and the estimated errors. The estimated errors were calculated based on the characteristic curves presented by Spedding and Rignot (1993).</td>
<td>26</td>
</tr>
<tr>
<td>3.1</td>
<td>Solid and liquid phase densities.</td>
<td>39</td>
</tr>
<tr>
<td>3.2</td>
<td>Maximum velocities of solid-liquid phase, relative velocities in Z axis and heat transfer coefficient between cubic particles and liquid mixtures at 1%CMC.</td>
<td>53</td>
</tr>
<tr>
<td>3.3</td>
<td>Maximum velocities of solid-liquid phase, relative velocities in Z axis and heat transfer coefficient between cylindrical particles and liquid mixtures at 1%CMC.</td>
<td>54</td>
</tr>
<tr>
<td>4.1</td>
<td>Experimental values of system parameters prior to the start of gelation.</td>
<td>67</td>
</tr>
<tr>
<td>4.2</td>
<td>Setup and particle sizes.</td>
<td>67</td>
</tr>
<tr>
<td>4.3</td>
<td>Solid area fraction distribution ($\alpha_\ell$) characteristics as influenced by aspect ratio, shape and solid concentration in the tube.</td>
<td>72</td>
</tr>
<tr>
<td>4.4</td>
<td>Solid volume fraction ($\nu_\ell$) distribution characteristics as influenced by aspect ratio, shape and solid concentration in the tube.</td>
<td>75</td>
</tr>
<tr>
<td>4.5</td>
<td>Theoretical maximum solid area fraction of cubes, rectangular and cylindrical particles</td>
<td>82</td>
</tr>
<tr>
<td>4.6</td>
<td>Solid area fraction ($\alpha_\ell$) distribution characteristics as influenced by aspect ratio, shape and solid concentration in the elbow.</td>
<td>84</td>
</tr>
<tr>
<td>4.7</td>
<td>Solid volume fraction ($\nu_\ell$) distribution characteristics as influenced by aspect ratio, shape and solid concentration in the elbow.</td>
<td>84</td>
</tr>
<tr>
<td>5.1</td>
<td>Dimensions of solid pieces used during the experiment.</td>
<td>101</td>
</tr>
<tr>
<td>Table 5.2.</td>
<td>Angular velocity ($\omega_z$: rad/s) about the z axis.</td>
<td>109</td>
</tr>
<tr>
<td>Table 5.3.</td>
<td>Angular velocity ($\omega_y$: rad/s) about the y axis.</td>
<td>110</td>
</tr>
<tr>
<td>Table 5.4.</td>
<td>Angular velocity ($\omega_x$: rad/s) about the x axis.</td>
<td>111</td>
</tr>
<tr>
<td>Table 6.1.</td>
<td>Solid and liquid phase densities.</td>
<td>129</td>
</tr>
<tr>
<td>Table 6.2.</td>
<td>Orientation angle $\alpha$ with the highest frequency of occurrence</td>
<td>142</td>
</tr>
</tbody>
</table>
### LIST OF FIGURES

| Figure 2.1. | Experimental setup | 10 |
| Figure 2.2. | a) Coordinates system and b) calibration apparatus | 13 |
| Figure 2.3. | Map of points for *in-situ* calibration | 14 |
| Figure 2.4. | Sample of calibration image using fiber optics wires | 14 |
| Figure 2.5 | Steps of the PTV algorithm | 16 |
| Figure 2.6. | Multi-frame tracking tree and technique | 17 |
| Figure 2.7. | Schematic of stereo matching process in 3D PTV | 19 |
| Figure 2.8. | Instantaneous raw velocity vectors of solid-liquid mixtures | 24 |
| Figure 2.9. | Interpolated instantaneous velocity vectors of solid-liquid mixtures | 25 |
| Figure 2.10. | Ranged raw instantaneous velocity vectors in YZ plane of CMC solution and 50\% cubic solid concentration (16x16mm) at 1.577x10^-4 m^3/s | 27 |
| Figure 2.11. | Ranged raw instantaneous velocity vectors in YZ plane of CMC solution and 50\% cylindrical solid concentration (8x16mm) at 3.154x10^-4 m^3/s | 28 |
| Figure 2.12. | Relative velocity between solid piece and fluid (CMC solution) in YZ plane at 50\% solid concentration and 3.154x10^-4 m^3/s: a) cubic (24x24mm) b) cylindrical (8x16mm) | 29 |
| Figure 3.1. | Experimental setup | 38 |
Figure 3.2. Ranged raw instantaneous velocity vectors in the axial (YZ) plane of CMC solution and 50% cubic solid concentration (16x16mm) at 1.577x10^{-4} m^3/s. ............................................. 42

Figure 3.3. Ranged raw instantaneous velocity vectors in the axial (YZ) plane of CMC solution and 50% cylindrical solid concentration (8x16mm) at 3.154x10^{-4} m^3/s. ................................................ 43

Figure 3.4. Ranged raw instantaneous velocity vectors in the cross-sectional (XY) plane of CMC solution and 50% cylindrical solid concentration (8x16mm) at 3.154x10^{-4} m^3/s. .................. 44

Figure 3.5. Ranged raw instantaneous velocity vectors in the axial (YZ) plane of CMC solution and 50% cubic solid concentration (8mm) at 3.154x10^{-4} m^3/s. ....................................................... 46

Figure 3.6. Ranged raw instantaneous velocity vectors in the axial (YZ) plane of CMC solution and 30% cylindrical solid concentration (8x8mm) at 1.577x10^{-4} m^3/s (Frame 1) .............................................................. 47

Figure 3.7. Ranged raw instantaneous velocity vectors in the axial (YZ) plane of CMC solution and 30% cylindrical solid concentration (8x8mm) at 1.577x10^{-4} m^3/s (Frame 2 after 1/4 s). ......................................................................................... 48

Figure 3.8. Ranged raw instantaneous velocity vectors in the axial (YZ) plane of CMC solution and 30% cylindrical solid concentration (16x24mm) at 1.577x10^{-4} m^3/s. ........................................... 49

Figure 3.9. Ranged raw instantaneous velocity vectors in cross sectional (XY) plane of CMC solution a) 50% cubic solid concentration (16mm) at 3.154x10^{-4} m^3/s and b) 30% solid concentration of cylindrical particles (8x8mm) at 3.154x10^{-4} m^3/s. .............................................................. 50

Figure 3.10. Relative velocity vectors between solid and fluid, a) cube in the axial (YZ) plane, and b) cylinder in (XY) plane at 30% solid concentration (16mm) at 3.154x10^{-4} m^3/s. .............................................................. 52

Figure 4.1. Experimental setup for immobilization of solid-liquid food mixture. .............................................................. 65
Figure 4.2  Slices of solidified solid-liquid mixtures that were used for area fraction measurement at 50% solid concentration (a) and (b) cylindrical particles (8x24mm), (c) cylindrical particles (8x8mm) and (d) rectangular particles (8x24mm). ................................................................. 66

Figure 4.3.  Experimental instantaneous solid area fraction distribution along the tube length for cubes of 8mm in side and 30% solid concentration. ............................................................... 70

Figure 4.4.  Instantaneous solid area and volume fraction distributions for cylinders (8x24mm in size and 50% solid concentration) along the tube length. .............................................. 71

Figure 4.5.  Random generated instantaneous solid area fraction distribution along the tube length. ................................................................. 71

Figure 4.6.  Distribution of solid area fraction for cubes and rectangular shapes in a straight tube (CU: cubes or rectangular shapes, 8x8mm or 8x24mm in size, LC: 30% solid concentration and HC: 50% solid concentration). .............................................. 74

Figure 4.7.  Distribution of solid area fraction for cylinders in a straight tube (C: cylinders, 8x8mm or 8x24mm in size, LC: 30% solid concentration and HC: 50% solid concentration). .............................................. 74

Figure 4.8.  Distribution of solid volume fraction for cubes and rectangular shapes in a straight tube (CU: cubes or rectangular shapes, 8x8mm or 8x24mm in size, LC: 30% solid concentration and HC: 50% solid concentration). .............................................. 75

Figure 4.9.  Distribution of solid volume fraction for cylinders in a straight tube (C: cylinders, 8x8mm or 8x24mm in size, LC: 30% solid concentration and HC: 50% solid concentration). .............................................. 75

Figure 4.10.  Aligned (a) and non-aligned (b) solids within a tube and their influence on solid area and volume fraction. ................................. 77
Figure 4.11. Distribution of solid area and volume fraction for cylinders in a straight tube (C: cylinders, 8x8mm or 8x24mm in size, LC: 30% solid concentration and HC: 50% solid concentration). ........................................ 77

Figure 4.12. Experimental solid area and volume fractions. ......................... 79

Figure 4.13. Distribution of solid area fraction for cylinders and rectangular shapes in a straight tube (CU: cubes or rectangular shapes, C: cylinders, 8x24mm in size, LC: 30% solid concentration and HC: 50% solid concentration). ... 79

Figure 4.14. Schematic location of cylinders for maximum solid area fraction ... 80

Figure 4.15. Schematic location of cubes for maximum solid area fraction ...... 81

Figure 4.16. Distribution of solid volume fraction for cylinders in elbow (C: cylinders, 8x8mm or 8x24mm in size, LC: 30% solid concentration and HC: 50% solid concentration). ..................... 83

Figure 4.17. Distribution of solid volume fraction for cubes and rectangular shapes in elbow (CU: cubes or rectangular shapes, 8x8mm or 8x24mm in size, LC: 30% solid concentration and HC: 50% solid concentration). ..................... 83

Figure 4.18. Distribution of solid area fraction for cubes and rectangular shapes in elbow (CU: cubes or rectangular shapes, 8x8mm or 8x24mm in size, LC: 30% solid concentration and HC: 50% solid concentration). ..................... 86

Figure 4.19. Distribution of solid area fraction for cylinders in elbow (C: cylinders, 8x8mm or 8x24mm in size, LC: 30% solid concentration and HC: 50% solid concentration). ..................... 86

Figure 4.20. Instantaneous solid area and volume fraction of cylinders (8x24mm in size and 30% solid concentration) in the elbow. ............. 87
Figure 4.21. Slices of solidified solid-liquid mixtures (in an elbow) that have been used for area fraction measurement at 50% solid concentration (a) and (b) cylinders 8x24mm and 8x8 mm respectively, c) and (d) cubes 8x24mm and 8x8mm respectively.

Figure 5.1. Experimental setup

Figure 5.2. Reference frame

Figure 5.3. Steps of the experiment

Figure 5.4. Euler angle definition

Figure 5.5. Rotation and translation of reference frame

Figure 5.6. Points of measurement a) Cube and b) Cylinder (side view)

Figure 5.7. Effect of flow rate on angular velocity about various axes at 30% solid concentration of cubes (24x24mm) (LF:1.577x10^4 m^3/s and HF:3.154x10^4 m^3/s)

Figure 5.8. Effect of aspect ratio on angular velocity about various axes at 30% solid concentration of cylinders at 3.154x10^4 m^3/s (16x16mm and 16x24mm in size)

Figure 5.9. Effect of solid concentration on angular velocity about various axes at 1.577x10^4 m^3/s of cubes of 8x8mm (LC and HC:30% and 50% solid concentration respectively)

Figure 5.10. Effect of particle shape on angular velocity about various axes at 30% solid concentration and 3.154x10^4 m^3/s (CU:cube;CY:cylinder, 8x8mm and 16x16 are size of particles)

Figure 5.11. Visualization of the motion of a representative cylinder (16x24mm) with at 30% solid concentration and 3.154x10^4 m^3/s flow rate (time/length scale: 1.15s/0.2m (tube section))
Figure 5.12. Visualization of the motion of a representative cube (8mm in side) with at 50% solid concentration and 3.154x10^4 m^3/s flow rate (time/length scale: 1.09s/0.2m (tube section)). ................................................. 118

Figure 5.13. Visualization of the motion of a cube (24mm in side) at 50% solid concentration and 1.577x10^4 m^3/s flow rate (time/length scale: 2.4s/0.2m (tube section)). ..................................... 119

Figure 6.1. Experimental setup ................................................................. 128

Figure 6.2 Reference frame ................................................................. 130

Figure 6.3. Sequence of Euler angles: a) rotation about the z axis, b) rotation about y axis and c) rotation about x axis. ................. 131

Figure 6.4. Illustration of x and y axes rotation to define the angle \( \alpha \). .................. 133

Figure 6.5. Orientation angles of cubes (16x24mm) as a function of time at 30% solid concentration and 1.577x10^4 m^3/s ............ 137

Figure 6.6. Orientation angles of cylinders (16x24mm) as a function of time at 30% solid concentration and 1.577x10^4 m^3/s ............ 137

Fig. 6.7 Orientation (\( \alpha \)) distribution for cylinders at 30% solid concentration (8x8mm and 16x16 mm refers to diameter and length respectively, LF and HF: refers to 1.577 10^4 m^3/s and 3.154 10^4 m^3/s flow rate respectively). .... 139

Fig. 6.8 Orientation (\( \alpha \)) distribution for cubes at 30% solid concentration (8x8mm and 16x16 mm refers to size diameter and length respectively, LF and HF: refers to 1.577 10^4 m^3/s and 3.154 10^4 m^3/s flow rate respectively). .... 140

Fig. 6.9 Orientation (\( \alpha \)) distribution for cubes of 8x8mm in size (LF and HF: refers to 1.577 10^4 m^3/s and 3.154 10^4 m^3/s flow rate respectively, HC and LC refers to 30% and 50% solid concentration respectively). ............. 140

Fig. 6.10 Orientation (\( \alpha \)) distribution for cylinders of 8x8mm in size (LF and HF: refers to 1.577 10^4 m^3/s and 3.154 10^4 m^3/s flow rate respectively, HC and LC refers to 30% and 50% solid concentration respectively). ................. 141
CHAPTER I

INTRODUCTION

Thermal processing in the food industry is carried out both to ensure sterility of the food and to increase its palatability. It differs from freezing and drying in that these two methods do not involve destruction of microorganisms. The product of thermal processing is shelf-stable and can generally be stored at room temperature. Heating is the classical method of food sterilization, and canning the best known packaging technique. Generally, the physical process of canning is not sterile, so that the container must be sterilized after it has been filled and sealed. A relatively new technology for sterilization is called aseptic processing. Unlike canning, aseptic processing involves continuous and separate sterilization of product and packaged followed by filling and sealing in a sterile environment. Since the product is heated directly before packing, the presumed advantages include better quality with less time of operation and energy savings. Therefore, this process is considered superior technically and economically. Aseptic processing is widely used in Europe, but it is restricted mainly to liquid foods. There is considerable industry interest in extending this technology to products which contain large solid pieces in liquid
(e.g. soup, beef stew).

Aseptic processing itself consist of different methods of heating: 1) conventional steam heating (scraped surface heat exchanger or helical tube) and 2) ohmic heating. The fundamental difference between these two processes is that in conventional heating heat is transferred from liquid medium to solid particles, however in ohmic heating liquid and solids are heated almost simultaneously. Thus, ohmic heating reduces the need to overprocess the liquid medium to ensure the sterility of the particles. Besides, mechanical damage may been held to a minimum; the absence of heat transfer surfaces reduces fouling, and product quality can exceed that obtained from conventionally heating. Ohmic heating involves an internal generation of heat by the passage of alternating electrical current. It is not a new concept, having been widely used for electric pasteurization in the 1920's, before languishing because of lack of suitable electrode materials, and controls. In recent years, the development of improved electrode materials and controls design (Simpson, 1983) has made the technology feasible again.

In the United States the Food and Drug Administartion (FDA) requires that all manufacturers of commercially sterile, low-acid food products, file their processes with them. In contrast, Europe and Japan do not have regulatory agencies. Low acid foods containing particulates larger than 3.2 mm processed aseptically are not commercially available in The United States, partialy due to the lack of basic information on flow and heat transfer behavior in liquid particulate mixtures. FDA requires appropriate experimental verification of achieving sterility to approve the aseptic processing of liquids
containing particles.

The revived version of the ohmic heating process was developed by the Electricity Council Research Center and licensed for further development to APV International (Biss et al., 1987). APV's version of the ohmic heater consists of a column which may contain four to seven electrodes. The column is mounted vertically with product flow being upward. Interconnecting tube sections are made of stainless steel with electrically insulating plastic linings.

Ohmic heating is promising technology to process solid-liquid food mixtures, high viscosity foods, and heat sensitive food products (Sastry, 1993). However, there are a number of questions to be addressed before this process becomes commercially viable. Two phase flows with large solid pieces, such as food products, exhibit complex velocity fields through the heater, possibly resulting in a residence time distribution. These flows play an important role in fluid mixing, helping to reduce heating nonuniformity. Also, it has been reported that orientation of solids and solid area fraction perpendicular to the electrical field are important parameters affecting ohmic processing (Sastry, 1992). Other key issues relate to the orientation distribution and solid rotation during processing.

Accordingly, the objectives of this research were to characterize:

1. The flow of solid-liquid mixtures, specifically the fluid interstitial velocities in three dimensions, and relative velocity and heat transfer coefficient distribution around the solids

2. Solid area fraction distribution over the tube length in continuous tube flow
3. Rotational behavior of the solid pieces in continuous flow.

