Measurements of Fluid Structures and Mass Transport in Channel with Fabric Base

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MEASUREMENTS OF FLUID STRUCTURES AND MASS TRANSPORT IN CHANNEL WITH FABRIC BASE

by

Karl David McAllister

A dissertation submitted to Graduate College in partial fulfillment of the requirements for the degree of Doctor of Philosophy
Mechanical and Aerospace Engineering
Western Michigan University
June 2018

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This thesis studies the relationships between flow structures and mass transport (dye concentration) within a Poiseuille water flow glass chamber using optical flow experimental techniques in turbulent conditions. Through optical flow methods, velocity, vorticity, kinetic energy, Reynolds stress and turbulent production metrics were determined by laser illuminated glass beads and Rhodamine 6G dye removing from three different fabric substrates for multiple horizontal planes and one vertical plane. From the dye intensity, mass concentration metrics were determined providing visualization of velocity and mass transport simultaneously along with kinetic energy, mass flux, and concentration fluctuations.
ACKNOWLEDGMENTS

To my angel wife – thank you your patience, longsuffering, support, sacrifice and believing in me to me realize my dreams. May we always spend our evenings together from now on.

To my daughter and sons – thank you for your encouragement and enduring this effort with me.

To my dad – who instilled in me an extraordinary work ethic.

To my mom – who saw the spark and fanned the flames when I was small.

To Master Tomasi – who further fanned the flames and gave me a positive Black Belt attitude and other life tools and encouraged me to start this journey and never give up.

To my PhD advisor, Dr. Liu – who was always fair in his assessments and slugged through this effort with me despite my ignorance.

To all mentioned and not mentioned (you know who you are) – I could not have done this without your support, listening ear and helping hand when time was precious and I owe my success to you and I thank you personally for all you have done for me.

Karl David McAllister
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1 INTRODUCTION

An abundance of research has studied hydrodynamic particle mobilization of particulate on both porous and non-porous substrates see [1-20] to name a few. Cutler [1], dedicated an entire chapter discussing particulate removal which included particulate size, surfactant levels, temperature, rate of agitation and the effect of particle, fiber and surfactant characteristics on particulate soil removal. Visser [2], placed sub-micron carbon black particles on a flat cellulose substrate in a Couette flow and determined that percent removal was directly related to both pH and shear stress. He also noticed that attached particles do not slide along the surfaces but, instead, are either lifted away from surface or remain at the same location. Hubbe [3-4], improved upon Visser’s work in both procedure and apparatus and showed that detachment of particles is directly related to the amount of shear stress and time applied. He also determined that higher pH (11 – 12.5) reduces the shear stress required to remove particle. Unlike Visser, he showed that particles which broke loose from surfaces up stream redeposited again on surfaces downstream. Sharma [5], studied the influence of variables such as flow rate, particle size, particle elasticity, ionic strength, pH, and gravity. He demonstrated that the mechanism of particle detachment is rolling rather than sliding or lifting and developed a model to explain the essential physics of particle detachment. Das [6], studied the effects of elastic deformation and surface roughness on hydrodynamic detachment of colloidal particles from surfaces with glass and polystyrene particles on glass and mica substrates. He determined that hydrodynamic force is dependent on particle roughness, roughness of the substrate and contact deformation. Montgomery [7], developed soil adhesion equations and using kaolinite soil, polyester fabric substrate and an atomic force microscope (AFM). Although his experimental generally worked, it yielded significant variation. Montgomery also showed that, again, by increasing the pH of the
fluid using sodium hydroxide, the adhesion force was reduced by an order of magnitude. He also developed methods to experimentally quantify an effective Hamaker constant on a surfaces and particle geometry generally difficult to quantify using analytical methods. Burdick [8-9] developed an analytical model in which he uses drag and lift force equations along with moment couple equations on spherical soil to determine a removal criterion that is expressed as a Reynolds number for hydrodynamic removal of micron-scale particles. This model was experimentally validated to predict particle adhesion force distribution. Bergendahl [10-12] developed a model to explore physically based colloid detachment in a porous media with respect to both thermodynamics and hydrodynamics. He concluded that detachment is realized when the applied rolling moment from hydrodynamic shear easily overcomes the resistance associated with strict vertical adhesion. Cleaver’s work [13] assumed that as flow passes over a flat surface a viscous sublayer is formed. This sublayer is continually disrupted by turbulent “bursts” which cause instantaneous lift forces. These lift forces are the reasons why particles detach from surfaces. A removal criterion was obtained which is in general agreement with previous empirical studies and correlates with the wall shear stress and particle diameter. Kaftori [14-15], furthered the work of Cleaver by determining that the turbulent “bursts” are actually funnel vortices that lie sideways against the surface with one side rising up from the surface. These sideways vortices seem to explain the reason for particle removal or lift off and potential re-deposition due to the inherent up and down corkscrewing draft of the sideways vortices. Ward [16], did a significant work and tried to determine the causes of fabric substrate particulate removal by defining the analytical model of fabric motion in a horizontal axis washing machine and measuring the expected shear stress with small block pressure probes placed inside tumbling horizontal axis (HA) washing machine. He also suggested that the cause of cleaning
performance was 81% due to detergent chemistry, 8% due to water temperature, 7% due to abrasion and warping and 3% due to detergent plus water temperature interaction. The remaining percentage was due to experimental noise. It should be noted that the HA washing machine studied by Ward had significantly more water than similar present day HA washing machines and stated results are more likely different in today’s horizontal axis washing machines. Kovitch [17], studied the influence of flow streams on fabric surfaces and tried to quantify the flow velocity required to remove carbon-black particulate from an IEC EMPA221 fabric substrate. Although flow streams placed both normal and tangential to the fabric surface between 1 to 8.5 m/s with various detergent concentration, temperature and time, resulted in no real particulate removal at the vicinity of the stream. What was observed, however, was during testing a noticeable ring of particulate removal formed along the framed edge (an embroidery ring) that held the fabric taught during testing. The fabric at the location of the ring experienced a significant amount of back and forth drum-like oscillation from the impinging fluid stream. This inherently caused an inordinate amount of pressure, fiber to fiber/yarn to yarn shear and fluid motion through the yarns. The resulting ring may indicate that mechanical action applied to fiber surfaces in the correct way has a greater role to play in the removal of surface particulate on fiber surfaces. Lee [18], also studied the role of mechanical action on a fabric substrate. He evaluated hydrodynamic flow, fabric flexing and the abrasion of a fabric substrate and determined that abrasion or shear action was the most effective mechanical action for soil removal as compared to other motions such as bending. Van den Brekel [19], did a ground breaking study in quantifying methods to understand yarn and pore porosity to determine mass transfer coefficients. Once understood, the chemical reactor theory was used to quantify flow through fabric substrates, which, if large enough, can have a significant effect on applied forces
on particles within the substrate. Detergent concentration and volumetric flow rates within the fabric and corresponding flows in the pores and yarns can then be determined by quantifying the change in concentration over time and fitting a curve to this result. This information provides a quantitative look as to how the concentration within the fabric substrate changes over time which in turn dislodges soil particulate from a fabric substrate. This work used an effective diffusion coefficient that was estimated using Karabelas [20] empirical analogy between momentum and mass transfer which incorporates the Sherwood number to determine an estimate of the mass-transfer coefficient because it is not exactly know.

Furthermore, optical flow methods continue to be used as a method to provide image-base fluid measurements see [21-26] for instance. Horn’s [21], ground breaking paper that linked information about the spatial arrangement of objects viewed and the rate of change of the arrangement. By resolving the second of two velocity constraints they presented a method which successfully computes optical flow from an image sequence. However flow visualizations and corresponding relationships were not physical and could not be linked to fundamental analytical flow relationships. Liu [22], provided this relationship with a ground breaking paper which linked fluid flow and optical flow with physics-based optical flow equations with direct comparisons between the optical flow method and experiments. Liu [23] further his work by measuring surface flow visualization via physics-based optical flow techniques and developing theoretical foundations skin-friction fields from surface mass-transfer visualizations as an inverse problem. Liu [24, 25], also developed theoretical foundations for extraction of skin-friction fields from surface mass-transfer visualization with pressure sensitive paint and sublimating coatings. The mass transport at the wall is expressed as the aforementioned optical flow equation in the image plane. Dezso-Weidinger [26], surveyed flow velocity, oil droplet
concentration and corresponding mass flux for the flows representing city street canyon using PTV methods and then compared the results to conventional techniques. He concluded that the measurements taken can improve modeling of turbulent diffusion.

The objective of this thesis is to study the flow metrics and transport phenomena using a physics based optical measurement technique developed by Liu [22]. The aim is to calculate flow velocity, Reynolds stress, kinetic energy, vorticity and turbulence production including the concentration kinetic energy, turbulent mass flux, concentration transport and concentration fluctuations, inside a glass walled rectangular flow chamber with four different chamber bottoms. The chamber bottoms include glass only, AHAM towel, EMPA221 and Terry fabric substrate. The above metrics were surveyed using both laser illuminated glass beads (for the glass only chamber bottom) and the above mentioned fabric substrates impregnated with fluorescent dye. Because the substrates have inherently different surface geometry (surface roughness or asperities) it is expected that the flow metrics and transport phenomena will show unique differences in the measured metrics in comparison to the glass only bottom [27 (pp 238), 28 (pp 232)]. The results were also compared to the numerical models such as those described in Perot et al [29] that use direct numerical simulation (DNS) from Kim et al [30].

2 EXPERIMENTAL SETUP

The experimental setup incorporates a quartz glass rectangular flow chamber supported by a metal frame to allow the fluid flow to be seen from the top or side directions. As fluid is forced through the flow chamber optical flow measurements of illuminated glass beads and fluorescence dye can be taken. The process as to how this is accomplished is described in detail below.
2.1 The Flow Chamber

A flow chamber apparatus was developed to enable both horizontal (side to side) and vertical (top to bottom) visualization of the flow. The flow chamber body was constructed with a nickel platted steel to prevent corrosion with dimensions of approximately 35 mm high, 214 mm long and 74 mm wide. The flow chamber within the flow chamber body was designed to be 25 mm high, 181 mm long and 34 mm wide as shown in the following figures.

Figure 1: Flow chamber top view with pull action toggle clamps and two pressure transducer taps.
Figure 2: Flow chamber side view with pull action toggle clamps and pressure taps.

The bottom of the flow chamber is open and is designed to accept a module like insert that fits up into the flow chamber called a bottom block see figure.

Figure 3: Flow Chamber bottom view with pull action toggle clamps.
This enables the operator to easily change out the bottom surface of the flow chamber as needed for experimental conditions. This bottom block can be made to have different heights. However, in this case only one height was used see figure below.

![Bottom block hollowed out with glass top surface.](image)

**Figure 4: Bottom block hollowed out with glass top surface.**

For this experiment, the bottom block height was designed to be 14.5 mm high, 183.87 mm long and 33.87 mm wide with a flange base. When the bottom block is inserted in the flow chamber it results in flow chamber that is 11.25 mm high, 191 mm long and 34 mm wide with quarts glass surrounding four sides. The material of the bottom block itself was removed and hollowed out so that surface visualization can be seen from the bottom if desired. The top was slightly recessed to accept a 0.6 mm thick, 174 mm long and 33.75 mm wide quarts glass sheet. The aluminum bottom block was anodized to prevent oxidation when exposed to water. The quartz glass sheets were attached to the bottom block using a permanent two-sided acrylic tape (3M – 4905, 2 inch, VHB Acrylic). The bottom block flange that spans the outer edge of this bottom block base was designed to be 7 mm thick and 9 mm wide. This flange allows the bottom block to seal against the chamber body bottom by using four push action compression
The compression clamps put pressure against the flange from underneath which in turn compresses an O-ring that resides between the flange and flow chamber body bottom and seals the bottom block against the flow chamber. The bottom block height (including its glass surface) was designed so that once it is clamped in place the top surface of the bottom block is flush with the bottom of the inlet and outlet flow openings of the flow chamber body.

Two quartz glass plates 1.60 mm thick, 174 mm long and 19.00 mm wide were installed to the vertical side flow chamber body from the inside using permanent two-sided acrylic tape (3M-4905, 2 inch, VHB Acrylic) for visual access from the sides. For easy access and to provide visual access a single quartz glass plate 1.60 mm thick, 198 mm long and 48 mm wide was installed on top of the flow chamber body as well. This particular glass plate was sealed to the flow chamber body by using an O-ring and an anodized aluminum retainer frame that spans the outside perimeter. Compression clamps attached to two clamp riser brackets located on the top side of the base plate were used to put force against the retainer frame thus compressing the O-ring and sealing the glass against the flow chamber body.

The underside of the flow chamber base plate is attached four, 41 mm by 50 mm by 51 mm tall riser blocks. Each block is installed with a ½ inch aluminum linear sleeve bearing see figure below.

1 The push action compression clamps are attached to an aluminum base plate, 12.7 mm thick, 300 mm long and 160 mm wide that is attached to the flow chamber body bottom.
Figure 5: Riser Blocks with ½ inch linear sleeve bearings attached to the underside of the flow chamber.

These sleeve bearings are used to precisely slide the flow chamber onto two, 0.0254 m diameter hardened precision steel shafts with support rails see figure.