4. Orientation distribution of solid pieces in continuous tube flow.
REFERENCES


CHAPTER II

INVESTIGATION OF SOLID-LIQUID INTERSTITIAL FLOW IN THREE DIMENSIONS USING PARTICLE TRACKING VELOCIMETRY

ABSTRACT

The flow behavior of solid-liquid mixtures through tubes is an important consideration for a proper design of continuous sterilization processes. Most methods (i.e. Pulsed Laser Velocimetry (PLV) and Laser Doppler Velocimetry (LDV) methods) cannot be applied to two phase flow when the solid pieces are large (same order of magnitude as the tube). Particle Tracking Velocimetry (PTV) is a recent technique that allows the measurement of the velocities of the two phases in three dimensions. In this study, we report the advancement of PTV techniques to study flows of coarse solid-liquid mixtures. The method has been adapted successfully to high solid concentration (30% and 50%) by matching the index of refraction of clear solid pieces and the carrier fluid. Digital image processing of tracer and solid piece motion recorded on stereoscopic motion picture films were used to identify solids and tracers, and obtain data on location and velocity. This technique permitted determination of the interstitial velocity between phases as well as the velocity distribution and relative velocity between phases.
I. INTRODUCTION

Little information is available on the flow of food materials. Although the motion of suspended solids in flowing liquids is of interest in many areas of engineering, most literature has considered the conveying of dense particles in the turbulent flow of water. Little work has been done on flows of the type found in aseptic processing systems, where solid pieces are of diameter in the same order of magnitude as the tube, and whose density is similar to that of the typically non-Newtonian carrier fluid (Zitoun, 1992; Balasubramaniam, 1993). Most methods developed for velocity measurement have been used for mixing and turbulent flow. These can be classified into two categories: optical methods and opaque methods. Most optical methods (i.e. Pulsed Laser Velocimetry (PLV) and Laser Doppler Velocimetry (LDV) methods) cannot be applied to two phase flow when the particles are large (D>1cm). For the case of opaque materials, Magnetic Resonance Imaging (MRI) can be used (Manavel et al., 1993) but its three-dimensional intensity distribution using transverse phase encoding gradient is based on the assumption that the motion of the flow is steady in the statistical sense along the flow direction within the test section (Altobeli et al., 1991; Sinton and Chow, 1991). Also, this MRI method needs knowledge of a general flow direction to get accurate information. Positron Emission Particle Tracking (PEPT) (Broadbent et al., 1993), Computer-Automated Radioactive Particle Tracking (CARPT) (Yang et al., 1993), and Gamma Ray Emission Particle Tracking (γEPT) (Larachi et al., 1995) work with opaque media but involve single particle measurements and suffer from slow data acquisition rates. These
experiments consist in letting a particle to flow for 10 to 12 hours until it maps the whole area of interest. This would require a closed vessel or a recirculating system.

Modern developments in image processing have been responsible for the use of flow visualization to arrive at vital quantitative flow velocity information with a high degree of accuracy. Particle Tracking Velocimetry (PTV) is one of several such tools which were developed over the past decade and have been applied to a variety of fluid mechanics problems (Adrian, 1991; Liu and Adrian, 1993). The advantages are its non-intrusive nature and that full field information can be obtained. PTV has been used in mixing (Venkat et al., 1995) and in fluidized beds for gas-liquid-solid mixtures (Chen and Fan, 1992). This method has been used in the past in some of NASA's microgravity experiments, in the study of internal combustion engines and turbulent mixing (Trigui et al., 1992). All previous work that dealt with PTV were for single phase flows. In this work, we extend traditional PTV techniques to coarse solid-liquid mixtures, using transparent solids that have the same index of refraction as the solution, to measure interstitial velocity at high solid concentration.

The goal of this research is to adapt the PTV technique to solid-liquid mixtures of high solid concentration and high solid to tube size ratio (1:2) to measure the relative velocity between the two phases and the interstitial velocities in a vertical tube.

II. MATERIAL AND METHODS

1. Image processing techniques using PTV

In this work we used a three-dimensional PTV algorithm to determine flow characteristics (Trigui et al., 1992). This algorithm was developed at The Ohio State
University by Dr. Y. Guezenneec and coworkers. The automated measurement of flow velocities in three dimensions requires the following steps:

1. Flow visualization
2. Image acquisition/digitization
3. Image processing
4. In-situ calibration
5. Image analysis

1.1. Flow visualization and experimental conditions

Three dimensional flow visualization requires two cameras which are synchronized or a single camera with a mirror arrangement to get two views of the flow volume of interest, in this case, the flow of large solid pieces in a tube. The camera-mirror arrangement used in our experiment is shown in Fig. 2.1. The stereo angle can be adjusted from a few degrees (stereo angle associated with human eyes being 6-7°) to orthogonal views (90°). The stereo angle in this study was maintained at 90°.

The experiment consisted of introducing cubic solid pieces (opaque as well as transparent) and tracers into the medium at the inlet section, and videotaping its motion as it moved upward. The test section consisted of a Pyrex tube of 0.0508 m inside diameter and 1.524 m length. The tracers were neutrally buoyant polystyrene microcarrier beads (diameter 450µm, Polysciences, Inc., Warrington, PA). The Stokes number for the microcarriers was of the order of 0.03, and the concentration used was dilute (1g/L), thus the tracers followed the fluid closely.
Fig. 2.1  Experimental setup.
Hence, it was reasonable to assume that they flowed at the same velocity as the liquid phase.

The solid-liquid mixtures were conveyed by air pressure from the inlet. The flow rate was measured and controlled using differential pressure transmitters (Model 1151DP Alphaline, Rosemount Inc., MN).

The tube curvature causes an optical distortion which decreases the extent of image received by the video camera. This problem was minimized by using the refractive index matching technique. The test section is enclosed in a rectangular box with a plexiglass window whose refractive index was of the same as that of glass tube (~1.5). The box was filled with the same fluid used for the experiment: Sodium carboxy methyl cellulose (CMC), to minimize the curvature effect. After recording the flow, the videotape was replayed, and the frames grabbed, processed and analyzed to determine the velocity vectors. Also, the system was precalibrated in-situ, (see procedures detailed later). Thus any errors due to distortion were eliminated.

1.2. Image acquisition and digitization

A CCD camera was used in this study (S-VHS Panasonic AG 450). The frames were grabbed at 1/30 s using a digital video recorder (Panasonic AG 7350) equipped with search/jog dial and frame grabber board (P360F, Dipix Technologies Inc., Ontario, Canada).

1.3. Image processing

Each frame sent from the frame grabber was first pre-processed to remove background and electronic noise, and improve image quality. Noise removal was achieved
by using grey level thresholding (both high and low pass filtering). The image quality was further improved by generating a bilevel image which was formed by deciding a threshold level and setting all images above the threshold to be saturated and below it to be zero.

1.4 In-situ calibration.

Determination of solid piece and tracer locations in three dimensions (3D) requires a relationship between the image coordinates and real world coordinates. In order to account for camera and mirror misalignment, changes in the index of refraction which distorted the reflected image, and optical aberrations from lenses, we conducted an in-situ calibration on the actual setup field, and analyzed it just prior to experimentation. For the present experiment, a fiber optics matrix was used with known X, Y and Z coordinates (see Fig. 2.2 for more details). The calibration consisted of inserting a plexiglass plate with an array of 60 points made by using plastic fiber light guide and illumination by using fiber optic illuminator (Model 170D, Dolan Jenner, Rochester, NH). The real coordinates \((X, Y, Z)\) and the image coordinates \((X_1, Y_1)\) and \((X_2, Y_2)\) from the left and right images respectively were correlated to relate the actual 3D positions to the (2D) locations in the two stereo views. The plate was moved to three different positions to map the whole area of interest (Fig. 2.3). The array of points were videotaped at known locations and analyzed using the PTV algorithm to identify the location of the bright spots in the left and right views (Fig. 2.4).

1.5 Details of image analysis

The image analysis was conducted after some modification of the algorithm written by Trigui et al. (1992) to obtain quantitative information from the images.
Figure 2.2. a) Coordinates system and b) calibration apparatus.
Fig. 2.3 Map of points for *in-situ* calibration

\[ i = 1 \text{ for left image} \]
\[ i = 2 \text{ for right image} \]

\[ Xi \]
\[ Yi \]

Fig. 2.4 Sample of calibration image using fiber optics wires.
Figure 2.5 outlines the steps involved in the algorithm to determine the velocity vectors of two phases. The following is a description of the process in common use with the PTV technique. Note that the word particle in this chapter refers to solid piece and tracer.

1.5.1. 2-D Particle location

The algorithm locates the particles and assigned a number for each particle, center location \( (X, Y) \), number of pixels spanned in the \( X \) and \( Y \) directions and the average light intensity.

1.5.2. Particle tracking

The frame to frame tracking is accomplished in two steps (Trigui et al. 1993): 1) the establishment of a search area and feasible particle trajectories and 2) a search for the actual particle path.

1.5.2.a. Search area: an estimate for the maximum distance a particle will travel is made from the knowledge of the geometry of the system and the flow conditions, the camera framing rate, and the length scale ratio between the tube and the digitized images. The field of view is made sufficiently large to ensure that the estimate is made generous on the high side. Each particle is tracked through search areas within successive frames. Within each frame, the challenge consists of identifying each particle with its counterpart in previous and successive frames. Since a given particle may take one of a number of possible paths, a "tree" of choices is set up, as illustrated in Fig. 2.6. Since the choices must be made for each frame, the tree grows rapidly.
Figure 2.5 Steps of the PTV algorithm.
Solid black track is the most probable path

Principle: Minimize a penalty function based on the concept of path coherence using a modified predictor scheme

Figure 2.6. Multi-frame tracking tree and technique
1.5.2. **Particle path**: Since the path, velocity and acceleration are all continuous and smooth functions, the procedure used is to look at each possible path in the tree and evaluate a penalty function that can help establish the most probable path (Fig. 2.6 shows more details). The penalty function is then compared for each possible branch in the search tree and the path associated with the lowest penalty function is retained as being the most likely physical path.

1.5.3. **Stereo matching left and right views**

Stereo match corresponds to the intersection of the two optical rays which image the particle location in each view (see Fig. 2.7). In the case of a realistic experiment with a possible distortion due to index of refraction, an experimental calibration can be used to eliminate this problem.

1.5.4. **Calculating the velocity field**

The spatial locations of particle paths are found from the two-dimensional stereo pair particle trajectories. The displacements, velocity vectors, and their standard deviations for the particle paths are then evaluated.

1.5.5. **Post processing velocity validation**

After obtaining the velocity vectors, particles with a stereomatching track represent the lowest of three penalty functions (one for each 2 dimensional track and one for the stereomatching).

1.5.6. **Data interpolation and presentation**

The final data interpolation in conventional PTV, involves smoothing and presentation of velocity vector data over a regular grid.
Near Intersection Point of Two Optical Rays

Figure 2.7. Schematic of stereo matching process in 3D PTV.
The technique used for this purpose is termed Adaptive Gaussian Window (AGW) interpolation. The details of the technique are as follows.

The interpolation function $F(x, y)$ at a point (node of the interpolation grid) is based on the weighted sum of each of the $k$ known data points (Spedding and Rignot, 1993):

$$F(x, y) = \frac{\sum_{k=1}^{n} w_k (x, y) f_k}{\sum_{k=1}^{n} w_k (x, y)}$$  \hspace{1cm} (1)

where,

$$w_k = e^{-\frac{d_k^2}{\sigma^2}}$$  \hspace{1cm} (2)

and $d_k$ is:

$$d_k = \sqrt{(x-x_k)^2 + (y-y_k)^2 + (z-z_k)^2}$$  \hspace{1cm} (3)

The accuracy of the AGW depends on four parameters: characteristic length of the flow ($L$); mean nearest neighbour distance between samples ($\delta$); displacement in the numerical differentiation ($h$) and the Gaussian window width ($\sigma$). The error introduced by the interpolation is given by the Root Mean Square Error ($RMSE$) and is expressed as follows:

$$RMSE = f \left( \frac{L}{h}, \frac{h}{\delta} \right)$$  \hspace{1cm} (4)

The mean nearest distance ($\delta$) was calculated based on the formula suggested by Adrian
\[ \delta = 0.55 \cdot C^{-1/3} \]  

(5)

2. Transparent solid pieces and refractive index matching:

The problem of light blockage due to the opaque solid pieces (potato), which restricted the use of the optical technique to high solid concentrations, was resolved using transparent solid pieces. By closely matching the refractive indices of solid and liquid, the scatter at the interface of solid and liquid were eliminated and measurements were then possible for high solid concentration. In this experimental study, clear solid pieces were made from polyacrylamide gels, commonly used for electrophoresis.

3. Clear solid piece preparation

The cubic and cylindrical shapes of solid pieces were obtained by using acrylamide solution and a special glass tube apparatus for molding. A solution of 30% acrylamide (29g acrylamide, 1g N,N'-methylenebisacrylamide, and H_{2}O to 100ml) was prepared and heated to 37°C to dissolve solutes. A solution of 10% ammonium persulfate (w/v, 1g /10ml of H_{2}O) was mixed in the previous solution by swirling. The mixture was cooled down by putting the beaker in an ice bath to slow down the polymerization (necessary to allow time to fill all the tubes). TEMED (N,N,N',N'-tetramethylethylenediamine, 35µl) was added, mixed and the tubes were slowly filled using a syringe (slowly to avoid air bubbles). A complete polymerization took around 45min. After that time, the gel was separated from the glass tube.

The glass tubes used for this purpose were prepared by cleaning: using deionized
water and siliconized fluid (Sigmacote, Sigma Chemical Co., St Louis, MO) to form a tight, microscopically thin film of silicone on glass to prevent the solid piece from sticking to the surface. Once the tubes were dried (using pressurized air) they were fixed in a standing position in a petri dish, filled beforehand with solidified agarose (GibcoBRL, Life Technologies Inc., Gaithersburg, MD).

III. RESULTS AND DISCUSSION

The velocity field representation has been made in three orthogonal planes: XY, YZ, and XZ, two axial planes (XZ, YZ) and one cross-sectional (XY). In the present discussion we have limited our graphical presentation to the YZ and XY planes. A common step in presenting the instantaneous velocity vectors is the interpolation of the randomly spaced velocity vectors onto a regular grid (Garcia-Briones et al., 1994; Trigui et al., 1992). Successful interpolation requires the presence of sufficiently high tracer density to resolve local velocity variations. The more complex the flow, the greater the required density (e.g. highly developed turbulence). In the absence of the required tracer density, interpolation can result in erroneous flow information. In our experiments, the instantaneous velocity vector data were too sparse for the interpolation, and may have introduced errors larger than those involved in the image processing steps.

An alternative approach to increasing data density up to 10 times is ensemble averaging, which is based on statistical averaging over several experiments, and has been used for mixing tanks (Yianneskis, 1987; Venkat et al., 1996). However, our interest was not in statistical averages, but instantaneous velocities; therefore statistical averaging could
Comparing instantaneous raw velocity (Fig. 2.8) and interpolated velocity vectors (8x8x18 grid) in the YZ plane (Fig. 2.9), it is noted that the interpolated velocity vectors may mislead the observer and some details of the flow are lost. Certain planes had only 10 tracks at high solid piece concentration; far fewer than recommended for Adaptive Gaussian Window (AGW) interpolation (Spedding and Rignot, 1993). The AGW technique was performed to test its effectiveness. Determination of error was obtained from the AGW performance analysis curves presented by Spedding and Rignot (1993). The estimated errors based on the value of our study is presented in Table 2.1. The interpolation in cartesian coordinates caused a range of errors from 8.5% to 40%. For this reason, we have presented our data as raw instantaneous velocity vectors. The data have been presented in the YZ and XY planes with respect to a range of X and Z interval values respectively rather than projections of all velocity vectors. The plots presented have the highest number of tracks in a specified plane.

Verification of accuracy

The accuracy of the velocity vectors was tested for a known velocity profile (single phase flow) and the theoretical results compared with the experimental findings. The experimental values were close: the maximum deviation was 0.09 cm/s, which corresponds to 4.6% error.

The presence of solid pieces altered the velocity profile of the carrier fluid in the three axes (X, Y, Z) due to the large momentum transfer between the two phases. Velocity vectors were deflected by the presence of the solid pieces causing the velocity
Figure 2.8. Instantaneous raw velocity vectors of solid-liquid mixtures (Y scale: 1:0.0254m, Z scale: 1:0.05m).

= 19.09 cm/s
Figure 2.9. Interpolated instantaneous velocity vectors of solid-liquid mixtures (Y scale: 1:0.0254m, Z scale: 1:0.05m).
Table 2.1. Characteristic parameters used in AGW interpolation and the estimated errors. The estimated errors were calculated based on the characteristic curves presented by Spedding and Rignot (1993).

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Parameter</th>
<th>Value</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>L</td>
<td>Characteristic length</td>
<td>5.080 cm</td>
<td>Tube diameter</td>
</tr>
<tr>
<td>δ₁</td>
<td>Mean nearest distance</td>
<td>0.521 cm</td>
<td>Based on 250 particles¹</td>
</tr>
<tr>
<td>δ₂</td>
<td></td>
<td>0.891 cm</td>
<td>Based on 50 particles¹</td>
</tr>
<tr>
<td>δ₃</td>
<td></td>
<td>1.524 cm</td>
<td>Based on 10 particles¹</td>
</tr>
<tr>
<td>h</td>
<td>Grid distance</td>
<td>0.635 cm</td>
<td>Largest grid distance</td>
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<tr>
<td>σ₁</td>
<td>Gaussian window width</td>
<td>0.646 cm</td>
<td></td>
</tr>
<tr>
<td>σ₂</td>
<td></td>
<td>1.105 cm</td>
<td></td>
</tr>
<tr>
<td>σ₃</td>
<td></td>
<td>1.889 cm</td>
<td></td>
</tr>
<tr>
<td>RMSE₁</td>
<td>Error function</td>
<td>8.5%</td>
<td>Based on L/h ~ 10 and h/δ ~ 1.22</td>
</tr>
<tr>
<td>RMSE₂</td>
<td></td>
<td>20%</td>
<td>Based on L/h ~ 10 and h/δ ~ 0.71</td>
</tr>
<tr>
<td>RMSE₃</td>
<td></td>
<td>&gt;40%</td>
<td>Based on L/h ~ 10 and h/δ ~ 0.42</td>
</tr>
</tbody>
</table>

¹-Mean particle distance has been using the formula suggested by Adrian (1991).

vectors shown in axial (YZ) plane (Figs. 2.10 and 2.11). The flow was forced to flow around the solid pieces which created a channeling between the solid pieces and the tube wall and therefore, increased the slip velocity between the solid and liquid phase. Relative velocities between solid piece and the fluid in YZ plane is presented in Fig. 2.12. The highest relative velocity was 0.025 cm/s and 0.017 for cubes and cylinders respectively. The effect of relative velocities on fluid-solid heat transfer is presented in a separate
Figure 2.10. Ranged raw instantaneous velocity vectors in YZ plane of CMC solution and 50% cubic solid concentration (16x16mm) at 1.577x10^-4 m/s (Y scale: 1:0.0254m, Z scale: 1:0.05 m).
Figure 2.11. Ranged raw instantaneous velocity vectors in YZ plane of CMC solution and 50% cylindrical solid concentration (8x16mm) at 3.154x10^4 m^3/s (Y scale: 1:0.0254m, Z scale: 1:0.05m).
Figure 2.12. Relative velocity between solid piece and fluid (CMC solution) in YZ plane at 50% solid concentration and $3.154 \times 10^{-4}$ m/s: a) cubic (24x24mm) b) cylindrical (8x16mm) (X scale: 1:0.0254m, Y scale: 1:0.0254m, Z scale: 1:0.05m).
This study demonstrates that it is now possible to experimentally determine interstitial velocities in continuous flow of solid-liquid mixtures. The technique has been successfully adapted to determine relative velocities between phases. A key observation is the widespread deviation of fluid flow from the parabolic velocity profile associated with tube flows.

IV. CONCLUSIONS AND RECOMMENDATIONS

Particle tracking velocimetry is a promising technique for velocity measurement, and has been adapted successfully to determination of interstitial velocities in the flow of solid-liquid mixtures. These studies reveal that there is a slip velocity between phases that is dependent on solid piece shape and aspect ratio. The velocity fields within such flows are extremely complex.
NOMENCLATURE

\( C \) \quad \text{Mean number of particles per unit volume}

\( d_i \) \quad \text{Distance between the interpolation points}

\( F(x,y) \) \quad \text{Interpolation function}

\( f_k \) \quad \text{Known data point}

\( h \) \quad \text{Displacement in the numerical differentiation (=grid size)}

\( L \) \quad \text{Characteristic length}

\( w_k \) \quad \text{Gaussian weighting function}

\( X, Y, Z \) \quad \text{Cartesian coordinates}

\( x, y, z \) \quad \text{Coordinates of the interpolated point}

\( x_k, y_k, z_k \) \quad \text{Coordinates of point } k

\( X_1, Y_1 \) \quad \text{Coordinates of left image}

\( X_2, Y_2 \) \quad \text{Coordinates of right image}

\( \delta \) \quad \text{Mean nearest neighbor distance between samples}

\( \sigma \) \quad \text{Gaussian window width}
REFERENCES


CHAPTER III

DETERMINATION OF RELATIVE VELOCITY BETWEEN SOLID AND LIQUID IN THREE DIMENSIONS IN CONTINUOUS FLOW USING PARTICLE TRACKING VELOCIMETRY

ABSTRACT

Particle Tracking Velocimetry (PTV) was used to measure instantaneous velocity vectors of flowing fluid and solid pieces in three dimensions. Instantaneous velocity vectors of both phases were measured, and relative velocity between the solid and the liquid and heat transfer coefficient were determined at different experimental conditions. Results showed that the velocity distribution is asymmetric and the typically presumed laminar regime does not apply even at low flow rate. Also, relative velocities exist in all the cases studied and decrease with the increase of the solid concentration and increases with the increase of aspect ratio and particle size. Increasing the flow rate, decreasing the solid concentration and solid size increased $h_f$. 

34
I. INTRODUCTION

The advantage of applying ohmic heating to particulate foods is in the potential for uniform heating both liquid and solid phases. In conventional food sterilization processes, heat is applied via an external medium. To ensure that every part of the solid piece is sterilized, surfaces of particles and the surrounding liquid must be overheated, thereby sacrificing quality (de Alwis et al. 1991). The flow behavior of food through the ohmic heater will influence performance. The electric field can be distorted around materials of high or low conductivity (Sastry and Palaniappan, 1992). The distortion can cause temperature variation in the carrier fluid around the particle under static conditions. In continuous flow systems, the interstitial velocity tends to mix the fluid and reduce nonuniformity. The models of solid-liquid mixtures available are based on homogenous flow approach. The homogeneous flow may occur on average while considerable local velocity differences between phases (Sastry, 1992) may still exist.

Mathematical modeling of flow and heat transfer of solid-liquid mixtures is a complex problem, requiring intensive computing effort. Yang et al. (1993) modeled solid-liquid mixtures in a helical tube. To simplify the problem they made a number of assumptions, such as negligible particle interactions, and Newtonian fluid behavior among others. Unrealistic assumptions can contribute to enormous errors and therefore, care is necessary since the problem deals with consumer safety. Design for safety requires experimental studies to identify worst-case scenarios that might happen during the sterilization process.

Little information is available on the flow of solid-liquid food materials (Sastry and
Zuritz, 1987) and although the body of literature has grown, fundamental understanding has not been achieved. Although the motion of suspended solids in flowing liquids is of interest in many areas of engineering, most literature has considered the conveying of dense particles in the turbulent flow of water. Few studies have been done on flows of the type found in aseptic processing systems, where the density of the particles (whose diameter is of the same order of magnitude as the tube) is similar to that of the carrier fluid, (typically non-Newtonian, Zitoun, 1992; Balasubramaniam, 1993). These experimental studies dealt with measurement of relative velocities for single particles and required manual measurement.

Particle Tracking Velocimetry (PTV) is one of several tools which were developed over the past decade and have been applied to a variety of fluid mechanics problems (Adrian, 1991; Liu and Adrian, 1993). The advantages are its non intrusive nature and in that full field information can be obtained. In this work we used a 3 dimensional PTV algorithm to determine flow characteristics (Trigui et al. 1992). This algorithm was developed at The Ohio State University by Dr. Y. Guezennec and coworkers. This method has been used in the past in some of the NASA's microgravity experiments, in the study of internal combustion engines, turbulent mixing and has been adapted successfully to solid-liquid mixtures (see Chapter II).

The goals of this research are to 1) characterize the flow of solid-liquid mixtures by determining the interstitial velocities and 2) to measure the local relative velocity between the two phases.
II. MATERIAL AND METHODS

The experiment consisted of introducing solid pieces (opaque and transparent) and tracers into the medium at the inlet section, and videotaping their motion as it moved upward (Fig. 3.1). The test section consisted of Pyrex tube of 0.508 m inside diameter and 1.524 m length. The tracers were neutrally buoyant polystyrene microcarrier beads (diameter 450µm, Cat. No. 15622, Polysciences, Inc., Warrington, PA). The Stokes number for the microcarriers was of the order of 0.03, and the concentration used was dilute (w/v, 1g/L), thus the tracers followed the fluid closely. Hence, it was reasonable to assume that they flowed at the same velocity as the liquid phase. The solid-liquid mixtures were conveyed by air pressure from the inlet. The flow rate was measured and controlled by using differential pressure transmitters (Model 1151DP Alphaline, Rosemount Inc., Minnesota, USA). The air pressure was controlled by an I/P controller (Fisher Governor, Co., Marshall town, IW) to keep the flow rate constant. The flow of solid-liquid mixture was videotaped using a CCD S-VHS video camera.

The experiment has been conducted at two levels of solid concentrations 30% and 50%. Two type of solid pieces have been used in this study, opaque (potato) and transparent (acrylamide gel). Transparent solid pieces were necessary in this study since they could not be identified by the PTV image as a particle and therefore, we were able to measure velocities in a vicinity of high solid concentration (see Chapter II for more details). Two flow rates $1.577\times10^{-4}$ and $3.154\times10^{-4}$ m$^3$/s at 1% CMC concentration were used. The density of each phase is presented in table 3.1.
Fig. 3.1 Experimental setup.
Table 3.1. Solid and liquid phase densities.

<table>
<thead>
<tr>
<th>Material</th>
<th>Density (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solution (1% CMC)</td>
<td>1004</td>
</tr>
<tr>
<td>Potato (solid pieces)</td>
<td>1060-1070</td>
</tr>
<tr>
<td>Acrylamide gels</td>
<td>1060-1070</td>
</tr>
<tr>
<td>Tracers</td>
<td>1004</td>
</tr>
</tbody>
</table>

1. Relative velocity and $h_p$ determination

Further analysis was also done to determine relative velocity by subtracting fluid velocity from the particle velocity found using the PTV algorithm. The solid pieces and tracer locations at each time (1/30s) were stored in the data files and were sufficient to determine the relative velocity around the solid piece based on velocity vectors of both phases in the axial (Z) direction (the dominant flow direction). The coordinate systems is as detailed in chapter II. The values of local heat transfer coefficient between the liquid and the solid can be back calculated using well known correlations such as that for a flat plate presented in Eq.1 (Incropera and De Witt, 1990):

$$Nu = 0.332 \ Re^{0.5} \ Pr^{0.33}$$  \hspace{1cm} (1)

The other correlations that have been used before (Zitoun and Sastry, 1994; Balasubramaniam and Sastry, 1996) like Ranz and Marshall (1952) and Whitaker (1972) cannot be used since they were developed for unbounded flow past spherical particles. No
relations appear to be available for forced convection about cubes or cylinders similar to
our case. However, our goal here was merely to find the trend around particles at high
solid concentrations and not to make an accurate prediction of heat transfer. For cylinders
the use of flat plate can be justified by using local instantaneous velocity vectors over a
short distance, so that the assumption of flat plate can be accepted. For heat transfer
coefficient calculations, only the instantaneous velocity vectors that were within a control
volume 10% larger than the volume of particles were considered. The 10% was not based
on the boundary layer thickness since the Reynolds number is relatively small which results
in a thick boundary layer. In most cases, the boundary layer thickness was larger than the
solid size and in that control volume, it was possible to accommodate another solid piece
that may have interfered with the instantaneous velocity vectors. For this reason we
limited our data to the vicinity of the particles by suggesting a control volume 10% greater
than the particle size, which corresponded to 3mm above the flat surface of the solid piece.

2. Rheological properties of fluid

The non-Newtonian fluids used were aqueous solutions of sodium
carboxymethylcellulose (CMC) of consistency coefficient \( K \) and flow behavior index \( n \).
The values of \( K \) and \( n \) were determined by using a coaxial cylinder viscometer (Rheomat
Model 115; Contraves Industrial Division; Cincinnati, OH). Results were analyzed based
on the Ostwald-de-Waele power law model, using a non-linear model program (Systat
1993, Systat, Inc.; Evanstan, IL). The flow (CMC solution) constants obtained for \( K \) and
\( n \) were 1.24 and 0.52 respectively. Under these conditions Reynolds numbers were 9.3 and
26.5 for \( 1.577 \times 10^4 \) and \( 3.154 \times 10^4 \) m/s flow rates respectively.
III. RESULTS AND DISCUSSION

As mentioned in chapter II, velocity vectors are presented as raw instantaneous velocity vectors. The discussion in this study includes only the salient results although they could be extended to the entire study.

The influence of solid particles in a liquid medium is presented in Fig. 3.2 with experimental instantaneous raw velocity vectors in a two-dimensional projection (YZ plane) field and is presented to provide a basic understanding of the flow patterns in solid-liquid mixtures. The complex behavior of solid-liquid mixture flow is a direct result of the local flow structure. Both the macroscopic and microscopic flow structures are time variant due to the intrinsic dynamic behavior of the dispersed solid phase motion and associated wake interaction. One of the interesting observations is that, although the tube is axially symmetric the flow is not. The flow pattern is not the same along different radii at a given height for the lower part of the figure. The drag forces and lift forces in addition to the particle rotation exist and they have been confirmed (Eichorn and Small, 1964) because of the velocity gradient in the system and the resulting asymmetric distribution of surface pressure. Even though the flow regime is laminar (Re was varied from 9.4 to 26) the parabolic velocity profile vanished with the existence of solid pieces at high solid concentration. In Fig. 3.2, one-dimensional (axial direction) flow is dominant. The presence of the particles altered the velocity profiles of the carrier fluid in the three axes (X, Y and Z) due to the large momentum transfer between the two phases (Fig 3.3 and 3.4). Due to the relatively large solid size (8x16) and the high solid concentration (50%).
Figure 3.2. Ranged raw instantaneous velocity vectors in the axial (YZ) plane of CMC solution and 50% cubic solid concentration (16x16mm) at $1.577 \times 10^{-3}$ m$^3$/s (Y scale: 1:0.0254m, Z scale: 1:0.05 m).
Figure 3.3. Ranged raw instantaneous velocity vectors in the axial (YZ) plane of CMC solution and 50% cylindrical solid concentration (8x16mm) at $3.154 \times 10^{-4}$ m$^3$/s (Y scale: 1:0.0254m, Z scale: 1:0.05m).
Figure 3.4. Ranged raw instantaneous velocity vectors in the cross-sectional (XY) plane of CMC solution and 50% cylindrical solid concentration (8x16mm) at $3.154 \times 10^{-4} \text{ m/s}$ (X scale: 1:0.0254m, Y scale: 1:0.0254m).
the relative velocity between the two phases is also considerable. The fluid was forced to flow around solids which created a channeling between the particle and the tube wall and therefore, increased the slip velocity between the liquid and solid phase (Figs. 3.3 and 3.4). The velocity field in Fig. 3.5 shows the structure of the flow field for 50% solid cubes (8mm) at $3.154 \times 10^{-4}$ m$^3$/s. Disturbance of the flow around the solid to the left and the right result from its presence. Therefore, it acts like an obstacle for some part of the fluid. This may cause pressure non-equilibrium due to hydrodynamic flow field around the solids. As the solid moves upward, some liquid is entrained in its wake and faster moving liquid decelerates because of the interactions with solids and the wall. Similar plots, Figs. 3.6 and 3.7 show instantaneous velocity vectors between the two phases for cylinders separated in time by 0.25 sec. In all cases we found that on average, solids lagged the fluid velocity. The relative velocity is a localized phenomenon which requires knowledge of the local fluid flow field and particle trajectories within the tube.

Increasing solid piece size (Fig. 3.8) increased relative velocity between phases and caused low density of instantaneous velocity vectors in the figure because of the decrease of volume fraction of the liquid phase. The figures in the cross sectional (XY) plane show the radial dispersion of the velocity vectors. In Fig. 3.9, we can notice that the increase of solid concentration increases the dispersion of the fluid, and solid motion is restricted. The latter is due to the interaction of solids during the flow. Notably, some parts in the figures were devoid of tracers. Since transparent solid pieces are similar in refractive index to fluid (they are nearly invisible) and it is sometimes difficult to identify a solid piece except by absence of tracers.
Figure 3.5. Ranged raw instantaneous velocity vectors in the axial (YZ) plane of CMC solution and 50% cubic solid concentration (8mm) at $3.154 \times 10^{-4} \text{ m}^3/\text{s}$ ($Y$ scale: 1:0.0254m, $Z$ scale: 1:0.05m).
Figure 3.6. Ranged raw instantaneous velocity vectors in the axial (YZ) plane of CMC solution and 30% cylindrical solid concentration (8x8mm) at $1.577 \times 10^{-4}$ m$^3$/s (Frame. Y scale: 1:0.0254m, Z scale: 1:0.05m).
Figure 3.7. Ranged raw instantaneous velocity vectors in the axial (YZ) plane of CMC solution and 30% cylindrical solid concentration (8x8mm) at $1.577 \times 10^{-4}$ m$^3$/s (Frame 2 after 1/4 s, Y scale: 1:0.0254m, Z scale: 1:0.05m).
Figure 3.8. Ranged raw instantaneous velocity vectors in the axial (YZ) plane of CMC solution and 30% cylindrical solid concentration (16x24mm) at $1.577 \times 10^{-4}$ m$^3$/s (Y scale: 1:0.0254m, Z scale: 1:0.05m).
Figure 3.9. Ranged raw instantaneous velocity vectors in cross sectional (XY) plane of CMC solution a) 50% cubic solid concentration (16mm) at $3.154 \times 10^{-4}$ m/s and b) 30% solid concentration of cylindrical particles (8x8mm) at $3.154 \times 10^{-4}$ m/s (X scale: 1:0.0254m, Y scale: 1:0.0254m).
Fig. 3.10 illustrates relative velocities between solid and liquid. It is clear that the relative velocity in the Z direction is dominant. The general trends of the relative velocity between the two phases is presented in tables 3.2 and 3.3 for cubes and cylinders respectively. Tables 3.2 and 3.3 show the highest relative velocity calculated from the difference of the instantaneous maximum velocity vectors of fluid and the solid particle. It must be pointed out again that X, Y and Z coordinates were taken into consideration for finding fluid maximum velocity. The experimentally determined relative velocity values were substituted into one of the available empirical Nusselt number correlations to back calculate \( h_{lp} \) values. The correlations were developed for external flow over a flat plate using eq.1. Tables 3.2 and 3.3 provide values of \( h_{lp} \) at different solid concentrations, flow rates, and solid shapes and sizes.

1. Influence of flow rate

As the flow rate increases the relative velocities values significantly increased (p<0.01, Tables 3.2 and 3.3). The maximum and minimum values of the relative velocity ranged from 0.019 to 0.12 m/s for cubes and 0.0175 to 0.091 for cylinders. Increasing the flow rate from \( 1.577 \times 10^{-4} \text{ m/s} \) to \( 3.154 \times 10^{-4} \text{ m/s} \) at 30% solid concentration of cubes of 8 mm side increased relative velocity and \( h_{lp} \) from 0.027 cm/s and 180.01 \( \text{W/m}^2\text{C} \) to 0.123 cm/s and 193.72 \( \text{W/m}^2\text{C} \) respectively. The same trend has been observed for 50% solid concentration but with lower values (tables 3.2 and 3.3). The rate of increase of relative velocity with the increase of flow rate decreased with the increase of solid concentration (statistically significant, p<0.01).
Figure 3.10. Relative velocity vectors between solid and fluid, a) cube in the axial (YZ) plane, and b) cylinder in (XY) plane at 30% solid concentration (16mm) at $3.154 \times 10^4$ m$^3$/s (Y scale: 1:0.0254m, X scale: 1:0.0254m, and Z scale: 1:0.05m).
Table 3.2. Maximum velocities of solid-liquid phase, relative velocities in Z axis and heat transfer coefficient between cubic particles and liquid mixtures at 1% CMC.