Figure 6: Support rail slide to anchoring flow chamber for testing.
These shafts and support rails are 0.305 m and mounted in parallel (0.121 m apart) to the top of a 0.0254 m thick aluminum table top. The two support rails spans a 0.067 m by 0.295 m opening so that when the flow chamber slides onto the support rails via the aforementioned slide bearings, the underside of the flow chamber can be accessed visually from underneath the table. A stop block with a pull-action toggle clamp is placed at the end of the support rail so that as the flow chamber is slid along the support rails a consistent stopping point is present.

![Figure 7: Stop Block with pull action toggle clamp to anchor and hold flow chamber in place.](image)

The pull-action toggle clamp attaches and holds the flow chamber against the stop block so that a consistent anchor point can be achieved. Thus the flow chamber can be accurately located each time the flow chamber is attached, removed and reattached.

On either end of the flow chamber body are attached flow expanders, 24 mm thick, 190 mm long and 74 mm wide.
These flow expanders are sealed to the chamber body by rubber O-rings that are held in place by two ¼ - 20 machine screws for each side. The ends of the flow expanders are tapped with a 3/8 inch – 18 NPT thread to accept a 3/8 inch copper piping. From this threaded point location, upstream of the flow, an 8 mm high channel centered within the flow expander expands (diverges) at an angle of 7.5 degrees to the flow chamber body. This 7.5 degree angle is an attempt to minimize flow separation as the channel widens from the 3/8 inch pipe to the flow chamber body. The size of the flow expander opening as it terminates into the flow chamber is 34 mm wide by 8 mm high. The fluid exits through a similar 34 mm wide by 8 mm high channel downstream of the flow chamber. This downstream flow expander converges the fluid back into a 3/8 inch pipe of the opposite side of the flow chamber. Both flow expanders have pressure taps 1.5 inches from either side of the flow chamber body to allow for differential pressure reading spanning the flow chamber. The pressure reading is recorded using a Validyne DP45-24 pressure transducer.

Attached to the upstream side of the flow expander is a 0.61 m long, 3/8 inch copper pipe with a 3/8 inch – 18 NPT thread.
Figure 9: 0.61 m copper pipe 3/8 inch with quick connect fitting attached to the upstream side of the flow chamber.

This relatively long pipe allows the fluid coming from the pump to develop into semi-steady state condition prior to entering the flow expander. A quick connect coupling is attached to the upstream end of this copper pipe so that the flow chamber can be easily unattached or reattached from the reservoir pump and feed system. Upstream of this is a manual ball valve which allows for intentional manual fluid shut off and prevents residual fluid from escaping from the hoses as the flow chamber is being serviced. Further upstream is attached a 120 volt solenoid valve. The solenoid valve allows for precise activation and deactivation of flow through the flow chamber using a control system discussed later. A flexible reinforced rubber hose attaches to this solenoid valve and runs down to the reservoir pump located under the table. The vertical distance between the quick connect and pump attachment is 0.619 m.

The reservoir pump used in this during the testing is a Little Giant model TE-5-MD-HC, 120/230 VAC, 60 Hz, 1 Phase, 1/8 HP, with an operating pressure of 12.7 psi (87.6 kPa).\(^2\) The pump is attached to a Nalgene, polypropylene ten gallon open top cylindrical reservoir tank via

\(^2\) This pump can provide flow rate ranges of 19.2 GPM at 3 ft of Head, 18.2 GPM at 6 ft of Head, 17.0 GPM at 9 ft of Head, 14.8 at 15 ft of Head, 12.7 GPM at 18 ft of Head and 8.4 GPM at 24 ft of Head.
an 0.46 m long hose that is 5/8 inch OD with a ½ inch ID. The reservoir and pump system just explained is what will be referred hereafter as the Reservoir Pump and Feed System.

Figure 10: Reservoir Pump and Feed System.

The downstream flow expander on the opposite side is attached to a 50 mm long 3/8 inch copper pipe. A threaded “T” is then attached to this pipe with another Validyne DP15-DL pressure sensor.³ This provides an overall gauge pressure reading of the system so that pressure losses within the flow chamber are known. After the threaded “T”, an easy-set 3/8 inch NPTF dry seal needle valve is attached to manually regulate the flow rate through the flow chamber.

³ Set for 0 to 140 kPa
Downstream from this is attached a 3/8 inch quick-connect coupling with a flexible rubber hose which bends directly to the ten gallon reservoir. The quick-connect coupling allows for easy removal of the flow chamber from the reservoir pump and feed system table.

![Image](image)

**Figure 11:** Pressure transducer port, needle valve and quick connect attached to the downstream flow expander.

The table top that the flow chamber is attached to via the support rails is a 0.0254 m thick by 0.727 m long by 0.502 m wide aluminum plate. This plate is anchored to a 0.727 by 0.727 m square frame made from extruded 0.0381 by 0.0381 m aluminum bar lengths. The height of the table frame top is made to be 0.914 m high. A bottom shelf to hold both the reservoir tank and pump feed system was also attached to the inside of the table frame.

A 3D cross-section and side view representation of the flow chamber and provided in the figures below.
To activate and deactivate the pump and solenoid valve at desired times a simple control system was used. This control system consist of a Lenovo W530 computer, Matlab software R2016b with Data Acquisition Toolbox version 3.8, National Instruments USB-6002 data acquisition and control unit (DAQ), a UDN 3985A driver chip, two 250 Volt, 8 amp relays, a 24 volt DC power supply and a 120 Volt AC power source. Matlab software interfaces with the
National Instruments DAQ and the corresponding driver chip and relays. The control unit sends out a +/- 5 volt signal for a specified time which then routes to the driver chip where it is amplified by the 24 Volt DC power supply. The 24 Volt signal is then sent to the relays where the coil is energized allowing the 120 Volt AC to pass through the two relays activating both the pump and solenoid valve enabling fluid to pass through the flow chamber. When the test is completed a zero volt signal is sent from the USB control unit and the relay coils are de-energized shutting down the pump and closing the valve thus stopping the flow into the chamber.

2.3 The Laser Apparatus

The Frame A modified PIV system from TSI was used to visualize and characterized the flow moving through the flow chamber. This system consisted of a Quantel dual laser system from Big Sky Lasers both with a 190 mJ Energy rating at 535 nm.

Figure 14: 190 mJ Quantel dual laser system.

The two lasers are cooled with two PIV190 – PS2 coolers filled with distilled water. Both lasers are combined and passed through an articulating fiber optic arm so that the laser light can be safely and easily located to a desired position.
The end effector of the articulating fiber optic arm is mounted to adjustable support structure that enable precise placement of the laser sheet into the flow chamber from above (vertical) and from the side (horizontal). The laser light sheet used for visualizing vertical and horizontal flows is created by a 15 mm cylindrical and a 500 mm spherical lens attached to the end effector which produced a 1.2 mm thick laser sheet. For cross-sectional flow visualization, the fiber optic arm was installed above the flow chamber with the laser sheet shining perpendicular to the flow. The spherical lens was changed to 1000 mm which increased the laser sheet thickness to 4.5 mm enabling better detection of the cross-sectional flow.

The cameras for the PIV system consisted of two 4-MP Powerview Plus cameras model number 630159 with a Nikon AF Nikkor 50 mm 1:1.8 D lenses (only one camera was used in this modified optical flow analysis). A laser pulse synchronizer model 610034 was used to link the camera exposure to the 500 $\mu$s laser pulses. For cross-sectional flow the camera exposure was set to 10 $\mu$s laser pulses. The laser, synchronizer and cameras were controlled using TSI.
Insight-4G control software. The camera was positioned to visualize the flow illuminated by the laser sheet from the side and top of the flow chamber. In other words, for a horizontal laser sheet condition the camera was positioned to view the flow from the top of the flow chamber. For a vertical laser sheet condition the camera was positioned to view the flow from the side of the flow chamber. For the cross-sectional views a vertical laser sheet was shined perpendicular to the flow chamber length. The camera was positioned to view the flow chamber from the top with a 20 degrees tilt from horizontal and positioned to be 0.165 m vertically from the center of the flow chamber and 0.329 m horizontally from the illuminated edge of the laser beam sheet. This enabled the camera to see the cross-sectional flow as it developed within the flow chamber.

3 MEASUREMENTS TECHNIQUES AND DATA PROCESSING

After camera and laser have been positioned and calibrated, flows within the flow chamber were determined by first filling the reservoir tank with 34 Liters of approximately 20 degrees C water. One-gram of glass beads of 8-12 microns (part number 10089 Prtcl-Glss-Hllw) was mixed into the reservoir tank with 30 Liters using a hand drill auger for about 30 seconds.

The bottom block top surface is either its original glass surface or three different attached surface types of EMPA 221, AHAM Towel or Terry Towel as previously discussed. For dye visualization, the surface types were dyed with Rhodamine 6G. Fabric was dipped in 3 grams of Rhodamine 6G dye and 150 g of isopropyl alcohol. This dye as it comes off the fabric surface illuminates very well when exposed to the 535 nm laser sheet.

The bottom block was then placed into the flow chamber bottom and sealed using the push-action toggle clamps. The entire flow chamber was moved to the aluminum table and then slid onto the parallel support rails against the stop block and locked in place by the pull-action toggle
clamp. The flow chamber is connected to the reservoir pump and feed system on either end by the 3/8 inch flexible rubber hoses and quick-connect couplings.

![Flow Chamber mounted on parallel support rails and pushed against the stop block.](image)

Figure 16: Flow Chamber mounted on parallel support rails and pushed against the stop block.

A final check is then made to ensure that the calibrated camera incorporates the outer edges of the flow chamber viewing windows within the length of the picture space so that the maximum number of pixels per length can be achieved when characterizing flow within the flow chamber.

With the room darkened, the pump and corresponding relays were activated using the Matlab control software via the Data Acquisition Toolbox and National Instruments USB-6002 data acquisition device. This commences the water flowing through the flow chamber and over the top of the porous substrate attached to the bottom block surface.

Two-thousand picture pairs are taken by the camera precisely when the laser sheet is pulsed at 500 $\mu$s for the vertical and horizontal conditions. A 10 $\mu$s pulse is use for cross-sectional views. Using the picture pairs with an optical flow algorithms flow visualization were
obtained for both glass beads and fabric dyed with Rhodamine 6G. Flow in the \( x \) and \( y \) -direction (laser sheet shining vertically down from the top) along the longitudinal center and 9 mm on either side of center. Flow is characterized in the \( x \) and \( z \) -direction in a similar fashion with three different vertical locations with the glass beads and four different vertical locations for the dyed fabric conditions as shown from the following figures.

![Figure 17: Flow chamber side window locations of the laser sheet represented by the blue bars for EMPA 221 fabric using glass beads. Bottom, Middle and Top laser positions shown.](image1.png)

![Figure 18: Flow chamber side window location of the laser sheet represented by the green bars for EMPA 221 fabric with Rhodamine 6G dye. Bottom, Level2, Level3 and Level4 laser positions shown.](image2.png)
Figure 19: Flow chamber side window locations of the laser sheet represented by the blue bars for AHAM Towel fabric using glass beads. Bottom, Middle and Top laser positions shown.

Figure 20: Flow chamber side window location of the laser sheet represented by the green bars for AHAM Towel fabric with Rhodamine 6G dye. Bottom, Level2, Level3 and Level4 laser positions shown.
The above figures indicated that the glass beads condition, the horizontal laser sheet is placed just above the fabric surface and as high as possible against the side window. The location of the middle laser sheet depends on the height of the fabric substrate and essentially splits the difference between the top and bottom laser sheet locations. For the dye condition the laser sheet was also placed just above the fabric surface with three more positions, one higher than the other.
at 1.75 mm apart. This allows for greater resolution to understand flow characteristics and mass transfer effects of dye as it moves from the surface of the substrates.

### 3.1 Fabric Characteristics and Substrate

Three different fabric types were used in testing, EMPA 221, AHAM (Association of Home Appliance Manufacturers) Towel and Terry cloth. The EMPA 221 fabric is a standard 100% cotton fabric, cretonne, bleached, without optical brighteners that is used on IEC stain strips (EMPA 105 and 109). This fabric is a stiff and tightly woven fabric material with a flat surface. The AHAM Towel is woven huckaback (puckered surface) 100% cotton that is soft and flexible. The AHAM Towel is part of the IEC-60456 – 2010 Fifth Edition standard ballast test load. The Terry cloth is 100% cotton fabric representing a simple practical hand towel. This woven Terry fabric has surface loops for absorbing large amounts of water. These fabric types were chosen for the different graduated surface roughness characteristics to influence the fluid as it flows through the chamber and across these surfaces.

These three different fabrics types were characterized by first measuring the empirical elastic and shear modulus and the different mean pore diameter, Darcy value, cumulative pore volume, yarn pore volume and cloth porosity as shown in the following tables.