<table>
<thead>
<tr>
<th>Solids</th>
<th>Flow rate</th>
<th>Size (x10^{-4} m)</th>
<th>1.577 x10^{-4} m^3/s</th>
<th>3.154 x10^{-4} m^3/s</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>8x8</td>
<td>16x16</td>
<td>24x24</td>
</tr>
<tr>
<td></td>
<td>V_t (x10^{-2} m/s)</td>
<td>12.55</td>
<td>13.63</td>
<td>16.17</td>
</tr>
<tr>
<td></td>
<td>V_p (x10^{-2} m/s)</td>
<td>9.79</td>
<td>9.29</td>
<td>9.02</td>
</tr>
<tr>
<td>30%</td>
<td>(V_t - V_p) (x10^{-2} m/s)</td>
<td>2.76^a</td>
<td>4.34</td>
<td>7.68</td>
</tr>
<tr>
<td></td>
<td>h_{tp} (W/m^2C)</td>
<td>180.01</td>
<td>139.86</td>
<td>109.00</td>
</tr>
<tr>
<td></td>
<td>V_t (x10^{-2} m/s)</td>
<td>10.75</td>
<td>12.51</td>
<td>13.60</td>
</tr>
<tr>
<td></td>
<td>V_p (x10^{-2} m/s)</td>
<td>8.79</td>
<td>9.04</td>
<td>8.31</td>
</tr>
<tr>
<td>50%</td>
<td>(V_t - V_p) (x10^{-2} m/s)</td>
<td>1.96^b</td>
<td>3.47</td>
<td>5.29</td>
</tr>
<tr>
<td></td>
<td>h_{tp} (W/m^2C)</td>
<td>147.43</td>
<td>122.75</td>
<td>87.70</td>
</tr>
</tbody>
</table>

^a and ^b Values with the same letter are not significantly different (p<0.01)

The increase of flow rate created unbalanced pressure equilibrium with respect to radial location of solids due to the tortuous path created by the random arrangements of solid pieces. This increased rotation of solids; specially cubes (see chapter IV); and therefore, the values of h_{tp} increased.
Table 3.3. Maximum velocities of solid-liquid phase, relative velocities in Z axis and heat transfer coefficient between cylindrical particles and liquid mixtures at 1%CMC.

<table>
<thead>
<tr>
<th>Flow rate</th>
<th>1.577 x10^-4 m^3/s</th>
<th>3.154 x10^-4 m^3/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solids</td>
<td>8x8</td>
<td>8x16</td>
</tr>
<tr>
<td>Size (x10^-4 m)</td>
<td>16x16</td>
<td>16x24</td>
</tr>
<tr>
<td>V_f (x10^-2 m/s)</td>
<td>11.56</td>
<td>13.14</td>
</tr>
<tr>
<td>V_p (x10^-2 m/s)</td>
<td>9.54</td>
<td>8.53</td>
</tr>
<tr>
<td>(V_f - V_p) (x10^-2 m/s)</td>
<td>2.02</td>
<td>4.61</td>
</tr>
<tr>
<td>h_p (W/m°C)</td>
<td>150.05</td>
<td>242.80</td>
</tr>
<tr>
<td>V_f (x10^-2 m/s)</td>
<td>11.21</td>
<td>12.23</td>
</tr>
<tr>
<td>V_p (x10^-2 m/s)</td>
<td>9.46</td>
<td>9.65</td>
</tr>
<tr>
<td>(V_f - V_p) (x10^-2 m/s)</td>
<td>1.75</td>
<td>2.58</td>
</tr>
<tr>
<td>h_p (W/m°C)</td>
<td>138.00</td>
<td>173.07</td>
</tr>
</tbody>
</table>

Values with the same letter are not significantly different (p<0.01)

2. Influence of solid concentration

The solid concentration played an important role in changing the velocity profile to a close to plug flow regime, which decreased the relative velocity. Increasing solid concentration from 30% to 50% decreased relative velocity for all cases and decreased h_p by 20% on average (Tables 3.2 and 3.3). The increase of solid fraction did not enhance h_p dramatically as reported by Mwangi et al. (1992). In their study they used 0%, 1.22% and 3.2% solids which was far less than in our study (30% and 50% solid concentration).
Further, their studies were for a turbulent regime, while the present flows were laminar. Based on these results we can conclude that the disturbance of the flow field around the solid increases with the solid concentration to a certain limit which after most free paths are blocked and disturbance will decrease but does not stop. Eventually, the solid-liquid mixture behavior converges to a plug flow regime. The cross-sectional (XY) plots (Fig 3.9) confirm that the longitudinal dispersion decreases by increasing the solid concentration with 0.01 level of significance. At high concentration of solids (50%), particle interaction increase, with limited possibility for fluid motion. Hence, the relative velocity will decrease.

3. Influence of particle shape

Longitudinal mixing of solids is produced as a consequence of the erratic movement of particles in the tube, especially due to solid to solid and wall to solid interactions. All data showed that cubes considerably affected the interstitial velocity (statistically significant, p<0.01). This phenomenon can be explained by the observation of the continuous flow in our laboratory. As the particles moved, wakes were formed behind them and interactions with other particles occurred. Both phenomena are responsible for the longitudinal mixing. The cubes have the tendency to rotate more than cylinders which will creates mixing and disturbance of the flow. This observation has been observed more often at low solid concentration. During experiments the solid was observed to roll or slide against the wall or interact with other solids thereby decreasing its velocity. The higher ability for cubes to rotate and change coordinates and angles at low solid concentration can be explained by the presence of sharp edges and the packing
of solids in the tube. For cylinders there are no sharp corners. When cylinders are in contact with the wall, the packing of smaller (8mm in diameter and 8mm in length) solids will be higher than for cubes (8mm in side) and this will result in less free space for solids to move. The decrease of free space limits solid rotation, and causes more interactions and collision with the wall. This tends to block the rotation in the three major axes, decreasing the mixing and therefore the interstitial velocity. The two phase flow and the sharp edges of the cubes complicate the configuration of the flow and create small eddies as the fluid flows in torturous paths around the solid matrix. This induces mixing and recirculation (Figs 3.8 and 3.10) of local fluid streams and axial dispersion of the fluid.

4. Influence of particle aspect ratio

The propensity of solid particles to cause mixing will also depend on the aspect ratio. For example, in table 3.3 the cylinders of 8x16mm and 16x24mm caused high relative velocity compared to those of larger volume and unity aspect ratio (p<0.01). The irregularity of solid dimensions have a tendency to cause more mixing but that depends on the alignment of the solid axis with the flow. Based on the observation of the solid-liquid flow, the solid has the tendency to rotate more frequently when the solid axis is perpendicular to the flow, which can be explained since the symmetric flow pattern does not exist in continuous multiphase flow. However, in some cases, particles did not rotate at all even when the axis of the particle (1:2 aspect ratio) was perpendicular to the flow. This happened when other solids surrounded it and prevented movement.

Thus, in general aspect ratio and particle shape are likely to enhance mixing and
might reduce temperature difference; cold and hot spots observed in a static heater by Sastry and Palaniappan (1992); within the fluid. As solid particle in a shear flow will experience hydrodynamic forces which cause pressure non-equilibrium and torques, causing the solid to rotate; this in turn will stir the fluid and promote dispersion. Based on our results the velocity gradients, particle shape, aspect ratio and solid concentration are critical factors for causing mixing.

In continuous flow sterilization and specially for ohmic heating the heating rate can be nearly uniform (Sastry and Palaniappan, 1992) and therefore, the plug flow regime is beneficial since it narrows the residence time distribution. This could avoid overheating of the liquid phase and result in uniform and better quality.

IV. CONCLUSIONS AND RECOMMENDATIONS

Motion pictures have been used in fluid mechanics to provide the basic understanding of phenomena that cannot be obtained from other experimental techniques. The major result of this work is the development of an experimental digital image processing technique to investigate the nature of interstitial fluid motions in multiphase solid-liquid flow. This provides the ability to simultaneously measure spatial and time dependent phenomena using quantitative data. The results showed that the velocity distribution is asymmetric and the typically presumed laminar regime does not apply even at low flow rate. Also, relative velocities exist in all the cases studied and decrease with the increase of the solid concentration and increases with the increase of aspect ratio and
particle size. Increasing the flow rate, decreasing the solid concentration and solid size increased \( h_p \). It is desirable and important to cross-validate such experiments for \( h \) measurement with other techniques like the liquid crystal method (Zitoun and Sastry, 1994) to get accurate results. The disturbance of flow in continuous flow of solid-liquid mixtures yields insight into how the flow field will behave during the process.
REFERENCES


dimensional particle image velocimetry. Preprint, 13th Symposium on Turbulence, University Missouri-Rolla.


CHAPTER IV

SOLID AREA FRACTION DISTRIBUTION OF SOLID-LIQUID
FOOD MIXTURES DURING OHMIC HEATING

ABSTRACT

The solid area fraction distribution within a tube during continuous flow was determined experimentally. Cubes, rectangulers and cylinders (potato and green beans) at volume fraction of 30% and 50% in a 5% agar solution were tested. The flowing mixture was rapidly immobilized by cooling-induced gelation. Samples were then sliced to determine solids area fractions. Results of the solid fraction distribution with respect to the tube and elbow sections showed a normal distribution. Increasing solid concentration flattened the distribution. The solid concentration was the only significant factor that affected both the area and flowing solid volume fraction. Solid volume fraction always was lower than solid area fraction. The aspect ratio and the shape effect were not statistically significant but they had slight effects on the mean and standard deviation. Rectangular solids exhibited lower solid area fraction and flattened the distribution more than cylinders at high solid concentration.
1. INTRODUCTION

Ohmic heating has received considerable recent interest since it shows promise as a continuous sterilization technology for high concentration solid-liquid mixtures. Models developed to simulate ohmic heating of solid-liquid food mixture have assumed that the distribution of cubes in the liquid is uniform. Palaniappan (1991) developed a probability model where the positional distribution of cubes in the incremental section was assumed to be a normal distribution and the particle faces to be parallel to the electrode surface. Using the average length, cross sectional area, and the number of solids, the resistance of the mixture at each position was determined. The effective conductivity of the liquid-solid mixture \( (\sigma_e) \) was then calculated using the total resistance and the dimensions of the incremental section. The program was restricted to cases where the orientation of particle axes was parallel to the applied field. The derivation of the size of the unit cell for spheres in Zhang and Fryer (1995) and the area and the length fractions of discontinuous phase in Sastry and Palaniappan (1992a, b) were based on the volume fraction of that phase, similar to the isotropic Kopelman model (Kopelman, 1966). Kopelman models for thermal conductivities of two component food systems consider only the volume fraction to calculate the area and length fractions of the solid phase.

\[
\begin{align*}
    a) \ A_{sp} &= A v_s^{2/3} \\
    b) \ \Delta x_{sp} &= \Delta x \ v_s^{1/3}
\end{align*}
\]  

Therefore, the effective electrical conductivity of the mixture in the circuit analysis model (Sastry, 1992) was based on the assumption that the solids were evenly distributed.
throughout the fluid. Similar to Sastry, Zhang and Fryer (1995) divided the tube into a number of unit cells, assuming that each unit cell is identical, therefore modeling one would be enough to predict the behavior of the whole.

For a solid-liquid mixture during the ohmic heating process, the behavior of the electric field distribution is a difficult problem, since the electrical conductivity at any location depends on whether that zone is occupied by solid and/or liquid. The cross section of solids through which the current flows depends on their orientation in the processing section. For that reason it is necessary to incorporate the effect of size, shape, and orientation of particles for the accurate determination of the effective electrical conductivity of food systems. Experimental studies of the solid fraction distribution are not available; solid area and volume fraction distribution along a section of the tube and elbow as a function of particle concentration, shape and size ratio needs to be conducted to determine the solid and liquid resistances. Thus, the objective of this study was to determine the distribution of solid area fraction of solid particles in continuous flow with respect to solid concentration, aspect ratio and particle shape.

II. MATERIALS AND METHODS

1. Experimental procedure

The experimental procedure involved immobilization of a flowing solid-liquid mixture by gelation, and then sampling slices of the gelled material to determine solid volume and area fraction distribution. The experimental setup is shown in Fig. 4.1. The liquid was a solution of agar which was prepared in a steam tank at 95°C and then cooled
to 75°C. The liquid was circulated through section (a) without cooling. Once steady-state was achieved, at a selected instant, colored solid particles at 4°C were introduced, and the flow diverted to section (b) so that the residual mixture in section (a) could rapidly be immobilized by cooling with alcohol at -20°C. This procedure ensured nearly instantaneous immobilization followed by quick cooling and eventual freezing of the material. The rapidity of immobilization was separately verified (see details below).

The frozen cylindrical sample produced by this process was sliced into sections at regular intervals. Slices were videotaped and images analyzed to determine the fraction of cross sectional area occupied by solids (see Fig. 4.2). The volume fraction of solids was also determined by weighing the solid phase of the slice and dividing by the density of the solids. Experimental values used in this experiment and setup characteristics are presented in Tables 4.1 and 4.2.

2. Verification of instantaneous immobilization

One preliminary question was whether the immobilization process would be instantaneous, thereby representing the true flowing solids concentration. This was verified in an experiment identical to the one described, except that a transparent test section (a) was used, with water as a coolant (see Fig. 4.3). A videotape of the experiment revealed that the solids were indeed immobilized almost instantly, with no rearrangement thereafter. It was observed that once the flow was stopped, the particles achieved an equilibrium position, and since they were closely packed, any further settling motion was essentially eliminated.
Figure 4.1. Experimental setup for immobilization of solid-liquid food mixture.
Figure 4.2 Slices of solidified solid-liquid mixtures that were used for area fraction measurement at 50% solid concentration (a) and (b) cylindrical particles (8x24mm), (c) cylindrical particles (8x8mm) and (d) rectangular particles (8x24mm).
Table 4.1. Experimental values of system parameters prior to the start of gelation.

<table>
<thead>
<tr>
<th>Material</th>
<th>Particle Type</th>
<th>Mass (Kg)</th>
<th>Temperature °C</th>
<th>Flow rate (m³/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cubic</td>
<td>3.90</td>
<td>5.85</td>
<td>75</td>
</tr>
<tr>
<td></td>
<td>Rectangular</td>
<td>3.90</td>
<td>5.85</td>
<td>75</td>
</tr>
<tr>
<td></td>
<td>Cylindrical</td>
<td>3.90</td>
<td>5.85</td>
<td>75</td>
</tr>
<tr>
<td></td>
<td>Potato</td>
<td>5.85</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Potato</td>
<td>5.85</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Green beans</td>
<td>5.85</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Liquid</td>
<td>Agar solution</td>
<td>11.70</td>
<td>11.70</td>
<td>6.23x10⁻⁴</td>
</tr>
</tbody>
</table>

Table 4.2. Test section and solid dimensions.

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length of the section</td>
<td></td>
</tr>
<tr>
<td>a</td>
<td>0.635m</td>
</tr>
<tr>
<td>b</td>
<td>0.540m</td>
</tr>
<tr>
<td>Inside diameter of tube and elbow</td>
<td>0.508m</td>
</tr>
<tr>
<td>Elbow radius</td>
<td>0.152m</td>
</tr>
<tr>
<td>Size of particles:</td>
<td></td>
</tr>
<tr>
<td>Cubic</td>
<td>0.008m</td>
</tr>
<tr>
<td>Rectangular</td>
<td>0.008x0.024m</td>
</tr>
<tr>
<td>Cylindrical</td>
<td>0.008x0.008m</td>
</tr>
</tbody>
</table>

The choice of particle size was based on those common in canned soups available in the market. Also, we planned to conduct the experiment at higher solid concentrations, but the tank outlet diameter could not accommodate higher concentrations than 50%.
3. Experimental design

The experiments were intended to study the effects of the shape (2 levels), aspect ratio (2 levels) and solid concentration (2 levels). A $2^3$ factorial design in 2 blocks confounded in 2 blocks of 4 runs each as described by Montgomery (1991) was employed (Appendix A, table A.1) to determine the effects of individual factors on solid fraction. To avoid bias, the experimental runs were conducted in a random order. Each run was replicated 3 times in a random order. The levels and coded values of each variable are given in Appendix A, table A.2.

4. Statistical analysis

4.1 Randomness

It was necessary to determine whether the distributions observed were statistical or chaotic in character. A truly random process is one that has no underlying structure (i.e. slope of the curve never saturates for so called “white noise”, which goes up and down in a non-controlled way). It has been found by Feder (1988) that random processes are characterized by Hurst dimension $D_H = 0.5$, while chaotic processes are correlated by $D_H = 0.7$, where:

$$D_H = \frac{2 \ln \left[ \frac{R(\xi)}{\sigma(\xi)} \right]}{\ln \xi} \quad (2)$$

where

$$R(\xi) = Max \chi(t,\xi) - Min \chi(t,\xi) \quad (3)$$
4.2 Distribution

The frequency distribution of the solid area fraction was tested for different distributions. Anderson-Darling and Ryan joiner test for normality available on Minitab (Minitab Inc., State College, PA) were used. If $\alpha > p$, the normality hypothesis was rejected and another test distribution was considered. In particular, the normal distribution was first tested. The probability density function for a standardized normal probability distribution for solid fraction can be expressed as:

$$F(\theta) = \frac{1}{\sqrt{2\pi}} e^{-\frac{(\theta - \mu)^2}{2\sigma^2}}$$

III. RESULTS AND DISCUSSION

Structural properties of solid-liquid mixtures in a static ohmic heater are stagnant and do not change. However, for continuous flow, solid shape, size, concentration and flow rate will affect the location and orientation of solids. Our experimental visualization of cross sections of slices confirms that the distribution is not arranged in regular arrays. The disorder is controlled by the contacts of solids (or interaction) and the space that they have within the tube. For any packing of solids, the space between the solids or free area fraction between particles changes over the tube length.

Instantaneous solid area fractions at various positions along the tube are presented in Figs. 4.3 and 4.4. Fig. 4.5 show data that were generated using a random generator and limiting the data to the range of the data found during the experiment. By comparing these and other figures of our experiment, no special pattern was observed. All the
instantaneous solid area and volume fraction plots in a straight tube were similar to white noise, with $D_\eta$ being around 0.5 in all cases. Thus, it was concluded that our data exhibited truly random variation.

Tables 4.3, 4.4, 4.6 and 6.7 present the solid area and volume fraction distribution as influenced by process parameters in the tube and the elbow. In all cases, the solid area and volume fractions were found to be normally distributed.

![Figure 4.3](image)

Figure 4.3. Experimental instantaneous solid area fraction distribution along the tube length for cubes of 8mm in side and 30% solid concentration.
Figure 4.4. Instantaneous solid area and volume fraction distributions for cylinders (8x24mm in size and 50% solid concentration) along the tube length.

Figure 4.5. Random generated instantaneous solid area fraction distribution along the tube length.
### Table 4.3. Solid area fraction distribution ($\alpha_r$) characteristics as influenced by aspect ratio, shape and solid concentration in the tube.

<table>
<thead>
<tr>
<th>Solid Concentration</th>
<th>Shape</th>
<th>Aspect Ratio</th>
<th>Mean of $\alpha_r$</th>
<th>SD of $\alpha_r$</th>
<th>Distribution Characteristics</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>30%</td>
<td>cylinders</td>
<td>1</td>
<td>0.268</td>
<td>0.059</td>
<td>Normal</td>
<td>0.257</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>0.267</td>
<td>0.066</td>
<td>Normal</td>
<td>0.635</td>
</tr>
<tr>
<td></td>
<td>cubes</td>
<td>1</td>
<td>0.277</td>
<td>0.090</td>
<td>Normal</td>
<td>0.582</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>0.250</td>
<td>0.071</td>
<td>Normal</td>
<td>0.910</td>
</tr>
<tr>
<td>50%</td>
<td>cylinders</td>
<td>1</td>
<td>0.378</td>
<td>0.089</td>
<td>Normal</td>
<td>0.230</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>0.337</td>
<td>0.081</td>
<td>Normal</td>
<td>0.339</td>
</tr>
<tr>
<td></td>
<td>cubes</td>
<td>1</td>
<td>0.380</td>
<td>0.071</td>
<td>Normal</td>
<td>0.809</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>0.329</td>
<td>0.098</td>
<td>Normal</td>
<td>0.395</td>
</tr>
</tbody>
</table>

### Table 4.4. Solid volume fraction ($\nu_f$) distribution characteristics as influenced by aspect ratio, shape and solid concentration in the tube.

<table>
<thead>
<tr>
<th>Solid Concentration</th>
<th>Shape</th>
<th>Aspect Ratio</th>
<th>Mean of $\nu_f$</th>
<th>SD of $\nu_f$</th>
<th>Distribution Characteristics</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>30%</td>
<td>cylinders</td>
<td>1</td>
<td>0.243</td>
<td>0.047</td>
<td>Normal</td>
<td>0.084</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>0.250</td>
<td>0.058</td>
<td>Normal</td>
<td>0.809</td>
</tr>
<tr>
<td></td>
<td>cubes</td>
<td>1</td>
<td>0.244</td>
<td>0.051</td>
<td>Normal</td>
<td>0.755</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>0.234</td>
<td>0.059</td>
<td>Normal</td>
<td>0.287</td>
</tr>
<tr>
<td>50%</td>
<td>cylinders</td>
<td>1</td>
<td>0.300</td>
<td>0.065</td>
<td>Normal</td>
<td>0.838</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>0.284</td>
<td>0.060</td>
<td>Normal</td>
<td>0.809</td>
</tr>
<tr>
<td></td>
<td>cubes</td>
<td>1</td>
<td>0.302</td>
<td>0.056</td>
<td>Normal</td>
<td>0.690</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>0.313</td>
<td>0.084</td>
<td>Normal</td>
<td>0.886</td>
</tr>
</tbody>
</table>
1. Tube Section:

1.1 Concentration effect on solid fraction:

Increasing of concentration flattened the distribution which increased the standard deviation in most cases (figs. 4.6 and 4.7). This is valid only for continuous flow because under static conditions, the increase of solid concentration should narrow the distribution due to lack of displacement or rotation of solids.

1.2 Influence of aspect ratio

The aspect ratio did not significantly affect the solid area and the solid volume fraction distributions for both shapes (cylinders and cubes) at 30% and 50% solid concentrations. Even though the effect is not statistically significant we noticed that at higher solid concentration (50%), the increase of aspect ratio decreased the solid area fraction for both shapes (cylinders and cubes), (Tables 4.3 and 4.5). This phenomenon is due to solid arrangement in the tube. High aspect ratio (1:3) particles have a tendency to align along their length (Fig. 4.2 b and c) but any misalignment will affect other solids by restricting their motion to fill the neighboring free space. This results in a decrease of the packing of solids and therefore decrease the solid area fraction. However, for 1:1 aspect ratio the solids can fill open spaces more freely than 1:3 aspect ratio (see Fig. 4.2c as compared to 4.2a). The rate of increase of the solid area fraction from 30% to 50% was lower for 1:3 aspect ratio compared to 1:1 aspect ratio, and was almost constant for the solid volume fraction for both shapes (see Fig.4.8 and 4.9). This observation indicates that there is more interaction at 1:3 aspect ratio with the wall and between the particles.
Figure 4.6. Distribution of solid area fraction for cubes and rectangular shapes in a straight tube (CU: cubes or rectangular shapes, 8x8mm or 8x24mm in size, LC: 30% solid concentration and HC: 50% solid concentration).

Figure 4.7. Distribution of solid area fraction for cylinders in a straight tube (C: cylinders, 8x8mm or 8x24mm in size, LC: 30% solid concentration and HC: 50% solid concentration).
Figure 4.8. Distribution of solid volume fraction for cubes and rectangular shapes in a straight tube (CU: cubes or rectangular shapes, 8x8mm or 8x24mm in size, LC: 30% solid concentration and HC: 50% solid concentration).

Figure 4.9. Distribution of solid volume fraction for cylinders in a straight tube (C: cylinders, 8x8mm or 8x24mm in size, LC: 30% solid concentration and HC: 50% solid concentration).
An example of aligned and non-aligned particles within a straight tube in static conditions is presented in Fig. 4.10. It shows that the aspect ratio variation of solids does not affect the solid area fraction when we compare cross sections AA and CC and volume fraction when we compare volume cross sections AABB and CCDD for the case of aligned particles. However, for non-aligned solids aspect ratio will affect the solid area fraction more significantly (Fig. 4.10, cross sections EE, FF, GG and HH) than solid volume fraction (Fig. 4.10, volume cross sections EEFF and GGHH). By comparing the maximum of the solid area fraction of 1:1 aspect ratio and 1:3 aspect ratio cases, we found that 1:1 aspect ratio gave a higher solid area fraction than 1:3 aspect ratio for both shapes (Fig. 4.6 through 4.9) and the difference between them can be explained by the combination of aligned and non-aligned particles at 1:3 aspect ratio. This observation was not the case for the solid volume fraction. These values were close since the distribution is narrower than the distribution of solid area fraction (lower standard deviation). Fig. 4.11, a comparison of solid area and volume fractions, reveals that for cylinders, the distribution of 1:1 aspect ratio and 1:3 aspect ratio almost overlap except for a flatter peak (negative Kurtosis value) which agrees with what we mentioned earlier about the existence of flowing aligned particles like what was shown in Fig. 4.2b and c. Comparison between the mean values (Tables 4.3 and 4.5) for cylinders and rectangular shapes at a constant aspect ratio shows that solid area fraction always gives higher values than solid volume fraction.
Figure 4.10. Aligned (a) and non-aligned (b) solids within a tube and their influence on solid area and volume fraction.

Figure 4.11. Distribution of solid area and volume fraction for cylinders in a straight tube (C: cylinders, 8x8mm or 8x24mm in size, LC: 30% solid concentration and HC: 50% solid concentration).
This average value observation were different from what was presented in Fig. 4.4 where we noticed that there were fluctuations from one slice to another and within the slice itself. These fluctuations suggest that the flow is not consistent and the solids flow in blocks of high and low solid concentration. A correlation between solid area and solid volume fractions has been determined (see Fig. 4.12). The Kopelman model hypothesis was rejected at 95% level of confidence based on our experimental data. It should be noted that, unlike the Kopelman model assumption, there was no slice without the presence of a solid phase. The experimental correlation is presented in eq. 5.

\[ A_{sp} = A (0.528) v_{sp}^{0.571} \quad r^2 = 0.883 \]  

(5)

1.3 Influence of particle shape

Rectangular particles have lower number of particles to fill than cylinders and therefore lower area fraction regardless of the dead space that exists between cylinders in contact (see details below). The effect of shape is not statistically significant on the solid area and volume fraction distributions, but rectangular shapes flatten the distribution more compared to cylinders, and this effect is more pronounced at high solid fraction (Fig. 4.13).

The number of solids and the solid area fraction are dependent on the shape of particles. For a static condition and ordered particle configuration, cylinders always give a higher solid area fraction than cubic particles, as can be proven mathematically. For cylinders the highest number occurs when solids are arranged around the circumference (see Fig. 4.14) as in eq. 6.
Figure 4.12. Experimental solid area and volume fractions.

Figure 4.13. Distribution of solid area fraction for cylinders and rectangular shapes in a straight tube (CU: cubes or rectangular shapes, C: cylinders, 8x24mm in size, LC: 30% solid concentration and HC: 50% solid concentration).
Schematic location of cylinders for maximum solid area fraction

For cubes, the highest number was found when we arranged solids in a square box with additional solids being added in the periphery (Fig. 4.15). The number of particles was found as:

\[ N_{M,xy} = 1 + \pi \sum_{m=0}^{M} \text{Int} \left[ \frac{(D-(2m+1)d)}{d} \right] \text{ if } (R - md) > \frac{d}{2} \]

\[ N_{M,xy} = \pi \sum_{m=0}^{M} \text{Int} \left[ \frac{(D-(2m+d)d)}{d} \right] \text{ if } (R - md) < \frac{d}{2} \]
Figure 4.15. Schematic location of cubes for maximum solid area fraction.
However, for continuous flow of solid-liquid mixtures as in our study, solid area fraction of both shapes were not significantly different and sometimes cubes even showed higher solid area fraction than cylinders. The sharp edges of rectangular shapes increased the standard deviation since they increased the probability of blocking free space compared to the absence of sharp edges for cylinders. It is obvious that for cubes adjacent to the wall there will be a region of relatively low solid area fraction due to the discrepancy between the radii of curvature of the wall and the solids. The wall decreased the overall solid area fraction due to the increase in local liquid surface area in the region near the wall. This has been observed in slices of the solidified mixtures (Fig. 4.2d). Thus interaction of solids to the wall and solids to solids have a great impact on the flow behavior, and specifically on solid area fraction.

Table 4.5 Theoretical maximum solid area fraction of cubes, rectangular and cylindrical particles.

<table>
<thead>
<tr>
<th>Cubes size (x10⁻³ m)</th>
<th>Cylinders diameter (x10⁻³ m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8x8 16x16 24x24</td>
<td>8x8 16x16 24x24</td>
</tr>
<tr>
<td>Number of particles</td>
<td>20 4 1</td>
</tr>
<tr>
<td>Solid area fraction</td>
<td>0.631 0.505 0.284</td>
</tr>
</tbody>
</table>

2. Elbow section:

From Figs. 4.16 and 4.17 the increase of concentration flattens the distribution in solid area fraction. Tables 4.6 and 4.7 reveal that the solid area fraction is always a higher
Figure 4.16. Distribution of solid volume fraction for cylinders in elbow (C: cylinders, 8x8mm or 8x24mm in size, LC: 30% solid concentration and HC: 50% solid concentration).

Figure 4.17. Distribution of solid volume fraction for cubes and rectangular shapes in elbow (CU: cubes or rectangular shapes, 8x8mm or 8x24mm in size, LC: 30% solid concentration and HC: 50% solid concentration)
Table 4.6. Solid area fraction ($\alpha_f$) distribution characteristics as influenced by aspect ratio, shape and solid concentration in the elbow.

<table>
<thead>
<tr>
<th>Solid Concentration</th>
<th>Shape</th>
<th>Aspect Ratio</th>
<th>Mean of $\alpha_f$</th>
<th>SD of $\alpha_f$</th>
<th>Distribution Characteristics</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>30%</td>
<td>cylinders</td>
<td>1</td>
<td>0.255</td>
<td>0.076</td>
<td>Normal</td>
<td>0.951</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>0.275</td>
<td>0.053</td>
<td>Normal</td>
<td>0.641</td>
</tr>
<tr>
<td></td>
<td>cubes</td>
<td>1</td>
<td>0.274</td>
<td>0.085</td>
<td>Normal</td>
<td>0.325</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>0.235</td>
<td>0.038</td>
<td>Normal</td>
<td>0.671</td>
</tr>
<tr>
<td>50%</td>
<td>cylinders</td>
<td>1</td>
<td>0.376</td>
<td>0.092</td>
<td>Normal</td>
<td>0.264</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>0.325</td>
<td>0.070</td>
<td>Normal</td>
<td>0.233</td>
</tr>
<tr>
<td></td>
<td>cubes</td>
<td>1</td>
<td>0.347</td>
<td>0.090</td>
<td>Normal</td>
<td>0.914</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>0.343</td>
<td>0.075</td>
<td>Normal</td>
<td>0.901</td>
</tr>
</tbody>
</table>

Table 4.7. Solid volume fraction ($\nu_f$) distribution characteristics as influenced by aspect ratio, shape and solid concentration in the elbow.

<table>
<thead>
<tr>
<th>Solid Concentration</th>
<th>Shape</th>
<th>Aspect Ratio</th>
<th>Mean of $\nu_f$</th>
<th>SD of $\nu_f$</th>
<th>Distribution Characteristics</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>30%</td>
<td>cylinders</td>
<td>1</td>
<td>0.235</td>
<td>0.044</td>
<td>Normal</td>
<td>0.601</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>0.233</td>
<td>0.056</td>
<td>Normal</td>
<td>0.314</td>
</tr>
<tr>
<td></td>
<td>cubes</td>
<td>1</td>
<td>0.241</td>
<td>0.052</td>
<td>Normal</td>
<td>0.152</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>0.206</td>
<td>0.027</td>
<td>Normal</td>
<td>0.868</td>
</tr>
<tr>
<td>50%</td>
<td>cylinders</td>
<td>1</td>
<td>0.351</td>
<td>0.092</td>
<td>Normal</td>
<td>0.894</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>0.301</td>
<td>0.046</td>
<td>Normal</td>
<td>0.287</td>
</tr>
<tr>
<td></td>
<td>Cubes</td>
<td>1</td>
<td>0.304</td>
<td>0.061</td>
<td>Normal</td>
<td>0.364</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>0.323</td>
<td>0.093</td>
<td>Normal</td>
<td>0.929</td>
</tr>
</tbody>
</table>
value than volume fraction which is similar to straight tube findings. The data in these plots (Figs. 4.16 through 4.21) are not as dense as for the straight tube, since the number of slices obtainable from the elbow was relatively low because of its relatively short dimension. Qualitative measurement of the shape is not enough to make conclusions on the distribution even though it looks like it appeared to be converging to a normal distribution. In Figs. 4.18 and 4.19 we found that there was no trend for solid shape and aspect ratio which was different from the straight tube section. The plots of solid area and volume fractions do not overlap due to the mixing effect which disturbed the flow behavior and resulted in variations from one slice to another (Fig. 4.20). The curvature of the elbow appeared to have changed the behavior of the flow. Most of the particles were dispersed everywhere only few cases of sufficiently low local concentration were thrown outwards (see Fig. 4.21c). The centrifugal force did not have a great impact on the solids possibly due to the flow rate \(6.23 \times 10^{-4} \text{ m}^3/\text{s}\) which resulted in low Reynolds number (39.8). The secondary flow created more mixing within the section which balanced the differences that exist in the elbow.
Figure 4.18. Distribution of solid area fraction for cubes and rectangular shapes in elbow (CU: cubes or rectangular shapes, 8x8mm or 8x24mm in size, LC: 30% solid concentration and HC: 50% solid concentration).

Figure 4.19. Distribution of solid area fraction for cylinders in elbow (C: cylinders, 8x8mm or 8x24mm in size, LC: 30% solid concentration and HC: 50% solid concentration).
Figure 4.20. Instantaneous solid area and volume fraction of cylinders (8x24mm in size and 30% solid concentration) in the elbow.
Figure 4.21. Slices of solidified solid-liquid mixtures (in an elbow) that have been used for area fraction measurement at 50% solid concentration (a) and (b) cylinders 8x24mm and 8x8 mm respectively, c) and (d) cubes 8x24mm and 8x8mm respectively.
IV. CONCLUSIONS AND RECOMMENDATIONS

Solid area and volume fractions in the straight tube were normally distributed. The solid area and volume fraction distribution in the elbow was not as clear as for the straight flowing tube case. The increase of solid concentration flattened the distribution. The solid concentration was the only significant factor that affects both the area and flowing volume solid fraction. The aspect ratio and the shape effect were not statistically significant but they make slight changes on the mean and standard deviation. The increase of aspect ratio decreases the solid area fraction for both shapes. High aspect ratio solids have a tendency to align with the flow. Rectangular solids gave lower solid area fraction and flattened the distribution more than cylinders at high solid concentration. More interactions have been observed for the case of rectangular shape because of their sharp edges.