<table>
<thead>
<tr>
<th>Fabric Type</th>
<th>Elastic Modulus (Mpa)</th>
<th>Shear Modulus (Mpa)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Warp</td>
<td>Fill</td>
</tr>
<tr>
<td>EMPA 221</td>
<td>6.475</td>
<td>3.082</td>
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<tr>
<td>AHAM Towel</td>
<td>0.597</td>
<td>0.644</td>
</tr>
<tr>
<td>Terry Towel</td>
<td>0.743</td>
<td>0.620</td>
</tr>
</tbody>
</table>

Table 1: Elastic Modulus for fabric types EMPA 221, AHAM Towel and Terry Towel. Values obtained from North Carolina State University textile labs.
Table 2: Mean Pore Diameter, Darcy, Cumulative Pore Volume, Cumulative Yarn Volume, Cloth Porosity for EMPA 221, AHAM Towel and Terry Towel. Values obtained from Porous Materials Inc.

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<tbody>
<tr>
<td>EMPA 221</td>
<td>1</td>
<td>17.03</td>
<td>15.46</td>
<td>3.51</td>
<td>1.47</td>
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<tr>
<td>AHAM Towel</td>
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<td>AHAM Towel</td>
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<td>Terry 1</td>
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<td>61.28</td>
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<td>0.51</td>
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The above tables indicate that EMPA 221 fabric has significantly higher elastic and shear modulus (0.682 and 0.062 MPa respectively). The EMPA 221 is a much stiffer fabric than either of the AHAM and Terry towels. The Terry towel has slightly higher elastic modulus (0.682 MPa) than the AHAM towel (0.620 MPa) but has lower shear modulus (0.015 MPa) than the AHAM towel (0.027 MPa). This indicates that both the Terry and AHAM towel have about the same stiffness. Furthermore, the Terry towel has the highest average mean pore diameter (60.92 µm) followed by the AHAM towel (22.02 µm) and the EMPA 221 fabric (15.46 µm).

Further fabric characteristics were then determined in terms of water to cloth ratio (WCR) which is the amount of water held within the fabric (in liters or kg) versus the amount of dry fabric mass (in kg). This metric was determined by pre-weighing the dry fabric then submersing it in a water bath and removing it. After 20 seconds of drip drying, the fabric was then reweighed. The difference between the two weights were then calculated to determine the amount of water the fabric holds and this value was then divided by the initial dry weight of the fabric. The fabric thickness and surface roughness was also determined. The fabric thickness metric was measured using simple vernier calipers. The values were determined by lightly squeezing the caliper jaws against the fabric at different locations. The surface contour roughness metric was measured using an industry standard KES-FB4 Surface Tester. This
apparatus applies a 20 gf/cm tension load to the fabric and drags a probe across the fabric surface to measure the roughness in μm. The results of these three metrics are shown in the following figures.

Figure 23: Water to cloth ratio for AHAM Towel, EMPA 221 and Terry Towel.

Figure 24: Measured fabric thickness both dry and wet condition for AHAM Towel, EMPA 221 and Terry Towel.
Figure 25: Measured fabric roughness both dry and wet condition for AHAM towel, EMPA 221 and Terry Towel.

From the above three figures, the EMPA 221 fabric has the lowest WCR at approximately 1.7, followed by the AHAM Towel at 2.7 with the highest WCR given to the Terry Towel fabric type a 4.1. For thickness, the EMPA 221 fabric type is the least thick at 0.32 mm followed by the AHAM Towel at 0.98 mm with the greatest thickness belonging to the Terry Towel at 1.5 mm. For roughness metric, the EMPA 221 also has the lowest roughness as expected at 6.9 microns followed by, surprisingly, the Terry Towel at 11.2 microns with the AHAM Towel having the greatest surface roughness of 15.8 microns. It was expected that the Terry Towel would have the largest roughness due to the inherent loops extending from the base fabric surface. However due to the loop spacing with five loops every 8 mm in the $x$ and $z$-direction the probe seemed to only measure the base surface between the loop rows and is most likely why the roughness measurement was not higher. To obtain an estimate of roughness, the loops were
measure to extend from the base surface approximately 1.8 mm high. However, these loops
generally lay against the base surface resulting in an effective loop height of 0.8 mm.

3.2 Fabric Attachment to the Bottom Block

The aforementioned fabric types were cut into strips to match the area dimension of the
bottom block. They were then attached to the bottom block glass surface by applying Loctite
Super Glue Gel Control (part number 45198) uniformly to the bottom block and quickly placing
the cut fabric onto glued quartz glass surface. A 1.745 kg steel block that spans the length and
width of the glass surface is then placed on top of the fabric for approximately five minutes to
ensure the entire fabric is uniformly pressed against the bottom block surface. Finally, the
bottom block and attached fabric was then inserted into the flow chamber for testing.

3.3 Flow Chamber Characteristics

Flow rates versus pressure within the flow chamber were determined by adjusting the
needle valve and simply measuring the gauge pressure. A weight scale was used to measure the
amount of water expelled in 30 seconds for three different flow settings set by the flow control
needle valve. This was then repeated three times giving the pressure versus volumetric flow
rates. The results are provide in the following figure.
These results indicate the volumetric flow rate capability of the flow chamber. Also the fabric flow chamber bottom generally yields higher pressure with similar flow rates compared to a glass bottom. This is unexpected due to the Bernoulli’s principle of velocity decreasing with increasing pressure. The surface roughness seems to create different turbulent conditions within the flow chamber resulting in slightly elevated pressure conditions.

The pressure versus Reynolds number was also calculated for the flow chamber using the following equation \( Re = \frac{u_d D}{\nu} \). Where \( u_d \) is the flow velocity in the \( x \)-direction, \( D \) is the hydraulic diameter calculated to be \( 1.73 \cdot 10^{-2} \) m and \( \nu \) is the kinematic viscosity of 20 degree water at \( 1.006 \cdot 10^{-6} \) m/s\(^2\). See the following figure.
These results indicate the flow rate range capability in Reynolds number of the flow chamber. Flow tests described above were conducted at the highest flow rates shown (3500-3800 Reynolds number). Furthermore, this flow rate leans toward the upper limit of the traditional transitional flow region. The turbulent conditions can also vary depending on system conditions and geometry and are most likely the reason different pressure and flow rates exist for different fabric types. This is one of the reasons the aforementioned flow profiles needed to be characterized within the flow chamber.

3.4 Optical Flow Determination

Two-thousand picture pairs were taken for one vertical and three horizontal locations as described above were taken for the glass bead base flow case providing metrics using the optical flow methods originally developed by Horn and Schunk [21] and further modified by Liu [22] by taking the weighted path-averaged velocity via unified perspective and applied here in this thesis. The metrics of velocities, vorticity, kinetic energy, Reynolds Stress and turbulent
production profiles where generated. The same metrics were applied to 2000 picture pairs for three different dye impregnated substrates for one vertical and four horizontal location as well. From the intensity of the dye, concentration values were determined and metrics of kinetic energy, turbulent mass flux and concentration fluctuations profiles were also developed.

4 GOVERNING EQUATIONS AND STATISTICAL TIME-AVERAGING

The governing equations that describe incompressible flow through the flow chamber and corresponding concentration flow calculation are described in Cartesian coordinates below. The most general form of equations are presented. In subsequent sections these forms are then discussed with corresponding assumptions and conditions.

4.1 Governing Equations

The following are the governing equations for incompressible flow for the flow chamber. They include the continuity equation 4-1 and the celebrated Navier-Stokes equation 4-2 [31]

\[
\frac{\partial u_i}{\partial x_i} = 0 \tag{4-1}
\]

\[
\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho} \frac{\partial P}{\partial x_i} + \nu \frac{\partial^2 u_i}{\partial x_i \partial x_j} \tag{4-2}
\]

Where \( u_i \) is the measured fluid flow in direction \( i \) (numbers 1, 2, 3 represent \( x, y, z \) direction respectively), \( p \) is the pressure of the fluid, \( \rho \) is the density of the fluid, \( \nu \) is the kinematic viscosity, \( t \) is time and \( x_i \) is displacement in the \( i \) direction. The first term of equation 4-2 on the left had side represents the time rate of change in flow. The second term on the left hand side represents nonlinear convection. The first term on the right hand side represents the flow pressure gradient. The second term on the right hand side represents the fluid viscosity.
A turbulent flow can be considered as an ensemble average of different solutions of the Navier-Stokes equations. In order to describe this the $u_i$ term (the experimentally measured term) can be decoupled into two more terms as shown below and called the decomposition rule

$$u_i = \langle U_i \rangle + u'_i$$ \hspace{1cm} 4-3

where $\langle U_i \rangle$ is the ensemble average and is defined by

$$\langle U_i \rangle = \frac{1}{N} \sum_{i=0}^{N} u_i$$ \hspace{1cm} 4-4

Where $N$ is the number of measured experiments. The $u'_i$ term is the flow fluctuation and the ensemble of a fluctuating quantity is zero by definition as shown in the following equation

$$\langle u'_i \rangle = \frac{1}{N} \sum_{i=0}^{N} (u_i - \langle U_i \rangle) = 0$$ \hspace{1cm} 4-5

Likewise the pressure $p$ can be decomposed into a mean and fluctuation components as shown below

$$p = \langle P \rangle + p'$$ \hspace{1cm} 4-6

Similarly the $\langle P \rangle$ and $p'$ terms are the average pressure and pressure fluctuation respectively similar to the aforementioned velocity composition equation 4-3. Furthermore, the concentration $c$ can also be decomposed into a mean and fluctuation components as well

$$c = \langle C \rangle + c'$$ \hspace{1cm} 4-7

Similarly the $\langle C \rangle$ and $c'$ terms are the concentration ensemble average and concentration fluctuation respectively similar to the aforementioned velocity and pressure decomposition.
It should be noted that concentration in g/lit was determined by correlating the picture intensity to the measured dye concentration in grams per liter as given by the following equation

\[ c = 9.521 \cdot 10^{-8} e^{0.0319 I} \]  

Equation 4-8

Where \( I \) is the picture dye intensity.

The \( u_i, p \) and \( c \) terms above are generally linked to laboratory situations in which measurements are taken at specific locations in a statistically steady and generally inhomogeneous flow field. Since the inhomogeneous flow field is position dependent, the ensemble average measurement, \( \langle U_i \rangle, \langle P \rangle \) and \( \langle C \rangle \) would be a function of position. Thus localized point location rather than spatial averages taken as information about the flow field will be lost due to averaging [32].

For time averaging to make sense the above integrals (equation 4-4 and 4-5) must be independent of time \( t_0 \). This means that the change in the mean measured flow rate \( \langle U_i \rangle \) must be steady and not vary with time assuming that \( T \gg t \) as shown in the following equation

\[ \frac{\partial \langle U_i \rangle}{\partial t} = 0 \]  

Equation 4-9

The measurement accuracy depends on the length of the averaging time \( T \) and is usually determined over a long time periods.

Because of time averaging, the mean value of the measured velocity \( u_i \) is equal to the corresponding spatial derivative of the mean flow value and the flow fluctuation mean of that measured velocity. Also the spatial derivative of the flow fluctuation mean \( u_i \) is zero as shown in the following equations
\[
\langle \partial U_i \rangle = \frac{\partial}{\partial x_j} \langle U_i \rangle 
\]

\[
\langle \partial u_i \rangle = \frac{\partial}{\partial x_j} \langle u_i \rangle = 0
\]

Since the flow chamber conditions are incompressible, the mean flow \( \langle U_i \rangle \) is constant in the same directional length as shown in the following equation:

\[
\frac{\partial \langle U_i \rangle}{\partial x_i} = 0
\]

Applying the decomposition rule 4-3 to the continuity equation 4-1 the following equation is produced

\[
\frac{\partial u_i}{\partial x_i} = \frac{\partial}{\partial x_i} \left( \langle U_i \rangle + u_i \right) = \frac{\partial \langle U_i \rangle}{\partial x_i} + \frac{\partial u_i}{\partial x_i} = 0
\]

Which indicates that the \( \partial u_i / \partial x_i \) term on the left hand side of the equation is equal to zero

\[
\frac{\partial u_i}{\partial x_i} = 0
\]

Furthermore, product averages of the measured flow can be determined as follows

\[
\langle u_i u_j \rangle = \langle (\langle U_i \rangle + u_i) (\langle U_j \rangle + u_j) \rangle
\]

\[
= \langle \langle U_i \rangle \langle U_j \rangle + u_i u_j + \langle u_i \rangle u_j + \langle u_j \rangle u_i \rangle
\]

\[
= \langle U_i \rangle \langle U_j \rangle + \langle u_i u_j \rangle
\]

The \( \langle U_i u_j \rangle \) terms are zero because the average of the fluctuations term \( \langle u_i \rangle \) is zero by definition. In contrast, the multiplication of two fluctuation average terms \( \langle u_i u_j \rangle \) from two
different directions are not zero because each term is not completely independent from the other term due to the turbulence influence with constantly changing flow in both directions. Thus multiplication of the fluctuation averages cannot be strictly zero.