The next step will focus on incorporating the distribution found in this study to determine the effect on the heating rate and what difference it will make compared to the uniform solid area fraction assumption published by previous studies.
**NOMENCLATURE**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A$</td>
<td>Tube cross sectional area ($m^2$)</td>
</tr>
<tr>
<td>$cu$</td>
<td>Cubic particle</td>
</tr>
<tr>
<td>$cyl$</td>
<td>Cylindrical particle</td>
</tr>
<tr>
<td>$D$</td>
<td>Diameter of the tube (m)</td>
</tr>
<tr>
<td>$d$</td>
<td>Particle diameter (m)</td>
</tr>
<tr>
<td>$D_h$</td>
<td>Hurst dimension</td>
</tr>
<tr>
<td>$\text{Int}(x)$</td>
<td>Integer function</td>
</tr>
<tr>
<td>$L$</td>
<td>Length of the side of the box (m)</td>
</tr>
<tr>
<td>$m$</td>
<td>Number of layers</td>
</tr>
<tr>
<td>$M$</td>
<td>Integer number</td>
</tr>
<tr>
<td>$N$</td>
<td>Number of particles</td>
</tr>
<tr>
<td>$p$</td>
<td>Smallest level of significance at which hypothesis can be rejected.</td>
</tr>
<tr>
<td>$O$</td>
<td>Origin of the circle</td>
</tr>
<tr>
<td>$R$</td>
<td>Tube radius</td>
</tr>
<tr>
<td>$R(\xi)$</td>
<td>Difference between the maximum and minimum value of $\chi(t,\xi)$</td>
</tr>
<tr>
<td>$S$</td>
<td>Side of the cube</td>
</tr>
<tr>
<td>$x$</td>
<td>Length of the slice</td>
</tr>
<tr>
<td>$\chi(t,\xi)$</td>
<td>Cumulative temporal variation</td>
</tr>
<tr>
<td>$\xi$</td>
<td>Record of length</td>
</tr>
<tr>
<td>$\sigma(\xi)$</td>
<td>Standard deviation</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>Standard deviation</td>
</tr>
</tbody>
</table>
\( \sigma_e \)  Effective electrical conductivity
\( \alpha \)  Level of significance
\( \alpha_i \)  Area fraction
\( \nu \)  Volume fraction
\( \theta \)  Mean value
\( \theta_i \)  Measured values

**Subscripts:**

\( f \)  Fluid
\( i \)  index
\( lp \)  Liquid phase
\( sp \)  Solid phase
REFERENCES


CHAPTER V

ROTATION BEHAVIOR OF SOLID PARTICLES DURING CONTINUOUS TUBE FLOW

ABSTRACT

Rotation of solids in continuous flow of solid-liquid mixtures is an important parameter affecting fluid mixing, and serves to reduce the temperature difference between the two phases. In this study, solid rotation behavior was investigated experimentally using the principle of Eulerian angles and direction cosine matrices. Cubic and cylindrical particles at 30% and 50% solid concentration were used to determine rotation behavior in continuous tube flow. The results of this study show that some mixing occurs during continuous flow which decreases with an increase of solid fraction and particle to tube size ratio.
I. INTRODUCTION

Heating uniformity of solid-liquid mixtures is related to temperature gradient between the two phases. Viscosity, liquid and solid electrical conductivities and orientation are important factors controlling the uniformity of the temperature distribution of solid-liquid food mixtures in ohmic heating. Rotation of solids is also an important factor affecting fluid mixing. High carrier viscosities for solid-liquid mixtures are necessary to entrain solids but they have an adverse impact on heat transfer since they do not readily transfer energy. Therefore, rotation is useful in continuous conventional aseptic processing since it minimizes temperature differences between phases. Also mixing has been identified as an advantage in ohmic heating using high viscosity fluids, when the solid and liquid phases are of different electrical conductivities. Khalaf and Sastry (1996) found that increasing of viscosities increased heating rates in vibrating and continuous ohmic heaters. However, increasing viscosities may also increase temperature non-uniformity, thus mixing behavior is important.

Åström and Bark (1994) determined the fluid to particle heat transfer coefficient ($h_{fp}$) of a cube immersed in the center of a rotating vessel of 200 mm diameter. Rotation at 60 rpm provided continuous motion and disturbance of flow surrounding the solids which resulted in $h_{fp}$ value higher by 15-30% than for a stationary particle. However, this was not observed for spheres which may be due to the absence of edges of the spherical surface compared to the cube. Placing the solid object close to the wall of the rotating vessel improved the heat transfer coefficient (eccentric rotation). Baptista et al. (1996) measured $h_{fp}$ by rotating a sphere in a stationary tank, and found that $h_{fp}$ increases with the
relative rotation and the relative velocity between the solid and the liquid when the solid is close to the wall. Balasubramaniam and Sastry (1996) studied the effect of rotational speed in a scraped heat exchanger and found that the increase of mutator speed enhanced the heat transfer between the fluid and the solid due to the fluid agitation and mixing. Zitoun and Sastry (1994a,b) found that $h_p$ for a cube under a laminar regime increased when the cube was away from the center of the tube. They explained this result based on the parabolic velocity profile. When the solid is away from the tube axis, it experiences torques that cause rotation. This phenomenon appears to be especially pronounced for solids with sharp edges like cubes which continuously renew the flow in contact with the solid.

No experimental studies have been conducted on rotation behavior during continuous flow of solid-liquid mixtures involving large solid concentrations. It is therefore of interest to determine the rotation behavior of particles to understand the extent of mixing of solids. Therefore the goal of this study was to determine the rotation of solids during continuous flow of solid-liquid mixture.

II. MATERIALS AND METHODS

1. Experimental procedure

The setup used in this experiment is presented in Fig. 5.1. The fluid-solid mixture was conveyed by air pressure from the inlet. Fig. 5.2 shows the coordinate system used for data analysis, with the respective angles of rotation about each axis. The steps of the experiment are outlined in Fig. 5.3 and consist of the following: The flow of the solid
Fig. 5.1 Experimental setup.
Figure 5.2 Reference frame.
Figure 5.3 Steps of the experiment.
liquid mixtures was videotaped using a S-VHS camera and a S-VHS video recorder. To clearly image the rotation, solids had each face coated with a different color. Frames were grabbed and digitized onto a computer using a board power grabber (ATVista, Truevision Inc., Indianapolis, IN). Determination of the coordinates of the solids (3 points) from left and right views for each frame were obtained using a commercial image processing software (Image-Pro, Media Cybernetics, Silver Spring, MD). Transformation of the data from image scale to real scale was conducted based on an in-situ calibration performed prior to the experiment (details are presented in chapter II), then stereomatching of the left and right views was performed to obtain the real x, y, and z coordinates of the solid pieces. A computer program was written to find the angle \( \theta, \psi \), and \( \phi \) based on the coordinates of the solids.

The data analysis consisted of determining angular velocity. For this we determined \( \theta, \psi \), and \( \phi \) and time by finding three non-collinear unit vectors fixed on the solid particle when it moved with respect to a reference (camera axis) and time, and then using the principle of Eulerian angles (Fig. 5.4) as detailed below.

In this study the view of the volume of interest was enlarged compared to the Particle Tracking Velocimetry (PTV) method (presented in chapter II) to sample a larger volume section. We were interested in measuring the rotation of particles for a longer period of time than in the PTV experiments.

The experiment was conducted at two levels of flow rates \( 1.577 \times 10^{-4} \) m\(^3\)/s and \( 3.154 \times 10^{-4} \) m\(^3\)/s, solid concentration 30% and 50% and 5 replications for each run. The solid characteristics are presented in table 5.1.
Figure 5.4. Euler angle definition: a) rotation about the z axis, b) rotation about y axis and c) rotation about x axis.
In this study the Reynolds number was 9.4 and 26 at flow rate of $1.577 \times 10^{-4}$ m$^3$/s and $3.154 \times 10^{-4}$ m$^3$/s. The constants obtained for $K$ and $n$ were 1.31 Pa$^n$s and 0.53 respectively.

2. Eulerian angles

The most common form of space orientation variables are the Euler angles. They have been used in this section to define particle orientation in a tube flow. They are defined to be three sequential rotations about a cartesian axis system (see Fig. 5.4) as follows:

1) A positive rotation $\psi$ about the $z$ axis, yielding axes $x'y'z$

2) A positive rotation $\theta$ about the new $y'$ axis, yielding axes $x''y'z'$

3) A positive rotation $\phi$ about the new $x''$ axis, yielding axes $x''y''z''$

Considering the matrix equations which indicate the individual rotations that are performed in going from the original $xyz$ system to the final $x''y''z''$ system; we obtain the following Eq. 1 (Greenwood, 1988).
where the Euler angles are limited to the ranges
\[-\pi/2 \leq \theta \leq \pi/2\]
\[0 \leq \phi < 2\pi\]
\[0 \leq \psi < 2\pi\]

2.1. Displacement of solid particle

In studying the possible displacements of a solid particle in tube flow, we can expect rotation and translation of the rigid body. The general displacement of a solid particle can be described as the superposition of the translational displacement of an arbitrary base point fixed in the particle plus a rotational displacement about an axis through that base point. Since the translational displacement does not change the orientation of the particle, and the rotational displacement does not change the location of the base point, it follows that the two portions of the total displacement can be performed in either order, even simultaneously. We can transform coordinates from the axis of the solid particle to the axis of reference, as follows:

2.2. Transformation of coordinates

At a time \(t\) considering a vector \(\mathbf{\bar{r}}\) in space from \(O\) to \(O'\) (see Fig. 5.5) can be represented in either of the frames as:

\[
\begin{align*}
\mathbf{x}' & = \begin{bmatrix} \cos\psi \cos\theta & \sin\psi \cos\theta & \sin\theta \end{bmatrix} \mathbf{x} \\
\mathbf{y}' & = \begin{bmatrix} \sin\psi \cos\phi + \cos\psi \sin\theta \sin\phi \cos\theta \sin\phi & \cos\psi \cos\phi + \sin\psi \sin\theta \sin\phi \cos\theta \sin\phi \cos\theta \sin\phi \end{bmatrix} \mathbf{y} \\
\mathbf{z}' & = \begin{bmatrix} \sin\psi \sin\phi - \cos\phi \sin\theta \cos\phi \cos(\theta \sin\phi) & -\cos\psi \sin\phi - \sin\psi \sin\theta \cos\phi \cos(\theta \sin\phi) \end{bmatrix} \mathbf{z}
\end{align*}
\]
Figure 5.5. Rotation and translation of reference frame.
To establish this relation, the \( \vec{f}, \vec{g}, \) and \( \vec{h} \) unit vectors are expanded in terms of the \( \vec{i}, \vec{j}, \) and \( \vec{k} \) unit vectors as:

\[
\begin{align*}
\vec{f} &= a_{11} \vec{i} + a_{21} \vec{j} + a_{31} \vec{k} \\
\vec{g} &= a_{12} \vec{i} + a_{22} \vec{j} + a_{32} \vec{k} \\
\vec{h} &= a_{13} \vec{i} + a_{23} \vec{j} + a_{33} \vec{k}
\end{align*}
\]

(3)

where,

\[
\begin{align*}
a_{11} &= \vec{i} \cdot \vec{f} = \cos \theta (\vec{i}, \vec{f}) \\
a_{12} &= \vec{i} \cdot \vec{g} = \cos \theta (\vec{i}, \vec{g}) \\
a_{13} &= \vec{i} \cdot \vec{h} = \cos \theta (\vec{i}, \vec{h}) \\
a_{21} &= \vec{j} \cdot \vec{f} = \cos \theta (\vec{j}, \vec{f}) \\
a_{22} &= \vec{j} \cdot \vec{g} = \cos \theta (\vec{j}, \vec{g}) \\
a_{23} &= \vec{j} \cdot \vec{h} = \cos \theta (\vec{j}, \vec{h}) \\
a_{31} &= \vec{k} \cdot \vec{f} = \cos \theta (\vec{k}, \vec{f}) \\
a_{32} &= \vec{k} \cdot \vec{g} = \cos \theta (\vec{k}, \vec{g}) \\
a_{33} &= \vec{k} \cdot \vec{h} = \cos \theta (\vec{k}, \vec{h})
\end{align*}
\]

(4)

substituting eq. 3 into eq. 2 yields

\[
\begin{align*}
\vec{S} &= (a_{11} S_x + a_{12} S_y + a_{13} S_z) \vec{i} \\
&+ (a_{21} S_x + a_{22} S_y + a_{23} S_z) \vec{j} \\
&+ (a_{31} S_x + a_{32} S_y + a_{33} S_z) \vec{k}
\end{align*}
\]

(5)
Equating the right sides of eq. 5 and eq. 2

\[
S_x = a_{11} S_{x'} + a_{12} S_{y'} + a_{13} S_{z'} \\
S_y = a_{21} S_{x'} + a_{22} S_{y'} + a_{23} S_{z'} \\
S_z = a_{31} S_{x'} + a_{32} S_{y'} + a_{33} S_{z'}
\]

(6)

\[
S = A S'
\]

(7)

where \( A \) is called the direction cosine matrix, whose entries are defined in equation 4.

\[
A = \begin{bmatrix}
  a_{11} & a_{12} & a_{13} \\
  a_{21} & a_{22} & a_{23} \\
  a_{31} & a_{32} & a_{33}
\end{bmatrix}
\]

(8)

As the body moves and rotates in space (flow in a tube) a point \( P \) that is fixed to the body is located in the stationary \( x-y-z \) reference by vector \( \mathbf{S}^0(t) \), which varies with time. Clearly, the vector \( \mathbf{S} \) in Fig. 5.5 depends on time, since it locates the origin \( O' \) of the \( x'-y'-z' \) frame as the solid body moves. Finally, the orientation which is defined relative to the fixed \( x-y-z \) frame, changes in time and is defined by the direction cosine matrix \( A(t) \), which must be a function of time. Since vectors \( \mathbf{S}^p \) and \( \mathbf{S}^q \) do not change with time, the same vector \( \mathbf{S}(t) \) and matrix \( A(t) \) define the position and orientation of the solid as it flows through the tube.

**2.3. Data analysis**

The analysis of experimental results was based on the absolute rotation rate of the particle. Based on Eulerian angles the angular velocity \( \omega \) of the particle can be
expressed in terms of the time derivatives of these angles except for the case where $\theta = \pm \pi/2$. The rotation rate about $x$, $y$ and $z$ axes can be expressed as follows (Greenwood, 1988):

$$
\begin{align*}
\omega_x &= \dot{\phi} - \psi \sin \theta \\
\omega_y &= \dot{\theta} \cos \phi + \psi \cos \theta \sin \phi \\
\omega_z &= \psi \cos \theta \cos \phi - \dot{\theta} \sin \theta
\end{align*}
$$

(9)

where $\theta$, $\psi$, and $\phi$ after angular velocity vectors.

Based on Eq. 9 angular velocities in $x$, $y$ and $z$ directions requires information $\theta$, $\psi$, and $\phi$ and time. Using Euler principle we need to determine only three non collinear fixed points (see Fig. 5.6) in the same plane of a solid to get two vectors $\vec{V}_1$ and $\vec{V}_2$ (Eq. 10).

$$
\vec{V}_1 = \begin{pmatrix}
    x_2 - x_1 \\
    y_2 - y_1 \\
    z_2 - z_1
\end{pmatrix} \quad \vec{V}_2 = \begin{pmatrix}
    x_3 - x_1 \\
    y_3 - y_1 \\
    z_3 - z_1
\end{pmatrix}
$$

(10)

where,

$$
\begin{align*}
x_2 - x_1 &= a_{11} & x_3 - x_1 &= a_{21} \\
y_2 - y_1 &= a_{12} & y_3 - y_1 &= a_{22} \\
z_2 - z_1 &= a_{13} & z_3 - z_1 &= a_{23}
\end{align*}
$$

(11)
Figure 5.6. Points of measurement a) Cube and b) Cylinder (side view).

The third vector $V_3$ is obtained by the cross product of $V_1$ and $V_2$. The coordinates of $V_3$ are:

$$
\begin{align*}
    a_{13} &= a_{21} a_{32} - a_{31} a_{22} \\
    a_{23} &= a_{31} a_{12} - a_{11} a_{32} \\
    a_{33} &= a_{11} a_{22} - a_{21} a_{12}
\end{align*}
$$

All vectors should be normalized. A computer program (see appendix B) has been developed to find the angles by solving Eq. 1. As mentioned earlier, in order to differentiate between the faces each face was coated with a different color.

4) Rheological properties of fluid

The non-Newtonian carrier fluids used were aqueous solutions of carboxymethyl cellulose (CMC). The values of $K$ and $n$ were determined by using a coaxial cylinder
viscometer (Rheomat Model 115; Contraves Industrial Division; Cincinnati, OH). Results were analyzed based on the Ostwald-de-Waele power law model ($\tau = K \gamma^n$). The values of $K$ and $n$ were obtained using a non-linear model program (Systat 1993, Systat, Inc.; Evanston, IL).

III. RESULTS AND DISCUSSION

1. Effect of flow rate

Increasing the flow rate from $1.577 \times 10^4$ and $3.154 \times 10^4$ m$^3$/s caused increasing flow disturbance. Even though the regime still was laminar we noticed a significant increase ($p<0.01$) of rotation from zero to a maximum value of 2.116 rad/s. Tables 5.2 through 5.4 summarize the angular velocity in continuous flow at 30% and 50% solid concentration of cubes and cylinders. Higher torques may have been created by increasing Reynolds number from 9.4 to 26. Fig 5.7 illustrates the increase of flow rate on rotation behavior on cubes. Rotation about the $x$ and $y$ axes had the highest values compared to the $z$ axis. The dominance of rotation around $x$ and $y$ axes caused changes of the cross sectional area perpendicular to the electrical field which would be expected to change the effective mixture resistance (Sastry and Palaniappan, 1992).