With the above equations, the fluid motion equations for the mean flow \( \langle U_i \rangle \) can be obtained by substituting equation 4-3 into 4-2 and taking the average (ensemble average) of all the terms as shown in the following equation

\[
\frac{\langle \partial (\bar{U}_i + u_i) \rangle}{\partial t} + \langle \partial (\bar{U}_j + u_j) \rangle \frac{\partial \langle U_i + u_i \rangle}{\partial x_j} = -\frac{1}{\rho} \langle \partial (\bar{P} + p') \rangle + \nu \frac{\partial^2 \langle U_i + u_i \rangle}{\partial x_i \partial x_j}
\] 4-16

Realizing that the time average of any fluctuation is zero the above equation is further reduced. The first term on the left hand side of the equation becomes zero by also applying equation 4-9. The second term on the left hand side reduces to the following equation

\[
\langle U_j \rangle \frac{\partial \langle U_i \rangle}{\partial x_j} + \langle u_j \frac{\partial u_i}{\partial x_j} \rangle
\] 4-17

Which can be rewritten further using the decomposed turbulent velocity fluctuation continuity equation 4-14 thus

\[
\langle u_j \frac{\partial u_i'}{\partial x_j} \rangle = \frac{\partial}{\partial x_j} \langle u_i u_j' \rangle
\] 4-18

The first term on the right hand side of equation 4-16 reduces to

\[
-\frac{1}{\rho} \frac{\partial \langle P \rangle}{\partial x_i}
\] 4-19

The second term on the right hand side of equation 4-16 reduces to
Putting these above terms (equations 4-17, 4-18, 4-19 and 4-20) together the Navier-Stokes equation for turbulence becomes the mean-flow equation otherwise known as the Reynolds momentum equation as shown below

\[
\frac{\partial \langle U_i \rangle}{\partial t} + \langle U_j \rangle \frac{\partial \langle U_i \rangle}{\partial x_j} = -\frac{1}{\rho} \frac{\partial \langle P \rangle}{\partial x_i} + \nu \frac{\partial^2 \langle U_i \rangle}{\partial x_j \partial x_j} + \frac{\partial}{\partial x_j} \langle u'_i u'_j \rangle
\]

\[
= \frac{1}{\rho} \frac{\partial}{\partial x_j} \left\{ -\langle P \rangle \delta_{ij} + \mu \left( \frac{\partial \langle U_j \rangle}{\partial x_j} + \frac{\partial \langle U_i \rangle}{\partial x_i} \right) - \rho \langle u'_i u'_j \rangle \right\}
\]

The second term on the left hand side of the equation is the convective term and introduces coupling between the mean and fluctuating (or turbulent) parts of the velocity field through the Reynolds stress tensor. The terms in the \{ \} are described from left to right as the mean pressure stress, the mean viscous stress tensor, and the Reynolds stress tensor respectively. The Reynolds stress tensor is much greater than the mean viscous stress tensor

\[
\rho \langle u'_i u'_j \rangle \gg \mu \left( \frac{\partial \langle U_j \rangle}{\partial x_j} + \frac{\partial \langle U_i \rangle}{\partial x_i} \right).
\]

The Reynolds stress term is a very important concept in turbulence theory it represents the following [32, 33]

1. The average momentum flux due to turbulent velocity
2. Mean transport of fluctuating momentum by turbulent velocity fluctuations which is the key of turbulent motion
3. Its divergence can be interpreted as the forcing of the mean flow by turbulence
4. It is the second order moment of the velocity components at a single point in space
5. It can be 500 times larger than the mean viscous stress tensor causing the viscous stress tensor to generally be neglected.

Furthermore, the turbulent kinetic energy is as follows:

\[
\frac{D}{Dt}\left(\frac{1}{2}\langle u_i'^2 \rangle\right) = \frac{\partial}{\partial x_j}\left(-\frac{\langle p u_j' \rangle}{\rho} + 2\nu u_i' s_{ij} - \frac{1}{2}\langle u_i'^2 u_j' \rangle\right) - 2\nu \langle s_{ij} s_{ij} \rangle - \langle u_i' u_j' \rangle \frac{\partial\langle u_i \rangle}{\partial x_j}
\]

4-22

The above equation represents the turbulent kinetic energy transfer within the fluid flow. The first term on the left hand side is the total change in turbulent kinetic energy. The first term on the right hand side represents fluid transport. The second term is the viscous dissipation and for fluctuation conditions this value is not small compared to the mean kinetic energy. The third term is the turbulent production. The \(s_{ij} = \frac{1}{2} \left( \frac{\partial u_i'}{\partial x_j} + \frac{\partial u_j'}{\partial x_i} \right)\) term is the strain rate tensor for the fluctuating field.

Similarly the concentration equation given the velocity and concentration decompositions produce the following time-averaged transport equation:

\[
\langle U_i \rangle \frac{\partial \langle C \rangle}{\partial x_i} = D \frac{\partial^2 \langle C \rangle}{\partial x_i^2} + \frac{\partial}{\partial x_i} \langle u_i' c' \rangle
\]

\[
= \frac{\partial}{\partial x_i} \left\{ D \frac{\partial \langle C \rangle}{\partial x_i} - \langle u_i' c' \rangle \right\}
\]

4-23

Where \(D\) is the molecular diffusion coefficient and is usually a very small number (\(\sim 10^{-5} - 10^{-9}\)). Both terms on the right hand side of the equation represent mass transport. The first term on the right hand side represents the transport due to molecular diffusion. The second term represent
the turbulent flux. Generally, the turbulent flux is much greater than the molecular diffusion coefficient, \( \langle u_i'c' \rangle \gg D \frac{\partial \langle C \rangle}{\partial x_i} \), thus the molecular diffusion transport term is neglected.

Similarly in order to predict the evolution of the concentration fluctuation an energy conservation equation for concentration fluctuation is as follows

\[
\langle U_i \rangle \frac{\partial \langle c'^2 \rangle}{\partial x_i} = -2 \left[ \langle u_k'c' \rangle \frac{\partial \langle c \rangle}{\partial x_k} + \langle u_j'c' \rangle \frac{\partial \langle c \rangle}{\partial x_j} \right] - \left[ \frac{\partial}{\partial x_k} \langle u_k'c'^2 \rangle + \frac{\partial}{\partial x_j} \langle u_j'c'^2 \rangle \right] - S
\]

(4-24)

Where \( S \) is the rate of reduction of the mean square fluctuations by molecular diffusion [34]. The first term on the right hand side of the equation is the turbulence concentration fluctuation term.

From the above equations, important physical measures of turbulent flow can be used to characterize flow and are generally discussed in many turbulent books such as [32, 33, 34, 35, 36]. These physical measures include Reynolds stress, turbulent kinetic energy, turbulent mass flux, turbulent production, turbulent concentration production and vorticity. Reynolds stress and mass flux terms developed above are shown in the following equations respectively

\[
\langle \tau_{ij} \rangle = -\rho \langle u_i' u_j' \rangle \]

(4-25)

\[
\langle \tau_{ci} \rangle = -2\langle u_i'c' \rangle
\]

(4-26)

Where \( \langle \tau_{ij} \rangle \) is the Reynolds stress ensemble average and \( \langle \tau_{ci} \rangle \) is the mass flux ensemble average and \( \rho \) is the density of water at 20°C (998.2 kg/m³).

Kinetic energy velocity and concentration turbulent fluctuations is generated during turbulent flow and transfers from place to place by convection and work done by the fluid.
against neighboring fluid through viscous stresses and pressure. The velocity and concentration kinetic energy equations are shown below respectively

\[
\langle K_u \rangle = \frac{1}{2} \left( \langle u_i u_i \rangle + \langle u_j u_j \rangle \right) \quad 4-27
\]

\[
\langle K_c \rangle = \frac{1}{2} \left( \langle \dot{c} \dot{c} \rangle \right) \quad 4-28
\]

Where \( \langle K_{ij} \rangle \) is the kinetic energy ensemble average and the \( \langle K_c \rangle \) is the concentration kinetic energy ensemble average.

Turbulent production is responsible for generating (or destroying) turbulent energy. The positive sign corresponds to energy production and the negative sign corresponds to energy destruction. It is interpreted as representing turbulence production by interaction between the mean flow and turbulence and contains more information about the nature of turbulence production owing to its tensorial nature

\[
\langle P_{ij} \rangle = -\langle u_i u_j \rangle \left( \frac{\partial \langle u_i \rangle}{\partial x_j} + \frac{\partial \langle u_j \rangle}{\partial x_i} \right) \quad 4-29
\]

For concentration condition the turbulence concentration fluctuations is defined as the mass flux multiplied by the change in concentration divided by the change in distance and is represented by the following equation

\[
\langle P_{cij} \rangle = -2 \left( \langle c \dot{u}_i \rangle \frac{\partial \langle c \rangle}{\partial x_i} + \langle \dot{c} u_i \rangle \frac{\partial \langle c \rangle}{\partial x_j} \right) \quad 4-30
\]
Vorticity is small scales of turbulence that are produced, maintained and amplified by stretching of vortex lines and especially arises at boundary locations. It is defined by the following equation

\[
\langle \omega_j \rangle = 2 \left( \frac{\partial \langle u_k \rangle}{\partial x_j} - \frac{\partial \langle u_j \rangle}{\partial x_k} \right)
\]

Subsequent sections discuss the simplified versions of the above equations and corresponding assumptions in detail.

5 BASE FLOW CONDITIONS

The baseline-flow was first characterized with glass only conditions devoid of any bottom porous substrates and set to the highest volumetric flow rate of the flow chamber system. PIV and optical flow measurements were taken which enables a base foundation to compare differences between other conditions such as the aforementioned rough and relatively porous substrates. Flow profiles for every case were measured along both the \(x-y\) and \(x-z\) plane. The \(x-y\) plane was measured at the center of the flow chamber (called Middle) using a vertical laser sheet shining along the central axial length of the flow chamber. The \(x-z\) plane was measured at various vertical heights (called Bottom, Middle and Top for glass beads condition and Bottom, Level2, Level3 and Level4 for dye conditions) with a horizontal laser sheet. During the experimentation, the laser sheets illuminate both glass beads flowing with the water and dye expelling from substrate surfaces within the flow chamber. As the fluid moves through the chamber, picture pairs are taken and processed via optical flow techniques so that the ensemble average of velocity, vorticity, Reynolds-stress, kinetic energy, and turbulence production and corresponding concentration metrics can be determined. It should be noted that the center
support bar of the flow chamber side window causes part of the vertical flow viewing area to be obstructed. This same support bar also casts a shadow in the span-wise direction along the viewing area when recording the horizontal flow with the camera. This area was generally neglected during the analysis of the aforementioned metrics. The vorticities, were normalized by the flow chamber height divided by the measured velocities through the flow chamber $H_y / U_{avg}$ where $H_y$ is the height of the flow chamber (0.01125 m) and $U_{act}$ is the measured average flow through the flow chamber (0.225 m/s). The kinetic energy and Reynolds-stress were normalized by the square of the actual velocities $1/U_{avg}^2$. Turbulence production were normalized by the height of the flow chamber and the measured velocity cubed $H_y / U_{avg}^3$.

Base flow conditions were developed by laser illuminating glass beads with no porous substrates attached to the base of the flow chamber. This base flow condition is necessary to compare with other dye impregnated porous surface base conditions present within the flow chamber. For base flow experiments, three horizontal conditions are analyzed and shown for the Bottom, Middle and Top vertical locations. One vertical condition is analyzed and shown for the Middle ($z / H_y = 0$) horizontal location. Specific vertical and horizontal numerical values for these locations have been provided in previous sections above.

5.1 Horizontal and Vertical Base Flow Velocity Magnitude Field

The normalized velocity magnitude field was calculated for the horizontal plane as shown in the following figures. In presenting the magnitude fields below, the calculated velocities were first normalized by the average maximum velocity through the flow chamber.
Figure 28: Horizontal velocity magnitude field at Bottom laser position, glass beads with no substrate attached to the flow chamber bottom.

Figure 29: Horizontal velocity magnitude field at Middle laser position, glass beads with no substrate attached to the flow chamber bottom.

Figure 30: Horizontal velocity magnitude field at Top laser position, glass beads with no substrate attached to the flow chamber bottom.

These field graphs for Bottom, Middle and Top horizontal sheet laser locations indicate a high velocity condition as the fluid enters the flow chamber and dissipates as the fluid progresses down the flow chamber. The increased flow at the beginning of the flow chamber is due to the flow entering the chamber through an orifice smaller than the cross-sectional area of the chamber box. The velocity magnitude is greatest at the Middle location as expected due to the location of this orifice at the flow chamber middle. The flow is shown to dissipate as it progresses through
the flow chamber. Higher velocity magnitudes seem to extend further along the length of the flow chamber for the Bottom and Top laser locations. The Middle laser location shows the highest overall velocity within the field. Velocity magnitudes for the bottom and middle laser location also seem to favor the positive side of the flow chamber at the beginning and move slightly to the negative sided of the flow chamber toward the end. This is most likely due to the flow development occurring from slight inconsistencies of the chamber geometries despite efforts using the long (0.61 m long 3/8 inch) copper pipe and flow expander previously discussed.

The velocity magnitude for the vertical laser positioned at the $z/H_y = 0$ location is shown in the following figure:

![Figure 31: Vertical velocity magnitude field at Middle laser position, glass beads with no substrates attached to the flow chamber bottom.](image)

As with the horizontal condition the velocity magnitude is shown to be higher at the beginning of the flow chamber and then gradually dissipate along the flow chamber length. Dark regions shown in the above figures are the result of the chamber side window structure obstructions which causes shadows to form along the left and right edges and center of these magnitude field graphs.
5.2 Base Flow Horizontal and Vertical Normalized Velocity Profile

The velocity profile was measured for three horizontal planes (Bottom, Middle and Top) and one vertical plane (Middle) located at $z/H_y = 0$ as previously discussed above. They were created using the ensemble average of 2000 picture pairs in the $x$-direction $\langle u_t \rangle$ which is normalized via $\langle u_t \rangle / \max(|u_t|)$. The maximum velocity of 0.175, 0.239 and 0.198 m/s for Bottom, Middle and Top laser positions respectively. The vertical plane was normalized by the maximum velocity of 0.195 m/s for the middle position. The profiles for these planes are shown in the following figures. It should also be noted that the terms $\langle \eta \rangle$ where $\eta$ represents $u$, $K_{13}$, $\tau_{13}$, $P_{13}$ and $\omega_2$ represents the average of the three different horizontal layers.

![Flow chamber normalized velocity profile with glass beads using horizontal laser sheet applied at the Bottom, Middle and Top laser positions, ensemble average of 2000 picture pair runs.](image)

Figure 32: Flow chamber normalized velocity profile with glass beads using horizontal laser sheet applied at the Bottom, Middle and Top laser positions, ensemble average of 2000 picture pair runs.
Figure 33: Normalized velocity average of Bottom, Middle and Top ensemble average laser position of flow chamber velocity with glass beads.

Figure 34: Flow chamber normalized velocity profile with glass beads using vertical laser sheet applied at the Middle laser position, ensemble average of 2000 picture pair runs.
As shown in Figure 32 above, the horizontal laser position ensemble average indicates a generally uniform symmetric profile with the maximum velocity generally at the flow chamber center. The three different curves are similar even though they are taken at different vertical locations within the flow chamber which could experience different turbulent flow conditions resulting in the differences from one profile to the next. The curves are somewhat pointed, but does not necessarily reflect the typical text book laminar profile compared to a turbulent flat nose profile. As shown in subsequent sections, flow profiles for the different metrics will be shown to be quite complex due to turbulence occurring within the flow chamber. Figure 33 shows the average of these three curves. The slight upturn of the profile at the sides of the chamber are due to reduced glass bead concentration present due to inherent boundary layers forming at these side locations which cause the glass particles to generally move away from the flow chamber sides. Furthermore, the upturn could also be caused by the reduce pixel resolution due to the overall window size being measured and velocity averaging calculation between the bulk flow and zero velocity side boundary. Thus measurements close to the side walls are not reliable.

Figure 34 is the vertical laser position ensemble average of the base flow in the $x$ - direction for the Middle location ($z = 0$) indicates a non-symmetric profile with the maximum velocity generally at the center of the flow chamber. The non-symmetry is due to the top portion of the flow chamber hidden by the viewing side window area. It is expected that if this window was fully extended to the top of the flow chamber the vertical profile would be approximately symmetric. The vertical profile is rounded at the center as expected for this flow condition. Again, the slight upturns of the profile at the sides of the chamber are due to minimal glass particulates, the pixel resolution averaging and boundary layer conditions.
5.3 Horizontal and Vertical Base Flow Normalized Kinetic Energy

Turbulence extracts energy from the mean flow at large scales and this gain is approximately balanced by viscous dissipation of energy at very small scales [32]. The kinetic energy profile was measured for three horizontal planes (Bottom, Middle and Top) and one vertical plane (Middle) as previously discussed above. The profiles for these planes are shown in the following figures.

Figure 35: Flow chamber normalized kinetic energy profile with glass beads, using horizontal laser sheet for Bottom, Middle and Top position, ensemble average of 2000 picture pair runs.
Figure 36: Normalized kinetic energy average of Bottom, Middle and Top ensemble average laser position of flow chamber velocity with glass beads.

Figure 37: Flow chamber normalized kinetic energy profile with glass beads using a vertical laser sheet at the Middle laser position with, ensemble average of 2000 picture pair runs.
In Figure 35 above, the ensemble average of the base flow normalized horizontal kinetic energy profile in the $x$-direction, $\langle K_{13} \rangle / \max(|\langle K_{13} \rangle|)$ where $K_{13} = \left( \langle u_i u_i \rangle + \langle u_3 u_3 \rangle \right)$ is given for the Bottom, Middle and Top conditions indicates a somewhat skewed symmetric profile with the maximum kinetic energy appearing offset from the flow chamber center toward the negative $z/H_y$ region. The maximum value of the previously normalized kinetic energy used for creating the normalized horizontal profile for the Bottom, Middle and Top laser position are 0.010, 0.010 and 0.009 respectively. The three different curves are similar even though they are taken at different vertical locations within the flow chamber. In the positive $z/H_y$ region, moving from the center to the side wall, the kinetic energy profile creates a condition where the kinetic energy reduces, then increases and reduces again. There also seems to be a similar anomaly, albeit small, in the negative $z/H_y$ region at a similar location. This is due to the reduction and increase of the turbulent fluctuation occurring in those areas from competing flow structures which cancel each other out within the flow chamber. Figure 36 shows the average of these three curves.

In Figure 37 the ensemble average of the base flow normalized vertical kinetic energy profile in the $x$-direction, $\langle K_{12} \rangle / \max(|\langle K_{12} \rangle|)$ where $K_{12} = \frac{1}{2} \left( \langle u_i u_i \rangle + \langle u_2 u_2 \rangle \right)$ is given for the Middle location ($z = 0$), indicates a mostly symmetric but flat nose profile with the maximum kinetic energy occurring generally at the center of the flow chamber. The maximum value of the previously normalized kinetic energy used for creating the normalized vertical profile for the Middle laser position is 0.021. Moving toward the bottom of this flow chamber the kinetic energy seems to decrease by 42% and then abruptly increase again. Indicating that the turbulent fluctuations decrease but close to the bottom kinetic energy abruptly increases again. It is
expected that if the viewing window was fully extended to the flow chamber top a similar trend would also be seen. Although this phenomena seems to be present as well with the horizontal configuration, this abrupt change may be due to the aforementioned issues of flow measured close to the chamber boundaries.

5.4 Horizontal and Vertical Base Flow Normalized Turbulent Reynolds Stress

The normalized turbulent Reynolds stress was measured for three horizontal planes (Bottom, Middle and Top) and one vertical plane (Middle) located at $z/H_y = 0$ as previously discussed above. Turbulent Reynolds stress is shear stresses that play a dominate role in mean momentum transfer by turbulent motion and is expected to be symmetric [32].

![Normalized Reynolds Stress Profile](image)

Figure 38: Flow chamber normalized Reynolds stress profile with glass beads using horizontal laser sheet at Bottom, Middle and Top laser positions, ensemble average of 2000 picture pair runs.
Figure 39: Normalized Reynolds stress average of Bottom, Middle and Top ensemble average laser position of flow chamber velocity with glass beads.

Figure 40: Flow chamber normalized Reynolds stress profile with glass beads using vertical laser sheet at Middle position, ensemble average of 2000 picture pair runs.
In Figure 38, the ensemble average of the base flow normalized horizontal Reynolds stress profile in the $x$-direction, $\langle \tau_{13} \rangle / \max(\langle |\tau_{13}| \rangle)$ where $\tau_{13} = -\rho \langle u'_i u'_3 \rangle$ is given for the Bottom, Middle and Top conditions is shown. The maximum value of the previously normalized Reynolds stress used for creating the normalized horizontal profile for the Bottom, Middle and Top laser position are -3.31, -4.05 and -2.77 respectively. The profiles indicates a generally skewed S-shape profile with zero Reynolds stress occurring at the approximate center and sides of the flow chamber. The positive and negative Reynolds stress occur within the negative and positive $z/H_y$ regions respectively with the positive Reynolds stress being less pronounced in the negative region. It was expected that the positive Reynolds stress be of the same magnitude as the negative portion of the Reynolds. However because of reduce turbulent fluctuation activity on that side of the flow chamber, due to what seems to be an artifact of the flow chamber itself, the turbulent Reynolds stress was reduced. A higher flow rate is expected to increase the magnitude of the positive turbulent Reynolds stress. The maximum and minimum Reynolds stress within the flow chamber occur at approximately at $z/H_y$ of 0.75 and -0.75, about 1/4 of the width of the flow chamber. The three different horizontal laser positions are similar even though they are taken at different vertical locations within the flow chamber. Figure 39 shows the average of these three curves.

In Figure 40 the ensemble average of the base flow normalized Reynolds stress profile in the $x$-direction, $\langle \tau_{12} \rangle / \max(\langle |\tau_{12}| \rangle)$ where $\tau_{12} = -\rho \langle u'_i u'_2 \rangle$, is given for the Middle location ($z = 0$), indicates an S-shape velocity profile condition within the flow chamber. The maximum value of the previously normalized Reynolds stress used for creating the normalized vertical profile for the Middle is -3.35e-05. The normalized Reynolds stress is zero at the bottom and
center of the flow chamber. It is expected that it would also be zero at the top of the flow chamber if it could be seen from the side window. The Reynolds stress maximum and minimum occurs at $y/H_y = 0.33$ and 0.7 respectively and are located approximately $1/3$ of the vertical distance as compared to $1/4$ of the horizontal distance in the horizontal plane.

### 5.5 Horizontal and Vertical Base Flow Normalized Turbulent Production

The normalized turbulent production was measured for three horizontal planes (Bottom, Middle and Top) and one vertical plane (Middle) located at $z/H_y = 0$ as previously discussed above.

Turbulent stresses creates fluid deformation work, the kinetic energy of the turbulence benefits from this work and is known as turbulent production [32]. The turbulent production term is always positive because the term is a positive semidefinite (eigenvalues are non-negative).

![Flow chamber normalized turbulence production profile with glass beads using horizontal laser sheet for Bottom, Middle and Top laser positions, ensemble average of 2000 picture pair runs.](image)

**Figure 41:** Flow chamber normalized turbulence production profile with glass beads using horizontal laser sheet for Bottom, Middle and Top laser positions, ensemble average of 2000 picture pair runs.
Figure 42: Normalized turbulent production average of Bottom, Middle and Top ensemble average laser position of flow chamber velocity with glass beads.

Figure 43: Flow chamber normalized turbulence production profile with glass beads using vertical laser sheet at Middle position, ensemble average of 2000 picture pair runs.
As shown in Figure 41 the ensemble average of the base flow normalized horizontal turbulent production profile in the $x$-direction, $\langle P_{113} \rangle / \max(|\langle P_{113} \rangle|)$ where $P_{113} = -\langle u_i u_j \rangle \left( \frac{\partial \langle U_1 \rangle}{\partial x_3} + \frac{\partial \langle U_3 \rangle}{\partial x_i} \right)$, is given for the Bottom, Middle and Top conditions are shown. The maximum value of the previous normalized turbulent production used for creating the normalized horizontal profile for the Bottom, Middle and Top laser position are $-1.70\times10^{-6}$, $-2.65\times10^{-6}$ and $-1.58\times10^{-6}$ respectively. The three different horizontal curves are similar even though they are taken at different vertical locations within the flow chamber. These profiles become zero at the sides of the flow chamber. The maximum turbulent production occurs at the negative $z/H_y$ side of the flow chamber at approximately $z/H_y = -0.65$ for the Bottom and Middle conditions. Maximum turbulent production for the Top condition occurs at approximately $z/H_y = -1.2$. A similar but smaller signal also occurs at approximately the same location but on the positive side of the flow chamber $z/H_y = 1.2$. The turbulent production within the flow chamber decreases from its maximum at the negative side of the flow chamber toward the center and reduces to approximately zero at the positive side of the flow chamber. It was expected that the signal be more symmetric at the positive $z/H_y$ side of the flow chamber instead, the signal stayed close to zero. The Top signal did show a slight increase than the other signals but it was minimal. The turbulent production reduction in the positive $z/H_y$ region is due to the minimal Reynolds stress that occurred in that region as discussed previously. Figure 42 shows the average of these three curves.
In Figure 43 the ensemble average of the base flow normalized vertical turbulent production profile in the $x$-direction, $\langle P_t \rangle / \max(|\langle P_t \rangle|)$ where $P_t = -\langle u'_i u'_z \rangle \left( \frac{\partial \langle U_i \rangle}{\partial x_2} + \frac{\partial \langle U_z \rangle}{\partial x_1} \right)$, is given for the Bottom, Middle and Top conditions are shown. The maximum value of the previous normalized turbulent production used for creating the normalized vertical profile for the Middle laser position is $-3.3542 \times 10^{-5}$. A sideways sinusoidal like shape is presented with the turbulent production profile starting from approximately zero at the bottom of the flow chamber and then increasing along the $y$-axis where it reaches a local maxima at approximately $y/H_y = 0.28$. The signal then decrease to zero at approximately $y/H_y = 0.55$. The signal increases again to another local maxima at approximately $y/H_y = 0.75$ and decreases to zero at the top of the flow chamber. This show a symmetrical behavior of the signal and indicates that the turbulent production is generally split equally between top to bottom of the flow chamber but in opposite directions and indicate layers of turbulent production.

### 5.6 Horizontal and Vertical Base Flow Normalized Vorticity

The normalized vorticity was measured for three horizontal planes (Bottom, Middle and Top) and one vertical plane (Middle) located at $z/H_y = 0$ as previously discussed above. Vorticies effectively extract energy from the mean flow and are maintained by shear [32].
Figure 44: Flow chamber normalized vorticity profile with glass beads using horizontal laser sheet for Bottom, Middle and Top laser positions, ensemble average of 2000 picture pair runs.