2. Effect of size and aspect ratios

Decreasing tube to solid size ratio decreased ($p<0.01$) the rotation about all axes for both shapes. From tables 5.2 through 5.4 we can conclude that the decrease of tube to solid size ratio decreased the rotation apparently due to increased interactions with the wall and with other solids. This phenomenon is due to solid arrangement in the tube. Also
increasing cylinder aspect ratio decreased (p<0.01) the rotation due to their tendency to align with the flow as discussed in chapter IV. High aspect ratio (1:3) solids have a tendency to align along their length (chapter IV) but if any misalignment occurs, these solids will have higher chance to rotate than low aspect ratio solids due to fluid-induced torque. In this study we found that solid size ratio had similar effects as did the tube to solid ratio. The increase of both ratios decreased the rotation (Fig. 5.8).

3. Effect of solid concentration

Rotation of solid particles decreased (p<0.01) with an increase of solid fraction from 30% to 50% (see Tables 5.2 through 5.4 and Fig. 5.9). The increase of solid concentration increased the interactions between solids and decreased the free...
space available for free motion.

4. Effect of solid shape

The effect of shape on the rotation behavior was statistically significant (p<0.01).

Table 5.3. Angular velocity ($\omega_y$: rad/s) about the y axis.

<table>
<thead>
<tr>
<th>Shape</th>
<th>Size x10^3 m</th>
<th>$\omega_y$ (rad/s)</th>
<th>30% Concentration</th>
<th>50% Concentration</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Flow Rate</td>
<td>Flow Rate</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.577 x10^4 m/s</td>
<td>3.154 x10^4 m/s</td>
</tr>
<tr>
<td>Cubes</td>
<td>8x8</td>
<td>1.630</td>
<td>2.015</td>
<td>0.645</td>
</tr>
<tr>
<td></td>
<td>16x16</td>
<td>1.148</td>
<td>1.944</td>
<td>0.624</td>
</tr>
<tr>
<td></td>
<td>24x24</td>
<td>0.934</td>
<td>1.011</td>
<td>0.313</td>
</tr>
<tr>
<td>Cylinders</td>
<td>8x8</td>
<td>0.826</td>
<td>1.680</td>
<td>0.541</td>
</tr>
<tr>
<td></td>
<td>8x16</td>
<td>0.676</td>
<td>0.908</td>
<td>0.344</td>
</tr>
<tr>
<td></td>
<td>16x16</td>
<td>0.664^a</td>
<td>1.264</td>
<td>0.361^b</td>
</tr>
<tr>
<td></td>
<td>16x24</td>
<td>0.627^a</td>
<td>0.802</td>
<td>0.350^b</td>
</tr>
</tbody>
</table>

Means with the same letter are not significantly different (p<0.01)

Cubes rotated more than cylinders, and this effect was more pronounced at lower solid concentration (Fig. 5.10). All data showed that cubes affect the rotation behavior considerably. This phenomenon may be due to the packing of particles in the tube. For cylinders the packing of smaller (8x8mm) solids is greater than for cubes (8mm) (see
chapter VI) which results in less free space for rotation.

Table 5.4. Angular velocity ($\omega_z$, rad/s) about the $x$ axis.

<table>
<thead>
<tr>
<th>Shape</th>
<th>Size x10^{-3} m</th>
<th>$\omega_z$ (rad/s)</th>
<th>30% Concentration</th>
<th>50% Concentration</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Flow Rate</td>
<td>Flow Rate</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.577x10^{-4} m^3/s</td>
<td>3.154x10^{-4} m^3/s</td>
</tr>
<tr>
<td>Cubes</td>
<td>8x8</td>
<td>1.857</td>
<td>2.116</td>
<td>0.674</td>
</tr>
<tr>
<td></td>
<td>16x16</td>
<td>1.321</td>
<td>1.893</td>
<td>0.617^b</td>
</tr>
<tr>
<td></td>
<td>24x24</td>
<td>0.756</td>
<td>1.507</td>
<td>0.418</td>
</tr>
<tr>
<td>Cylinders</td>
<td>8x8</td>
<td>0.868</td>
<td>1.643</td>
<td>0.596</td>
</tr>
<tr>
<td></td>
<td>8x16</td>
<td>0.583</td>
<td>0.794</td>
<td>0.557^c</td>
</tr>
<tr>
<td></td>
<td>16x16</td>
<td>0.832</td>
<td>1.419</td>
<td>0.374</td>
</tr>
<tr>
<td></td>
<td>16x24</td>
<td>0.552^a</td>
<td>0.583^a</td>
<td>0.321</td>
</tr>
</tbody>
</table>

Means with the same letter are not significantly different ($p<0.01$)

The decrease of free space limits the solids from rotating freely and causes more interactions and collision with the wall. Even though cubes have a lower packing density than cylinders, they have a higher number of faces and edges, and therefore a greater chance of interaction with the wall and with each other. The sharp edges of rectangular shapes apparently increase their tendency to rotate by increasing the probability of interacting with other solids. It was observed that cubes adjacent to the wall rotated more than cylinders, perhaps due to the discrepancy between the radii of curvature of the wall and the solids. Cases of non-rotation occurred mainly with
cylinders. With cubes, such behavior was only temporary; particles soon started flipping and changing location and angles of orientation. The interstitial velocity study (chapter III) showed channeling effects and deflection of velocity vectors due to wake effects and the sharp edges of cubes which may have caused local torques resulting in rotation. The sharp edges of the cubes complicated the configuration of the flow and created small eddies as the fluid flowed in torturous paths created by the solid matrix. This induced mixing and recirculation of local fluid streams.

![Diagram](image)

**Fig 5.7** Effect of flow rate on angular velocity about various axes at 30% solid concentration of cubes (24x24mm) (LF: $1.577 \times 10^{-4}$ m$^3$/s and HF: $3.154 \times 10^{-4}$ m$^3$/s).
Effect of aspect ratio on angular velocity about various axes at 30% solid concentration of cylinders at $3.154 \times 10^{-4}$ m$^3$/s (16x16mm and 16x24 mm in size).

Effect of solid concentration on angular velocity about various axes at $1.577 \times 10^{-4}$ m$^3$/s of cubes of 8x8mm (LC and HC: 30% and 50% solid concentration respectively).
Fig. 5.10 Effect of particle shape on angular velocity about various axes at 30% solid concentration and 3.154x10^4 m^3/s (CU: cube; CY: cylinder, 8x8mm and 16x16 are size of particles).
Angular velocity ranged from 0.321 rad/s (3.07 rpm) to 2.116 rad/s (20.20 rpm) about the x axis, from 0.313 rad/s (2.99 rpm) to 2.015 rad/s (19.24 rpm) about the y axis and from 0.106 rad/s (1.01 rpm) to 1.843 rad/s (17.60 rpm) about the z axis.

Comparing solids rotation to mixing theory in tanks could provide insight into the magnitude of agitation in continuous flow of solid-liquid mixtures. Therefore we may consider rotating solids to act as impellers and non-rotating solids behave as baffles, since they reverse and block the flow because of their non rotation. This observation might be supported by the interstitial velocity in the xy plane (see chapter III). Only salient results were considered to determine Reynolds number for mixing. Reynolds number was calculated assuming that solid size is the diameter of the "impeller" and the values obtained were ranged from $3 \times 10^{-4}$ to 0.1. The regime of agitation had been classified as laminar since Reynolds number was far below 10 (Brodkey and Hershey, 1988). The rotation of solids ranged from 1.01 rpm to 20.20 rpm which is far less than that used in mixing and the mutator speed in a scraped surface heat exchanger (120 rpm).

To visualize the movement of a typical solid within the mixture in continuous flow we may plot the $\theta$, $\psi$, and $\phi$ angles with their corresponding x, y, and z coordinates and time $t$ using a visualization software (I-DEAS, Structural Dynamics Research Corporation, Mildford, OH). Figures 5.11 through 5.13 show typical examples to illustrate the behavior of a solid object within a solid-liquid mixture. It may be noted that these particles have a tendency to rotate even within brief time frames ($1/10$ of a second as compared to an overall time scale of few minutes). These
cases have been chosen to show the rotation of solids and their change of angles of orientation. Overall, the change of orientation of solids causes a significant variations in all cases, ranging from various rotation rates to changes of the relative position. This behavior is beneficial in ohmic heating since it helps to achieve uniformity of heating.
Figure 5.11. Visualization of the motion of a representative cylinder (16x24mm) with 30% solid concentration and $3.154 \times 10^{-4} \text{ m}^3/\text{s}$ flow rate (time/length scale: 1.15s/0.2m (tube section)).
Figure 5.12. Visualization of the motion of a representative cube (8mm in side) with at 50% solid concentration and $3.154 \times 10^{-4}$ m$^3$/s flow rate (time/length scale: 1.09s/0.2m (tube section)).
Figure 5.13. Visualization of the motion of a cube (24mm in side) at 50% solid concentration and $1.577 \times 10^{-4} \text{ m}^3/\text{s}$ flow rate (time/length scale: 2.4s/0.2m (tube section)).
IV. CONCLUSIONS AND RECOMMENDATIONS

Solid rotation is dependent on shape, solid concentration, aspect ratio and flow rate. Flow rate and solid concentration have a greater impact on rotation of solids than shape or aspect ratio. Cubes created more mixing than cylinders due to the sharp edges of the particle. The increase of aspect ratio decreased the rotation about all axes since it helped the solids to align with the flow direction. The rotation of particles caused some mixing in the flow field that may be beneficial for conventional aseptic processing and ohmic heating. The degree of mixing (1.01 rpm to 20.20rpm) is relatively low but its existence should be helpful to create local turbulence in the vicinity of the particle that may lead to increase of heat transfer.
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Cosine matrix</td>
</tr>
<tr>
<td>(a_o)</td>
<td>Vector coordinates</td>
</tr>
<tr>
<td>(\hat{f})</td>
<td>Unit vector in (X') direction</td>
</tr>
<tr>
<td>(\hat{g})</td>
<td>Unit vector in (Y') direction</td>
</tr>
<tr>
<td>(\hat{h})</td>
<td>Unit vector in (Z') direction</td>
</tr>
<tr>
<td>(\hat{i})</td>
<td>Unit vector in (X) direction</td>
</tr>
<tr>
<td>(\hat{j})</td>
<td>Unit vector in (Y) direction</td>
</tr>
<tr>
<td>(\hat{k})</td>
<td>Unit vector in (Z) direction</td>
</tr>
<tr>
<td>(k)</td>
<td>Consistency coefficient ((Pa\ s^2))</td>
</tr>
<tr>
<td>(n)</td>
<td>Flow behavior index</td>
</tr>
<tr>
<td>(p)</td>
<td>Smallest level of significance at which hypothesis can be rejected</td>
</tr>
<tr>
<td>(S)</td>
<td>Reference point translation vector</td>
</tr>
<tr>
<td>(\vec{S}')</td>
<td>Vector joining (O') and another point</td>
</tr>
<tr>
<td>(\vec{V}_1)</td>
<td>Vector joining points 1 and 2 on the solid piece</td>
</tr>
<tr>
<td>(\vec{V}_2)</td>
<td>Vector joining points 1 and 3 on the solid piece</td>
</tr>
<tr>
<td>(x,x',x'')</td>
<td>Cartesian (x) axes and modified</td>
</tr>
<tr>
<td>(y,y',y'')</td>
<td>Cartesian (y) axes and modified</td>
</tr>
<tr>
<td>(z,z',z'')</td>
<td>Cartesian (z) axes and modified</td>
</tr>
<tr>
<td>(x_1,y_1,z_1)</td>
<td>Coordinates of point number 1</td>
</tr>
<tr>
<td>(x_2,y_2,z_2)</td>
<td>Coordinates of point number 2</td>
</tr>
</tbody>
</table>
\( x_3, y_3, z_3 \) Coordinates of point number 3

\( \theta \ (a, b) \) Angle between \( a \) and \( b \)

\( \phi, \theta, \psi \) Rotation about \( x \), \( y \), and \( Z \) axes respectively

\( \phi, \theta, \psi \) Angles derivative in \( x \), \( y \), and \( z \) axes respectively

\( \omega \) Angular velocity (rad/s)

\( \tau \) Shear stress

\( \gamma \) Shear rate

\( \alpha \) Level of significance

**Subscript:**

\( x, y, z \) \( x \), \( y \), and \( z \) axes respectively

\( x', y', z' \) \( x' \), \( y' \), and \( z' \) axes respectively

**Superscript:**

\( P \) Point on solid piece

\( Q \) Point on solid piece
REFERENCES


CHAPTER VI

ORIENTATION DISTRIBUTION OF SOLID PARTICLES IN CONTINUOUS FLOW IN A VERTICAL TUBE

ABSTRACT

Orientation is important in determining the heating rate of solid-liquid food mixtures. In this study, solids orientation was investigated experimentally using the principle of Eulerian angles and direction cosine matrices. Cubes and cylinders at 30% and 50% solids concentration at $1.577 \times 10^{-4}$ m$^3$/s and $3.154 \times 10^{-4}$ m$^3$/s flow rates were used to determine the orientation in continuous tube flow of solid-liquid mixtures. The results show that overall 50% of particle orientation was aligned with the flow. Increasing aspect ratio resulted in an increase of the particle alignment parallel to the tube axis to 69% for cylindrical particles and 25% for cubic particles.
1. INTRODUCTION

Since ohmic heating is accomplished by passing an electrical current through the product, it is essential that the electrical conductivity ($\sigma$) of each phase, as well as the effective conductivity and resistance of the mixture, be known for purposes of process design. Since electrical resistance depends on the length and cross-sectional area of the conductor, solid orientation effects will be significant, as illustrated by de Alwis and Fryer (1989) for a long rectangular particle. It must be noted that the orientation is a critical parameter creating local variations of voltage gradients within the ohmic heater. Based on the aspect ratio of the solid (length and width) two studies have been conducted to study the effect of the orientation 1) unity aspect ratio (cube) Sastry and Palaniappan (1992); 2) long thin rectangular particle (non unity aspect ratio) de Alwis and Fryer (1989). In the latter study, two food particles were considered: potato pieces of $\sigma=0.6$ mS/cm in liquid of $\sigma=5.8$ mS/cm and egg albumin of $\sigma=20$ mS/cm in liquid of $\sigma=3.8$ mS/cm. Solids were heated with their large faces parallel and perpendicular to the field. For potato of $\sigma$ lower than the medium, particles heated faster than the liquid when they were perpendicular to the field, and slower than the liquid when parallel to it. The results for egg albumin, of higher $\sigma$ than the liquid, were reversed, highest heating rates were achieved when the axis of the solid was parallel to the field. To some extent, these effects can be explained using an analogy with simple circuit theory; when the solid is effectively in series with the liquid, if it is less conductive than the liquid then it will tend to heat at a higher rate, whereas if it is more conductive it will heat less fast. The case where the solid is in parallel with the field is more complex, however: when the solid is more
conductive, it will "suck in" the electrical current from the surrounding fluid, and if it is not too conductive, will heat faster than the liquid as a result (de Alwis and Fryer, 1989). In both cases, when the solid conductivity is very high, the heat generated is very low, and the solid underheats.

Sastry and Palaniappan (1992) developed a mathematical model to determine the extent of orientation dependence for the case of a cubes. Based on orientation they determined the cross-sectional area of solids to get the particle and liquid resistances. Sastry and Palaniappan (1992) also conducted an experimental study for the case of unity aspect ratio (cubes). Two potato cubes (0.01 m side) were placed within a fluid within a static ohmic heater and both particles were mounted at the desired orientation. In all cases, both experimental and mathematical model results showed that the orientation had only a slight effect on the overall resistance of the mixture. As $r_{c} (= \sigma_{c}/\sigma_{l})$ decreased, the range of variation in resistance increased, but even at $r_{c}=0.01$, the variation was less than 10%. Therefore, the heating rate of unity aspect ratio is not significantly dependent on the orientation. The absence of a pronounced orientation effect is primarily due to the aspect ratio of the solids, and the presence of a parallel (liquid) conduction path at all points (Sastry, 1992).

Note that while these studies indicate small orientation effects for individual particles, it is not necessarily true if large solid populations are involved. No experimental studies on orientation have been conducted on continuous ohmic heaters involving large particle populations. Since we have previously determined (see chapter IV) that the instantaneous solid area fraction is normally distributed, it may be interesting to determine
the orientation distribution with respect to time to understand the extent of change of solid orientation. Therefore the goal of this study was to determine the orientation distributions of solids relative to the axis and orientation variations over time during continuous flow of solid-liquid mixtures.

II. MATERIALS AND METHODS

The experiment consisted of image processing of continuous flow of solid-liquid mixtures. Measurement of orientation of solid particles was based on the principle of Eulerian angles. The experiment consisted of introducing solid particles (opaque and transparent) into the fluid medium from the inlet section, and videotaping it as it moved upward. The test section consisted of a glass tube of 0.508 m inside diameter and 1.524 m length. The schematic diagram of the test facility is given in Fig. 6.1. The solid-liquid mixtures were conveyed by air pressure from the inlet. The flow rate was measured using differential pressure transmitters (Model 1151DP Alphaline, Rosemount Inc., MN). The air pressure was controlled by an I/P controller (Fisher Governor. Co., Marshalltown, IA) to keep the flow rate constant. The flow was videotaped using a S-VHS CCD camera.

The experiment was conducted at two levels of solid concentrations 30% and 50%. Two types of solid particles were used in this study, opaque (potato) and transparent (acrylamide gel). Preparation of acrylamide gel is presented in detail in chapter II. The density of each phase is presented in table 6.1.
Fig. 6.1 Experimental setup.
Table 6.1. Solid and liquid phase densities.