Figure 45: Normalized vorticity average of Bottom, Middle and Top ensemble average laser position of flow chamber velocity with glass beads.
In Figure 44 ensemble average of the horizontal base flow normalized vorticity profile along the \( x \)-direction, \( \langle \omega_z \rangle / \max(\langle |\omega_z| \rangle) \), where \( \omega_z = 2 \left( \frac{\partial \langle u_z \rangle}{\partial x_3} - \frac{\partial \langle u_x \rangle}{\partial x_1} \right) \), is given for the Bottom, Middle and Top conditions are shown. The maximum value of the previously normalized vorticity used for creating the normalized horizontal profile for the Bottom, Middle and Top laser position are 1.84, 1.77 and 1.82 respectively. The three different horizontal curves are similar even though they are taken at different vertical locations within the flow chamber. The profiles indicates a generally skewed S-shape profile with zero vorticity occurring at the sides and approximate center of the flow chamber. The maximum and minimum normalized vorticity occurs next to the sides of the flow chamber (approximately \( z / H_y = -1.4 \) and 1.4) with positive and negative vorticity occurring at the positive and negative \( z / H_y \) regions respectively. Moving
from the maximum vorticity toward the center of the flow chamber, the vorticity tends to
generally decrease linearly. However, as the vorticity decreases there seems to be a small local
maxima and minima at approximately \( z/H_y = 0.5 \) and \(-0.5\). This seems to indicate layers of
fluid rotating at different speeds moving from the sides of the flow chamber to the center. Once
the center is reached the vorticities reverses and rotate at similar speeds at similar fluidic layers.
Figure 45 shows the average of these three curves.

In Figure 46 the ensemble average of the vertical base flow normalized vorticity profile in
the \( x \)-direction, \( \langle \omega_x \rangle / \max(|\langle \omega_x \rangle|) \), where
\[
\omega_x = 2 \left( \frac{\partial \langle u_2 \rangle}{\partial x_1} - \frac{\partial \langle u_1 \rangle}{\partial x_2} \right)
\]
for the Middle location (\( z/H_y = 0 \)), indicates a reversed S-shape normalized vorticity within the flow chamber. The
maximum value of the previously normalized vorticity used for creating the normalized vertical
profile for the Middle laser position are 1.98. The lowest and highest vorticity seems to occur
toward the bottom and top of the flow chamber bottom at approximately \( y/H_y = 0.13 \) and 0.76
respectively. The vorticity is approximately zero at the center of the flow chamber. The
normalized vorticity moves almost linearly going from the bottom to the top of the flow
chamber. There are slight small local maxima and minima along this linear region moving
toward the center of the flow chamber. Vorticity direction changes with similar magnitudes
from negative to positive moving from the bottom to the top of the flow chamber.

5.7 Horizontal and Vertical Base Flow Combined Summary

In the preceding sections above velocity, vorticity, kinetic energy, Reynolds stress and
turbulent production metrics for the three horizontal planes (Bottom, Middle and Top) and one
vertical plane (Middle) at \( z/H_y = 0 \) were shown for individual base flow conditions. In this
section these metrics were combined together for comparison. In these combined plots the trends are shown to have similar behavior as discussed in Pope [35] chapter seven and Perot [36] using DNS data.

Figure 47: Combined profiles of a horizontal Bottom laser sheet position with glass beads, ensemble average of 2000 picture pair runs.

Figure 48: Combined profiles of a horizontal Middle laser sheet position with glass beads, ensemble average of 2000 picture pair runs.
Figure 49: Combined profiles of a horizontal Top horizontal laser sheet position with glass beads, ensemble average of 2000 picture pair runs.

Figure 50: Combined overall average horizontal laser sheet profiles with glass beads of ensemble average of 2000 picture pair runs.
From a turbulent standpoint, the overall measured velocity $u_i$ and its decomposed terms of mean velocity $\overline{U}_1$ and fluctuation term $u'_i$ help calculate the above metrics. Regardless of the laser sheet direction, the velocity shows a classical profile which peaks at the middle and symmetrically reduces toward either side of the flow chamber. The vorticity by definition is

$$\langle \omega_j \rangle = 2 \left( \frac{\partial \langle u_j \rangle}{\partial x_k} - \frac{\partial \langle u_k \rangle}{\partial x_j} \right)$$

indicates a direction reversal depending on the side of the flow chamber. The vorticity profiles between the horizontal and vertical laser potions should have opposite directions due to the sign change shown in the equations. However, the program generating the profile only assumes an $x$ - $y$ axis case and solves only for the $\omega_3$ vorticity regardless of laser position. The vorticity eventually reaches its maximum as the velocity reduces moving toward the side of the flow chamber.
The kinetic energy shown in the above combination curves as defined by
\[ K_{13} = \frac{1}{2} \left( \langle u_1 u_1 \rangle + \langle u_3 u_3 \rangle \right) \] for the horizontal laser positions and
\[ K_{12} = \frac{1}{2} \left( \langle u_1 u_1 \rangle + \langle u_2 u_2 \rangle \right) \] for the vertical laser position, generally follows the velocity profile with a flatter curve along the flow chamber center with its maximum along the flow chamber center. The kinetic energy for both horizontal and vertical positions seem to fluctuate close to the flow chamber sides. A higher maintained kinetic energy occurs with higher Reynolds stress (both positive and negative directions) and higher turbulent production signals. In contrast, the kinetic energy seems to reduce with a lower Reynolds stress and turbulent production signals as shown in positive \( z/H_y \) side of the horizontal laser profiles.

The Reynolds stress as defined by
\[ \tau_{13} = -\rho \langle u_1 u_3 \rangle \] and
\[ \tau_{12} = -\rho \langle u_1 u_2 \rangle \] for the horizontal and vertical laser position respectively and has both positive and negative values across the window being measured. The maximum and minimum Reynolds stress conditions occurs along the reducing slopes of the velocity curve. A high or low Reynolds stress is correlated to a high or low turbulent production condition respectively.

The turbulent production as defined by
\[ P_{13} = -\langle u_1 u_3 \rangle \left( \frac{\partial \langle u_1 \rangle}{\partial x_3} + \frac{\partial \langle u_3 \rangle}{\partial x_1} \right) \] and
\[ P_{12} = -\langle u_1 u_2 \rangle \left( \frac{\partial \langle u_1 \rangle}{\partial x_2} + \frac{\partial \langle u_2 \rangle}{\partial x_1} \right) \] for the horizontal and vertical laser position respectively is generally positive across the measured span of the flow chamber. The turbulent production, vorticity and Reynolds stress are zero at both the approximate flow chamber center and side boundaries.
6 FABRIC SUBSTRATE

Dye impregnated substrate flow conditions were developed by laser illuminating Rhodamine 6G fluorescent dye as it expels from the flow. Three different bottom substrate surfaces (AHAM towel, EMPA221 and Terry fabric) were used within the flow chamber. In these experiments four different horizontal laser positions are analyzed and shown for the Bottom, Level2, Level3 and Level4 vertical locations. Similar to the base flow conditions, one vertical condition is analyzed and shown for the Middle \((z/H_y = 0)\) horizontal location. The specific vertical and horizontal numerical values for these locations have been previously discussed in detail the above sections. The dye velocity magnitude field and conditions of normalized velocity, kinetic energy, Reynolds stress, turbulent production and vorticity including corresponding maximum values for these different metrics are shown in the following sections.

6.1 Horizontal and Vertical Dyed Substrate Flow Velocity Magnitude Field

As with the glass bead case, the following figures show the flow velocity magnitude field for four different laser horizontal laser sheet positions at the Bottom, Level2, Level3 and Level4 locations and one vertical laser sheet position at the Middle location for dye saturated AHAM, EMPA221 and Terry substrates.

![Figure 52: Horizontal velocity magnitude field for Bottom laser position with dye impregnated AHAM substrate attached to the flow chamber bottom.](image-url)
Figure 53: Horizontal velocity magnitude field for Level2 laser position with dye impregnated AHAM substrate attached to the flow chamber bottom.

Figure 54: Horizontal velocity magnitude field for Level3 laser location with dye impregnated AHAM substrate attached to the flow chamber bottom.

Figure 55: Horizontal velocity magnitude field for Level4 laser position with dye impregnated AHAM substrate attached to the flow chamber bottom.

Figure 56: Vertical velocity magnitude field for Middle laser position with dye impregnated AHAM substrate attached to the flow chamber bottom.
Figure 57: Horizontal velocity magnitude field for Bottom laser position with dye impregnated EMPA221 substrate attached to the flow chamber bottom.

Figure 58: Horizontal velocity magnitude field for Level2 laser position with dye impregnated EMPA221 substrate attached to the flow chamber bottom.

Figure 59: Horizontal velocity magnitude field for Level3 laser position with dye impregnated EMPA221 substrate attached to the flow chamber bottom.

Figure 60: Horizontal velocity magnitude field in for Level4 laser position with dye impregnated EMPA221 substrate attached to the flow chamber bottom.
Figure 61: Vertical velocity magnitude field for Middle laser position with dye impregnated EMPA221 substrate attached to the flow chamber bottom.

Figure 62: Horizontal velocity magnitude field for Bottom laser position with dye impregnated Terry substrate attached to the flow chamber bottom.

Figure 63: Horizontal velocity magnitude field for Level2 laser position with dye impregnated Terry substrate attached to the flow chamber bottom.

Figure 64: Horizontal velocity magnitude field for Level3 laser position with dye impregnated Terry substrate attached to the flow chamber bottom.
6.1.1 Dyed AHAM Substrate Flow Velocity Magnitude Field

For the dyed AHAM substrate, the horizontal velocity magnitude field plots (Figure 52 - Figure 55) indicate that velocity is lowest at the Bottom laser position and shows a slight expansion of the high velocity region moving toward the downstream side of the flow chamber. The velocity magnitude favors the longitudinal center of the flow chamber where the inlet orifice is positioned. Even though there are inherent dead zones at the center and ends of the flow chamber that cannot be measured due to shadows caused by the side window structure, it can be seen that there are regions with less velocity regions at the upstream side of the flow chamber. Higher velocity regions seem to be larger at the upstream and especially downstream side of the flow chamber with a slight regional reduction at the center of the flow chamber. Maximum velocity regions occur at both the upstream and downstream side of the flow chamber. For Level2 laser position, the overall velocity magnitude increases slightly from the Bottom laser position and shows a strong expansion of the high velocity region moving from the upstream to the downstream side of the flow chamber. The expansion of the high velocity region is due to
the developing flow coming from the flow chamber orifice. As the flow develops, more dye is picked up from the substrate surface and transferred to the moving bulk fluid unlike the Bottom laser position where the velocities are more uniform across the substrate surface. The maximum velocity for the Level2 laser position occurs at both the upstream and downstream side of the flow chamber with a majority of maximum flow conditions occurring at the downstream side of the flow chamber. For the Level3 laser position, the flow velocity is measured generally at the center of the flow chamber. The velocity magnitude field is approximately 2.5 times higher than the measured average velocity, the Bottom and Level2 laser position. This is due to the difference in measuring dye rather than glass beads and a substrate bottom rather than a glass bottom. Because of this high velocity, it may indicate that there are even higher velocities that were not picked up specifically by the three laser levels for the non-substrate empty flow chamber previously discussed glass beads case. The expansion of the maximum velocity region from the upstream to the downstream side of the flow chamber was not as prevalent as the Level2 case but still showed a slight increase of higher flow regions moving from upstream to downstream side of the flow chamber. Also the maximum flow generally occur mostly at the upstream side of the flow chamber. The Level4 laser position shows the velocities increase to more than four times what was measured for the Bottom and Level2 laser position. This, again, is due to the difference in measuring dye conditions with a rough substrate bottom rather than glass beads and a smooth glass bottom. Overall the velocity magnitudes seems to increase moving from the flow chamber bottom to the top of the flow chamber. It is expected that even higher velocities will occur toward the top of the flow chamber. The expansion of the high velocity region from the upstream to the downstream side of the flow chamber is even more
prevalent than the Level2 case. Also the maximum flow generally occur mostly at the downstream side of the flow chamber.

The dyed AHAM substrate for the vertical velocity magnitude field plot (Figure 56) indicates a generally uniform velocity with slightly higher velocity magnitude field than the average measured velocity. The region with the highest velocity region occurs at the upstream side of the flow chamber. The lowest velocity region occurs at the bottom and either end of the flow chamber. It is expected that velocity magnitude field is reduce at either end of the flow chamber due to the flow entering the downstream orifice that is smaller than the flow chamber cross-sectional area and butting up against the orifice wall.

6.1.2 Dyed EMPA221 Substrate Flow Velocity Magnitude Field

For the dyed EMPA221 substrate, the horizontal velocity magnitude field plots (Figure 57 - Figure 60) indicate that velocity is lowest at the Bottom laser position and shows a strong expansion of the of the high velocity region moving toward the downstream side of the flow chamber. The velocity magnitude favors the positive $z/H_z$ side of the flow chamber where the inlet orifice is positioned. As with the AHAM substrate, there are inherent dead zones at the center and ends of the flow chamber that cannot be measured due to shadows caused by the side window structure. There are regions with less velocity at the upstream side of the flow chamber. Higher velocity regions are larger at the downstream side of the flow chamber. Maximum velocity regions occur mostly at the downstream side of the flow chamber. For Level2 laser position, the overall velocity magnitude field increases to more than four times that shown on the Bottom laser position and shows a slight expansion to almost uniform high velocity field. The maximum velocity field for the Level2 laser position occurs at both the upstream and downstream side of the flow chamber with a majority of maximum flow conditions occurring at
the upstream side of the flow chamber. For the Level3 laser position, the velocity field is almost uniform throughout the flow chamber with slightly lower velocity fields at the upstream sided of the flow chamber. The velocity magnitude field is approximately two times higher than the measured average velocity and two times less than the Level2 laser position. Again, this magnitude difference is due to the different measuring techniques using dye rather than glass beads and a substrate bottom rather than a glass bottom. It is expected to that there may be even higher velocities as a limited amount of laser positions where taken within the flow chamber. The maximum flow generally occurs at both the upstream and downstream side of the flow chamber. The Level4 laser position shows the velocity field decrease to approximately the same level as the Bottom laser position. These differences are due to the interaction between the flow and the rough substrate conditions. Overall the velocity magnitudes seems to increase dramatically from the Bottom laser position and then decrease moving toward the top of the flow chamber. The expansion of the high velocity region from the upstream to the downstream side of the flow chamber is even more prevalent for the Level4 case. The maximum flow generally occur at both the upstream and downstream side of the flow chamber. The expansion of the high velocity region is due to the flow developing as it moves down the flow chamber as more dye is picked up from the substrate surface and transferred to the moving bulk fluid.

The dyed EMPA221 substrate for the vertical velocity magnitude field plot (Figure 61) shows a similar condition to the AHAM and Terry substrates with a generally uniform velocity region. The velocity field magnitude is slightly less than the average measured velocity. The lower velocity region generally occurs at the bottom of the flow chamber and either end of the flow chamber. The highest velocity occurs at the upstream side of the flow chamber. There is a
slight fluctuation toward the $x/H_y = 9.5$ location and is most likely due to the turbulence caused by the rough surface substrate bottom.

### 6.1.3 Dyed Terry Substrate Flow Velocity Magnitude Field

For the dyed Terry substrate, the horizontal velocity magnitude field plots (Figure 62 - Figure 65) indicate that velocity magnitude is highest at the Bottom laser position at 12 times the average measured velocity. This is due to the difference in measuring dye rather than glass beads and a rough substrate bottom rather than a smooth glass bottom. There is also a slight expansion of the high velocity region moving from the upstream to the downstream side of the flow chamber. The Terry substrate also has inherent dead zones the center and ends of the flow chamber that cannot be measured due to the shadows caused by the side window structure. The higher velocity region increases moving from the upstream to the downstream side of the flow chamber. Maximum velocity regions occur at both the upstream and downstream side of the flow chamber. For Level2 laser position, the overall velocity magnitude decreases to approximately six times the average measured velocity compared to the Bottom laser position. There is a strong expansion of the high velocity region moving from the upstream to the downstream side of the flow chamber being favored to the positive $z/H_y$ side of the flow chamber. As the flow develops, more dye is picked up from the substrate surface and transferred to the moving bulk fluid. The maximum velocity for the Level2 laser position occurs at both the upstream and downstream side of the flow chamber. For the Level3 laser position, the flow velocity is measured generally at the center of the flow chamber. The velocity magnitude field is approximately 1.3 times higher than the measured average velocity. There is almost no expansion of the maximum velocity region moving from the upstream to the downstream side of the flow chamber compared to the Bottom and Level2 laser position. The maximum flow
generally occur at both the upstream and downstream side of the flow chamber. The Level4 laser position shows the velocities decreasing further to about the same as the average measured velocity compared to the Bottom, Level2, and Level3 laser position. This, compared to the other substrates indicate the effect of different substrate roughness on the flow. There is an expansion of the high velocity region from the upstream to the downstream side of the flow chamber and is centered across the flow chamber. The maximum flow generally occur mostly at the downstream side of the flow chamber. Overall the velocity magnitudes decrease moving from the flow chamber bottom to the top of the flow chamber.

The dyed Terry substrate for the vertical velocity magnitude field plot (Figure 66) indicates similar conditions as previous substrates discussed with a generally uniform velocity region being the similar magnitude as the average measured velocity. The lower velocity region generally occurs at the bottom of the flow chamber and either end of the flow chamber. The highest velocity region occurs at the upstream side of the flow chamber.

6.2 Horizontal and Vertical Dye and Concentration Metric Profiles

The following sections discuss four different horizontal laser positions (Bottom, Level2, Level3, Level4) and one vertical laser position (Middle) located at $z/H_y = 0$ within the flow chamber. With the signal normalization of the different metrics described above the signal maximums did not equate to one. Thus the maximum of the normalized signal was then determined and applied to the signal and presented in the following figures as was done previously for the glass bead case but for three different substrate surfaces (AHAM, EMPA221 and Terry) attached to the flow chamber bottom and includes both dye (impregnated within the substrate) and dye concentration condition calculations with an ensemble average of 2000 pairs.
The concentration kinetic energy $K_{cij}$ was normalized by the square of the maximum concentration ($C_{\text{max}}^2$). The concentration mass flux $\tau_{cij}$ was normalized by the multiplication of the maximum concentration and the average flow rate ($C_{\text{max}}U_{\text{avg}}$). The concentration turbulent production was normalized by the flow chamber height divided by the quantity of the maximum concentration squared multiplied by the average flow rate ($h/(C_{\text{max}}^2U_{\text{avg}})$). The vorticity was normalized by the average flow rate divided by the flow chamber height ($U_{\text{avg}}/h$). Short run or instantaneous profile conditions are also provided for the concentration condition with the ensemble averages of 10 picture pairs to try to explain the constant behavior observed with the large ensemble averaging. These normalized signal maximums are provided in subsequent sections. As with the glass beads conditions in the above section the terms $\langle \eta \rangle$ where $\eta$ represents $u_1$, $K_{13}$, $K_c$, $\tau_{13}$, $\tau_{c1}$, $\tau_{c3}$, $P_{113}$, $P_{c1}$ and $\omega_2$ represents the average of the four different horizontal layers.

For the given vertical laser position profiles a signal offset in the figures will be observed between the different substrate profiles. This is because of the varying thickness of the substrate and using the top of the substrate as reference bottom. Furthermore, the side window of the flow chamber does not extend to the top of the flow chamber. Thus the signal at top of the flow chamber cannot be observed which inherently shows a non-symmetric profile behavior for the vertical laser position.

6.2.1 Dye Horizontal and Vertical Normalized Velocity Profile

The dye velocity profile was plotted for four horizontal laser planes and one vertical plane for three different fabric substrates discussed above. The ensemble average of 2000 picture pairs and the profiles for these planes are shown in the following figures. The maximum normalized
velocity $u_1$ for creating the normalized horizontal AHAM substrate profile for the Bottom, Level2, Level3 and Level4 laser levels are 0.199, 0.231, 0.608 and 1.00 respectively. The maximum normalized velocity $u_1$ for creating the horizontal EMPA221 substrate profile for the Bottom, Level2, Level3 and Level4 laser levels are 0.172, 0.913, 0.473 and 0.204 respectively. The maximum normalized velocity $u_1$ for creating the horizontal Terry substrate profile for the Bottom, Level2, Level3 and Level4 laser levels are 2.70, 1.51, 0.300 and 0.247 respectively. The maximum normalized velocity $u_1$ for creating the vertical AHAM, EMPA and Terry substrate profile are 0.258, 0.212 and 0.251 respectively.

Figure 67: Velocity profile of a dyed AHAM substrate bottom, with Bottom, Level2, level3 and Level4 horizontal laser positions, ensemble average of 2000 picture pair runs.
Figure 68: Velocity profile of a dyed EMPA221 substrate bottom, with Bottom, Level2, Level3 and Level4 horizontal laser position, ensemble average of 2000 picture pair runs.

Figure 69: Velocity profile of a dyed Terry substrate bottom, using Bottom, Level2, Level3 and Level4 horizontal laser position, ensemble average of 2000 picture pair runs.
Figure 70: Average normalized velocity profiles of average dyed AHAM, EMPA221, and Terry substrate using Bottom, Level2, Level3 and Level4 horizontal laser positions, ensemble average of 2000 picture pair runs.

Figure 71: Velocity profile of a dyed AHAM, EMPA221 and Terry substrate using Middle vertical laser position at the flow chamber middle, ensemble average of 2000 picture pair runs.
As shown in Figure 67 through Figure 69 above, the ensemble average normalized horizontal velocity profile in the \( x \)-direction \( (\langle u_x \rangle / \max(\|u_x\|)) \) of the dye saturated substrate bottom and indicates a generally symmetric profile with the maximum velocity generally at the flow chamber center even though they are taken with four different laser positions with three different substrates. Overall, the AHAM substrate indicates a more smooth uniform and less variable curve for each of the four vertical laser locations compared to the EMPA221 and Terry substrate even though the AHAM substrate has a more rough surface than the EMPA221. The inherent puckering of the substrate surface is most likely the cause of this uniformity and minimum variability. The EMPA221 and Terry fabric have more variation in their profile and shows a more flat velocity curvature at the vertex of the curve compared to the AHAM substrate.

For the EMPA221 substrate specifically the Level4 location shows a more typical curvature similar to the base flow and AHAM substrate velocity curves, whereas the other laser positions have a more flat nose configuration and are more curve variability. The Bottom and Level2 locations have a similar velocity profile. However the higher Level3 profile is different than all the others profiles. This indicates a more turbulent variable conditions occurring within the vertical layers of the flow. For the Terry substrate Level3 and Level4 have a similar velocity profile. The Bottom layer has more variability but the Level2 location is different than all the others. Again this indicates that there are flow regions that have more fluctuations due to the inherent turbulence occurring within the flow turbulence than other regions. Figure 70 show the overall average for the three substrates.

In Figure 71 the ensemble average of the normalized vertical velocity profile along the \( x \)-direction \( (\langle u_y \rangle / \max(\|u_y\|)) \) of the three dye saturated substrates attached to the flow chamber bottom and indicates a non-symmetric but similar curvature. The maximum velocity is generally
located at the flow chamber center. It is expected that the top portion of the profiles would be
more symmetrical (as shown in the previous horizontal laser conditions) if the area at the top of
the flow chamber could be seen directly through the side window. In comparison these profiles
are similar to the base flow vertical velocities.

6.2.2 Short Run Dye Horizontal and Vertical Normalized Velocity Profile
In this short run or instantaneous measurement case, the ensemble average of 10 instead of
2000 picture pairs for four horizontal laser planes and one vertical plane for three different fabric
substrates where taken and the profiles for these planes are shown in the following figures. The
maximum normalized velocity $u_i$ for creating the normalized horizontal AHAM substrate profile
for the Bottom, Level2, Level3 and Level4 laser levels are 0.243, 0.259, 0.282 and 0.280
respectively. The maximum normalized velocity $u_i$ for creating the horizontal EMPA221
substrate profile for the Bottom, Level2, Level3 and Level4 laser levels are 0.215, 0.286, 0.251
and 0.263 respectively. The maximum normalized velocity $u_i$ for creating the horizontal Terry
substrate profile for the Bottom, Level2, Level3 and Level4 laser levels are 0.252, 0.253, 0.267
and 0.280 respectively. The maximum normalized signal for creating the vertical AHAM,
EMPA and Terry substrate profile are 0.273, 0.229, and 0.300 respectively.
Figure 72: Short run normalized velocity profile of a dyed AHAM substrate bottom for Bottom, Level2, Level3 and Level4 horizontal laser positions, ensemble average of 10 picture pair runs.

Figure 73: Short run normalized velocity profile of a dyed EMPA221 substrate bottom for Bottom, Level2, Level3 and Level4 horizontal laser positions, ensemble average of 10 picture pair runs.
Figure 74: Short run normalized velocity profile of a dyed Terry substrate bottom for Bottom, Level2, Level3 and Level4 horizontal laser positions, ensemble average of 10 picture pair runs.

Figure 75: Short run normalized average velocity profiles of average dyed AHAM, EMPA221, and Terry substrate using Bottom, Level2, Level3 and Level4 horizontal laser positions, ensemble average of 10 picture pair runs.
Figure 76: Short run normalized velocity profile of a dyed AHAM, EMPA221 and Terry substrate using Middle vertical laser position, ensemble average of 10 picture pair runs.