<table>
<thead>
<tr>
<th>Material</th>
<th>Density (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solution (1% CMC)</td>
<td>1004</td>
</tr>
<tr>
<td>Potato</td>
<td>1060-1070</td>
</tr>
<tr>
<td>Acrylamide gels</td>
<td>1060-1070</td>
</tr>
<tr>
<td>Tracers</td>
<td>1004</td>
</tr>
</tbody>
</table>

1. Procedure

In studying the possible displacements of a solid particle in tube flow, it is expected that food particles rotate and translate during continuous flow. The general displacement of a solid particle can be described as the superposition of the translational displacement of an arbitrary base point fixed on the particle plus a rotational displacement about an axis through that base point. Since the translational displacement does not change the orientation of the solid, and the rotational displacement does not change the location of the base point, it follows that the two portions of the total displacement can be performed in either order, even simultaneously. To study the displacement, we need to transform the coordinates from the axis of the solid particle to the axis of reference (details on transformation of coordinates is presented in chapter VI). For this reason, the experiment consisted of determining three non-collinear unity vectors fixed on the solid particle when it moved with respect to a reference (camera axis) and time (Fig 6.2), and then using the principle of Eulerian angles to determine the orientation angles with the x, y,
and z coordinates and time t. Briefly, the Euler angles are defined to be three sequential rotations about a cartesian axis system (see Fig. 6.3) as follows (the details of the methodology are presented in detail in chapter V):

1) A positive rotation $\psi$ about the z axis, yielding axes, x'y'z

2) A positive rotation $\theta$ about the new y' axis, yielding axes x''y'z'

3) A positive rotation $\phi$ about the new x'' axis, yielding axes x''y''z''

Figure 6.2 Reference frame.
Figure 6.3. Sequence of Euler angles: a) rotation about the $z$ axis, b) rotation about $y$ axis and c) rotation about $x$ axis.
The matrix equations which indicate the individual rotations that are performed in going from the original xyz system to the final x"y"z" system is presented by eq. 1 (Greenwood, 1988):

\[
\begin{bmatrix}
    x'' \\
y'' \\
z''
\end{bmatrix} =
\begin{bmatrix}
    \cos\psi \cos\theta & \sin\psi \cos\theta & \sin\theta \\
    -\sin\phi \cos\theta & \cos\phi \cos\theta & \sin\phi \\
    \sin\phi \sin\theta & -\cos\phi \sin\theta & \cos\phi
\end{bmatrix}
\begin{bmatrix}
x \\
y \\
z
\end{bmatrix}
\] (1)

Assuming that the Euler angles are limited to the ranges:

\[-\pi/2 \leq \theta \leq \pi/2 \quad 0 \leq \phi < 2\pi \quad 0 \leq \psi < 2\pi\]

A computer program (see appendix A) was written to find the angles \(\theta,\phi,\) and \(\psi\) by solving eq. 1.

In order to differentiate between the faces we coated each face with a different color. Note that the rotation about the x and y axes causes differences in cross sectional area which will cause differences in the resistance. However, rotation about the z axis will not create any change of the cross sectional area, therefore the angle is not of interest. Since the cross sectional area depends on both rotation about x and y axes, both angles were combined to one angle \(\alpha\) (see Fig. 6.4 and details later).

1.1. Experimental steps:

The frames of the flow of the solid liquid mixtures were grabbed and digitized using a board power grabber (ATVista, Truevision Inc., Indianapolis, IN).
Figure 6.4 Illustration of x and y axes rotation to define the angle $\alpha$. 
Determination of the coordinates of the three points from left and right views \((x_1, y_1, x_2, y_2, x_3, y_3)\) for each frame were obtained using a commercial image processing software (Image-Pro, Media Cybernetics, Silver Spring, MD). Details have been described in chapter V.

The cross product of the two vectors obtained from the three measured data points was necessary to determine a third vector required to solve the cosine matrix. The transformation of the data from image scale to real scale was conducted based on the in-situ calibration performed prior to the experiment, (details are presented in chapter II) then stereomatching of the left and right views was performed to get the real \(x\), \(y\), and \(z\) coordinates of the solid particle. Only the orientation about \(x\) and \(y\) axes is responsible for change of the cross section area of the solid particles perpendicular to the electrical field. For this reason, this study concentrated on the angle \(\alpha\).

1.2. Determination of axial orientation angle \(\alpha\)

The angle \(\alpha\) was defined as the orientation of the solid body's major axis of with respect to the \(z\) axis and represents the solid orientation after a rotation about the \(x\) axis followed by another about the \(y\) axis. Figure 6.4 illustrates the rotation about \(x\) and \(y\) axes and defines the angle \(\alpha\). The value of \(\alpha\) may be determined as follows:
\[ \begin{align*}
OA &= L \\
OB &= \frac{L}{\cos \theta} \\
AB &= \frac{L}{\cos \theta} \sin \theta \\
BC &= \frac{L}{\cos \theta \cos \phi} \sin \phi \\
AC &= \sqrt{\frac{L^2 \sin^2 \phi}{\cos^2 \theta \cos^2 \phi} + \frac{L^2 \sin^2 \theta}{\cos^2 \theta}}
\end{align*} \]

\[ \alpha = \tan^{-1} \left( \frac{AC}{OA} \right) = \tan^{-1} \left( \frac{1}{\cos \theta} \sqrt{\tan^2 \phi + \sin^2 \theta} \right) \] (2)

2. Statistical analysis

Orientation angles \( \alpha \) ranged from 0 to 90° for cylinders and from 0 to 45° for cubes, to avoid duplication of the angles that give the same cross sectional area. Because of the symmetry of a cube, angles greater than 45° showed the same repeating pattern in area fraction as angles below 45°. Next, a frequency analysis of the angle \( \alpha \) was conducted to determine the orientation distribution of the solids in continuous flow.

It was necessary to ascertain whether the observed distributions were statistical or chaotic in character. A truly random process is one that has no underlying structure (i.e., slope of the curve never saturates for so called "white noise", which goes up and down in a non-controlled way). It has been found by Feder (1988) that random processes are characterized by Hurst dimension \( D_H = 0.5 \), while chaotic processes are correlated by
D_H = 0.7., where D_H is given by:

\[ D_H = \frac{2 \ln \left[ \frac{R(\xi)}{S(\xi)} \right]}{\ln \xi} \]  

(2)

where,

\[ R(\xi) = \text{Max } \chi(t,\xi) - \text{Min } \chi(t,\xi) \]  

(3)

3. Rheological properties of fluid

The non-Newtonian carrier fluids used were aqueous solutions of carboxymethyl cellulose (CMC) of consistency coefficient K and flow behavior index n. Values of K and n were determined using a coaxial cylinder viscometer (Rheomat Model 115; Contraves Industrial Division; Cincinnati, OH). Results were analyzed based on the Ostwald-de-Waele power law model (\( \tau = K \gamma^n \)). K and n were obtained using non-linear model program (Systat 1993, Systat, Inc.; Evanston, IL). Values obtained for K and n were 1.24 and 0.52 respectively. Under these conditions Reynolds number was 9.3 and 26.5 for \( 1.577 \times 10^4 \) m\(^3\)/s and \( 3.154 \times 10^4 \) m\(^3\)/s flow rate respectively.

III. RESULTS AND DISCUSSION

The change of orientation angles with respect to time are presented in Figs. 6.5 and 6.6. The data in these figures are not restricted to the ranges previously discussed. From these figures it can be noted that the orientation of particles changed in an irregular manner. Orientation angle \( \alpha \) of the cubes (Fig. 6.5) increased until it touched the wall,
Figure 6.5. Orientation angles of cubes (8x8mm) as a function of time at 50% solid concentration and $3.154 \times 10^4$ m$^3$/s flow rate (values not ranged).

Figure 6.6. Orientation angles of cylinders (16x24mm) as a function of time at 30% solid concentration and $1.577 \times 10^4$ m$^3$/s flow rate (values not ranged).
or another solid or rotated, changing its angle of orientation. Fig. 6.6 shows the
distribution of cylinders with respect to time. These figure also show that orientation
changes in an irregular manner with time. The analysis of the Hurst dimension revealed
that all $D_h$ values varied from 0.53 to 0.73. Thus, it was concluded that these data
exhibited a non random variation for values 0.53 and may indicate an underlying structure
for values close to 0.70 (Feder, 1988). This variation apparently arises from the complexity
of the problem, where there are interactions between particles which affects the orientation
in a manner dependent on several factors.

Fig. 6.7 through 6.10 present orientation distributions for cubic and cylindrical
particles. Fig. 6.7 shows that increasing aspect ratio tended to align cylindrical particles
with the flow direction, however, cubes showed no trend. The orientations were spread
all over the range with no significant difference in magnitude (see Figs 6.8). The effect
of flow rate on orientation distribution was not clear. The only observation that can be
mentioned is that the increase of flow rate increased the frequencies for angles between
60° and 90° for cylinders. No special trend was observed when the solid concentration
was increased from 30% to 50% for both shapes. Figs. 6.9 and 6.10 present the effect of
solid concentration for cubes and cylinders respectively. Comparing cubes to cylinders
(compare Fig. 6.9 and 6.10) it can be concluded that the cylinders always have a
dominant angle (0°-10°). However for cubes, the orientation distribution was relatively
uniform. This observation is due to the higher rotation of cubes compared to cylinders
(as described in chapter V). The sharp edges of cubes increased the rotation and
therefore, orientation was affected by the shape. Because of the symmetry effect of a
cubic solid when it rotates, orientation distribution of the angle $\alpha$ was relatively comparable in magnitude over the range $0^\circ$ to $45^\circ$ (Fig. 6.8 and 6.9) compared to cylinders where only one angle ($0^\circ - 10^\circ$) was dominant.

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Fig. 6.7 Orientation ($\alpha$) distribution for cylinders at 30% solid concentration (8x8mm and 8x16 mm refers to diameter and length respectively, LF and HF: refers to $1.577 \times 10^4$ m$^3$/s and $3.154 \times 10^4$ m$^3$/s flow rate respectively).
Fig. 6.8 Orientation ($\alpha$) distribution for cubes at 30% solid concentration (8x8mm and 8x16 mm refers to size diameter and length respectively, LF and HF: refers to $1.577 \times 10^{-4}$ m$^3$/s and $3.154 \times 10^{-4}$ m$^3$/s flow rate respectively).

Fig. 6.9 Orientation ($\alpha$) distribution for cubes of 8x8mm in size (LF and HF: refers to $1.577 \times 10^{-4}$ m$^3$/s and $3.154 \times 10^{-4}$ m$^3$/s flow rate respectively, HC and LC refers to 30% and 50% solid concentration respectively).
Fig. 6.10 Orientation ($\alpha$) distribution for cylinders of 8x8mm in size (LF and HF: refers to $1.577 \times 10^4$ m/s and $3.154 \times 10^4$ m/s flow rate respectively, HC and LC refers to 30% and 50% solid concentration respectively).

The most frequently occurring orientations are summarized in table 6.2. From table 6.2, 69% of cylinders are aligned with the flow (0°-10°) compared to 25% of cubes. This observation can be supported by the decrease of rotation (chapter V) since the increase of aspect ratio, the increase of solid concentration and the absence of sharp edges for the cylinder increased the tendency of solids to align with the flow compared to cubes. This behavior was observed in the solid area fraction study where the slices of the mixture showed that most of the particles were aligned with the flow (chapter V). The increase of the solids size (or solid to tube aspect ratio) showed that solids had a tendency to align
with the flow.

Table 6.2. Orientation angle $\alpha$ with the highest frequency of occurrence.

<table>
<thead>
<tr>
<th>Shape</th>
<th>Size $x10^{-3}$ m</th>
<th>Angle $\alpha$ (degree)</th>
<th>30% Concentration</th>
<th>50% Concentration</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Flow rate $1.577$ x$10^{-4}$ m$^3$/s</td>
<td>Flow rate $3.154$ x$10^{-4}$ m$^3$/s</td>
</tr>
<tr>
<td>Cubes</td>
<td>8x8</td>
<td>30</td>
<td>40</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>16x16</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>24x24</td>
<td>0</td>
<td>30</td>
<td>0</td>
</tr>
<tr>
<td>Cylinders</td>
<td>8x8</td>
<td>0.30</td>
<td>20</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>8x16</td>
<td>0</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>16x16</td>
<td>20</td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>16x24</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

By comparing 8x8mm and 24x24mm cubes it can be stated that the cubes of 0.5 aspect ratio (24x24mm) had a higher frequency of alignment with the flow at all combinations of flow rate and solid concentration (Table 6.2). This observation was similar for cylinders and it might be due to the interactions with the wall that limited the rotation of solids at higher solids size. However, the effect of solid concentration on
orientation distribution had no trend. Based on the experimental results presented in chapter V, the increase of solid concentration restricted solids from rotation and therefore, the orientation distribution with respect to solid concentration depended on the initial orientation of the particles.

An important observation is that all angle values were low which resulted in low cross sectional area perpendicular to the electrical field for cylindrical particles. Sastry and Palaniappan (1992) found that orientation of cubes from 0° to 45° had no effect on the mixture resistance. The change of the orientation resulted in a variation less than 10%. Based on these findings particle shape and aspect ratio could be carefully controlled to minimize the orientation effect.

VI. CONCLUSIONS AND RECOMMENDATIONS

The orientation study of cubes and cylinders with respect to time during continuous flow revealed that there was a change of the angles with the increase of flow rate and solid concentration. These changes were observed even at low flow rate due to particle interactions and interactions with the tube wall. Higher aspect ratio solids showed a tendency to align with the flow direction. Cylinders showed a greater tendency to align (69%) with the flow (specially at high aspect ratios) compared to cubes (25%). In some cases, no change of angles were identified and these should be taken into consideration during process design of ohmic heating of solid liquid mixtures. Mathematical models for solid liquid mixtures during ohmic heating can be improved by including these results.
particularly the extreme cases (0° and the highest corresponding orientation angle values) to predict the worst-case scenarios which are important for process design.
NOMENCLATURE

$D_h$  Hurst dimension

$K$  Consistency coefficient

$L$  Distance between O and A

$n$  Flow behavior index

$r_c$  Electrical conductivity ratio ($\sigma_1/\sigma_i$)

$R(\xi)$  Difference between the maximum and minimum value of $\chi(t,\xi)$

$S(\xi)$  Standard deviation

$x,x',x''$  Cartesian x axes and modified

$y,y',y''$  Cartesian y axes and modified

$z,z',z''$  Cartesian z axes and modified

$x_1,y_1,z_1$  Coordinates of point number 1

$x_2,y_2,z_2$  Coordinates of point number 2

$x_3,y_3,z_3$  Coordinates of point number 3

$\phi, \theta, \psi$  Rotation about x, y, and Z axes respectively

$\alpha$  Level of significance

$\chi(t,\xi)$  Cumulative temporal variation

$\xi$  Record of length

$\tau$  Shear stress

$\gamma$  Shear rate

$\sigma$  Electrical conductivity
Subscripts:

s  Solid
l  Liquid
REFERENCES


CHAPTER VII

CONCLUSIONS AND RECOMMENDATIONS

1) Particle tracking velocimetry is a promising technique for velocity measurement, and has been adapted successfully to determination of interstitial velocities in the flow of solid-liquid mixtures. The accuracy of this method has been tested and the maximum error was 4.7%.

2) These studies reveal that there is a slip velocity between phases that is dependent on solid piece shape and aspect ratio. The velocity fields within such flows are extremely complex.

3) The results showed that the velocity distribution is asymmetric and the typically presumed laminar regime does not apply even at low flow rate.

4) Relative velocities exist in all the cases studied. Relative velocities decrease with the increase of the solid concentration and increases with the increase of aspect ratio and particle size.

5) The disturbance of flow in continuous flow of solid-liquid mixtures yields insight into how the flow field field paths will behave during the process.

6) Solid area and volume fractions in the straight tube were normally
distributed. The solid area and volume fraction distribution in the elbow
not as clear as for the straight flowing tube case.

7) The increase of solid concentration flattened the distribution. The solid
concentration was the only significant factor that affects both the area and
flowing volume solid fraction. The aspect ratio and the shape effect were
not statistically significant but they make slight changes on the mean and
standard deviation. The increase of aspect ratio decreases the solid area
fraction for both shapes and we found that high aspect ratio solids have a
tendency to align with the flow. Rectangular solids gave lower solid area
fraction and flattened the distribution more than cylinders at high solid
concentration.

8) Solid rotation is dependent on shape, solid concentration, aspect ratio and
flow rate. Flow rate and solid concentration have a greater impact on
rotation of solids than shape or aspect ratio.

9) Cubes created more mixing than cylinders due to the sharp edges of the
particle. The increase of aspect ratio decreased the rotation about all axes
since it helped the solids to align with the flow direction.

10) The rotation of particles caused some mixing in the flow field that may be
beneficial for conventional aseptic processing and ohmic heating. The
degree of mixing (1.01 rpm to 20.20rpm) is relatively low but its existence
should be helpful to create local turbulence in the vicinity of the particle
that may lead to increase of heat transfer.
The orientation study of cubes and cylinders with respect to time during continuous flow revealed that there was a change of the angles with the increase of flow rate and solid concentration. These changes were observed even at low flow rate due to particle interactions and interactions with the tube wall.

Higher aspect ratio solids showed a tendency to align with the flow direction. Cylinders showed a greater tendency to align (69%) with the flow (specially at high aspect ratios) compared to cubes (25%).

In some cases, no change of angles were identified and these should be taken into consideration during process design of ohmic heating of solid liquid mixtures.

RECOMMENDATIONS

1) Temperature and velocity measurements in three dimensions including solid orientation and angular velocity are possible for continuous flow of solid-liquid mixtures by using the facilities available at The Ohio State University, Food, Agricultural and Biological Engineering Department.

2) The next step of solid area fraction distribution study will focus on incorporating the distribution found to determine the effect on the heating rate and what difference it will make compared to the uniform solid area
fraction assumption published by previous studies.

3) Further analysis of rotation effect on temperature uniformity will be helpful to determine a quantitative relationship of particle rotation to $h_{ri}$ values in continuous solid-liquid mixtures and can be conducted using liquid crystal solution for temperature measurement.

4) The mathematical model of solid liquid mixtures during ohmic heating can be improved by including the results found for the orientation distribution study specially the extreme cases ($0^\circ$ and the highest corresponding orientation angles values) to predict the worst-case scenarios which are important for process design.
BIBLIOGRAPHY