As shown in Figure 72 through Figure 74 above, the short run ensemble average normalized horizontal velocity profile in the $x$-direction ($\langle u_x \rangle / \max(|\langle u_x \rangle|)$ of the dye saturated substrate bottom and indicates a generally symmetric profile with the maximum velocity varying across the center of the flow chamber. Overall, the AHAM substrate indicates a more smooth and uniform profile for each of the four vertical laser locations except for the Level3 position where it has some fluctuation toward the center of the curve. In general the short run case is similar to the ensemble average of the 2000 picture pair except for some variation seen in with Level3. Comparing this to the EMPA221 substrate it can be seen that significant more variation occurs again with the EMPA221 substrate even though it has a less rough surface. It seems that the inherent up and down puckering of the AHAM surface, even with less picture pairs averaging, contributes to a more stable and uniform profile. It is surprising that the Terry substrate, which has more asperities than the EMPA221 has a more uniform and less variable
profile. For the EMPA221 substrate specifically, the laser position levels have significant variation with the Bottom level having two local maximums at the center of the curve, Level2, Level3 and Level4 have one local maximum but the cure varies significantly moving across the flow chamber width. The ensemble averaging of 2000 picture pairs generally reduces the signal variation seen for the short run case. For the Terry substrate Level3 and Level4 have again similar velocity profiles. The Bottom layer has more variability but the Level2 location is again different than all the others and generally correlates to what was shown in the 2000 picture pair ensemble average. Figure 75 shows the overall average for the three substrates.

In Figure 76 the short run ensemble average of the normalized vertical velocity profile along the x-direction \( \left( \frac{\langle u_i \rangle}{\max(\langle |u_i| \rangle)} \right) \) of the dye saturated substrate bottom shows similar conditions as the 2000 picture pair ensemble average yielding a non-symmetrical profile with maximum velocity generally at the flow chamber center and with offsets due to the differences in fabric height.

### 6.2.3 Dye Horizontal and Vertical Normalized Kinetic Energy

The ensemble average of 2000 picture pairs for four horizontal laser planes and one vertical plane for three different fabric impregnated dyed substrates where taken and the kinetic energy profiles for these planes are shown in the following figures. The maximum normalized kinetic energy \( K_{13} \) for creating the normalized horizontal AHAM substrate profile for the Bottom, Level2, Level3 and Level4 laser levels are 0.018, 0.020, 1.16, and 5.04 respectively. The maximum normalized kinetic energy \( K_{13} \) for creating the horizontal EMPA221 substrate profile for the Bottom, Level2, Level3 and Level4 laser levels are 0.0202, 4.21, 0.675 and 0.030 respectively. The maximum normalized kinetic energy \( K_{13} \) for creating the horizontal Terry substrate profile for the Bottom, Level2, Level3 and Level4 laser levels are 0.381, 14.29, 0.048...
and 0.019 respectively. The maximum normalized kinetic energy $K_{12}$ for creating the vertical AHAM, EMPA and Terry substrate profile are 0.018, 0.095 and 0.014 respectively.

Figure 77: Normalized kinetic energy profile of a dyed AHAM substrate bottom, using Bottom, Level2, Level3 and Level4 horizontal laser positions, ensemble average of 2000 picture pair runs.
Figure 78: Normalized kinetic energy profile of a dyed EMPA221 substrate bottom, using Bottom, Level2, Level3 and Level4 horizontal laser positions, ensemble average of 2000 picture pair runs.

Figure 79: Normalized kinetic energy profile for a dyed Terry substrate bottom, using Bottom, Level2, Level3 and Level4 horizontal laser positions, ensemble average of 2000 picture pair runs.
Figure 80: Average normalized kinetic energy profiles of average dyed AHAM, EMPA221, and Terry substrate using Bottom, Level2, Level3 and Level4 horizontal laser positions, ensemble average of 2000 picture pair runs.

Figure 81: Normalized kinetic energy profile for a dyed Terry substrate bottom, using Middle vertical laser position, ensemble average of 2000 picture pair runs.
As shown in Figure 77 through Figure 79 above, the normalized kinetic energy profile in the $x$-direction ($\langle K_{13} \rangle / \max(|\langle K_{13} \rangle|)$) of the dye saturated substrate bottom and overall indicates a somewhat symmetric profile with the maximum kinetic energy generally at the flow chamber center with some exceptions. There are unique profile differences for the different laser position levels and subsequent substrate types. The profile differences in the above figures for the different laser positions are related to the different surface roughness resulting from each substrate. For the AHAM substrate case, the Bottom and Level2 laser position have a flat and more variable profile at the center of the flow chamber. This indicates that the square of the velocity fluctuations in both the $x$ and $y$ directions are occurring in a more broad and uniform distributed way across the substrate surface. The Level3 and Level4 laser positions indicates a more typical smooth and less variable profile with the apex occurring at the approximate center of the flow chamber with the profile decrease almost monotonically toward the ends of the flow chamber and indicates a less uniformly distributed fluctuations. For the EMPA221 substrate case, the kinetic energy profiles for the different laser positions show a typical non-uniform distributed profile for the different laser positions. However, each specific profile vary from one another and have different shapes toward the center of the flow chamber. This indicates that the square of the velocity fluctuations in both the $x$ and $y$ directions are generally the same regardless of the different laser positions. For the Terry substrate case, the kinetic energy profiles are more broad across the middle than the EMPA221 substrate case with the Bottom position showing an almost flat but narrowing curve toward the center of the flow chamber. The maximum kinetic energy is offset from the flow chamber center. The Level2 position shows the maximum kinetic energy that is even more offset from the center than the Bottom level. The Level3 position has a more round profile at the flow chamber center and the maximum is
generally at the center of the flow chamber. The higher Level4 position has a significantly offset and an atypical curvature. These curves indicate that the square of the velocity fluctuations in both the x and y –directions are sometimes more uniformly distributed across the center of the flow chamber width compared to other horizontal laser positions especially when compared to the base flow conditions. These kinetic energy profiles show loose similarities with base flow profiles. Figure 80 shows the overall average for the three substrates.

In Figure 81 the ensemble average of the normalized vertical kinetic energy profile along the x -direction \( \langle K_{12} \rangle / \max(|\langle K_{12} \rangle|) \) of the dye saturated substrate bottom and indicates a non-symmetric but similar curvature between the different substrates. The maximum kinetic energy does not occur at the flow chamber center but occurs between approximately 0.22 for the AHAM and EMPA221 substrate and 0.31 for the Terry substrate which then dissipates moving to the top of the flow chamber. Close to the substrate surface the kinetic energy is more variable with all three substrates becoming erratic with similar profile shapes. In comparison to the vertical base flow profiles the profiles are very different as the base flow has a more constant and uniform profile moving from the bottom to top of the flow chamber.

6.2.4 Concentration Horizontal and Vertical Normalized Kinetic Energy Profile

The ensemble average of 2000 picture pairs for four horizontal laser planes and one vertical plane for three different fabric substrates where taken and the profiles for these planes are shown in the following figures. The maximum normalized kinetic energy \( K_{13} \) and concentration fluctuation for creating the normalized horizontal AHAM substrate profile for the Bottom, Level2, Level3 and Level4 laser levels are 0.441, 1.41e-05, 0.171 and 0.310 and 2.04e-04, 9.71e-06, 2.3575e-05 and 4.7378e-05 \( g/\text{lit} \) respectively. The maximum normalized kinetic energy and concentration fluctuation for creating the horizontal EMPA221 substrate profile for
the Bottom, Level2, Level3 and Level4 laser levels are 0.137, 0.306, 0.177, 3.71e-06 and 2.06e-05, 4.65e-05, 2.43e-05, 9.7793e-06 g/lit respectively. The maximum normalized kinetic energy $K_{13}$ and concentration fluctuation for creating the horizontal Terry substrate profile for the Bottom, Level2, Level3 and Level4 laser levels are 0.411, 0.356, 0.019 and 0.85e-05 and 1.22e-04, 6.47e-05, 1.20e-05 and 9.66e-06 g/lit respectively. The maximum normalized kinetic energy $K_{12}$ and concentration fluctuation for creating the vertical AHAM, EMPA and Terry substrate profile are 1.42e-05, 1.41e-05 and 1.78e-05 and 9.83e-06, 9.82e-06 and 9.83e-06 g/lit respectively.

Figure 82: Normalized kinetic energy concentration profile for a dyed AHAM substrate bottom, using Bottom, Level2, Level3 and Level4 horizontal laser position, ensemble average of 2000 picture pair runs.
Figure 83: Normalized kinetic energy concentration profile for a dyed EMPA221 substrate bottom, using Bottom, Level2, Level3 and Level4 horizontal laser position, ensemble average of 2000 picture pair runs.

Figure 84: Normalized kinetic energy concentration profile for a dyed Terry substrate bottom, using Bottom, Level2, Level3 and Level4 horizontal laser positions, ensemble average of 2000 picture pair runs.
Figure 85: Average normalized kinetic energy concentration profiles of average dyed AHAM, EMPA221, and Terry substrate using Bottom, Level2, Level3 and Level4 horizontal laser positions, ensemble average of 2000 picture pair runs.

Figure 86: Normalized kinetic energy concentration profile for a dyed Terry substrate bottom, using Middle vertical laser position, ensemble average of 2000 picture pair runs.
As shown in Figure 82 through Figure 84 above, the ensemble average normalized horizontal concentration kinetic energy profile in the $x$-direction ($\langle K_c \rangle / \max(\langle K_c \rangle)$ of the dye saturated substrate bottom and indicates an unique behavior in some horizontal laser positions. The AHAM substrate shows a uniform concentration and constant behavior across the width of the flow chamber for the Bottom, Level3 and Level4 laser position. However, Level2 is different in that there is a significant kinetic energy variation due to the change in concentration fluctuations occurring at this level across the width of the flow chamber. This indicates that there is some transition occurring at different levels within the flow chamber. For the EMPA221 and Terry substrate, the Bottom, Level2 and Level3 laser positions shows a similar uniform and constant concentration behavior as observed by the AHAM substrate. The Level4 laser positions, in these cases, shows the significant kinetic energy variation even though these substrates have different thickness and roughness attributes. The AHAM and Terry substrates have the most variable profile across the width of the substrate and transitions toward zero moving closer to the flow chamber sides. EMPA221 substrate has a more uniform profile across the width of the flow chamber with similar transition to zero close the sides of the flow chamber. Figure 85 shows the overall average for all three substrates.

In Figure 86 the ensemble average of the normalized vertical concentration kinetic energy profiles along the $x$-direction ($\langle K_{c12} \rangle / \max(\langle K_{c12} \rangle)$ of the dye saturated substrate bottom and indicates a non-symmetric but similar curvature between the different substrates and for the strict dye case. The maximum concentration kinetic energy does not occur at the flow chamber center but occurs between approximately 0.24 for the AHAM and 0.19 for the Terry substrate and 0.12 for the EMPA221 substrate. The normalized concentration kinetic energy then reduces to zero for the AHAM, EMPA221 and Terry substrate moving toward the top of the flow chamber.
6.2.5 Short Run Concentration Horizontal and Vertical Normalized Kinetic Energy

In the short run case, the ensemble average of 10 instead of 2000 dye picture pairs where taken and normalized kinetic energy profiles are shown in the following figures. In this short run case, the ensemble average of 10 picture pairs for four horizontal laser planes and one vertical plane for three different fabric substrates where taken and the profiles for these planes are shown in the following figures. The maximum normalized kinetic energy and concentration fluctuation for creating the normalized horizontal AHAM substrate profile for the Bottom, Level2, Level3 and Level4 laser levels are 0.99e-05, 0.820e-05, 0.190 and 0.138 and 9.83e-06, 9.72e-06, 9.72e-06 and 9.70e-06 g/lit respectively. The maximum normalized kinetic energy and concentration fluctuation for creating the horizontal EMPA221 substrate profile for the Bottom, Level2, Level3 and Level4 laser levels are 0.53e-05, 2.10e-06, 0.138 and 0.110 and 9.74e-06, 9.71e-06, 9.76e-06 and 9.79e-06 g/lit respectively. The maximum normalized kinetic energy and concentration fluctuation for creating the horizontal Terry substrate profile for the Bottom, Level2, Level3 and Level4 laser levels are 2.55e-06, 2.38e-06, 0.125 and 0.161 and 9.73e-06, 9.69e-06, 9.67e-06 and 9.78e-06 g/lit respectively. The maximum normalized kinetic energy and concentration fluctuation for creating the vertical AHAM, EMPA and Terry substrate profile are 1.42e-05, 1.41e-05 and 1.78e-05 and 9.83e-06, 9.82e-06 and 9.83e-06 g/lit respectively.
Figure 87: Short run normalized kinetic energy concentration profile for a dyed AHAM substrate bottom, using Bottom, Level2, Level3 and Level4 horizontal laser position, ensemble average of 10 picture pair runs.

Figure 88: Short run normalized kinetic energy concentration profile for a dyed EMPA221 substrate bottom, using Bottom, Level2, Level3 and Level4 horizontal laser position, ensemble average of 10 picture pair runs.
Figure 89: Short run normalized kinetic energy concentration profile for a Terry substrate bottom, using Bottom, Level2, Level3 and Level4 horizontal laser position, ensemble average of 10 picture pair runs.

Figure 90: Short run average of normalized kinetic energy concentration profiles of average dyed AHAM, EMPA221, and Terry substrate using Bottom, Level2, Level3 and Level4 horizontal laser positions, ensemble average of 10 picture pair runs.
Figure 91: Short run normalized kinetic energy concentration profile for a dyed AHAM, EMPA and Terry substrate bottom, using Middle vertical laser position, ensemble average of 10 picture pair runs.

As shown in Figure 87 through Figure 89 above, the short run ensemble average for the normalized horizontal concentration kinetic energy profile in the $x$-direction ($\langle K_c \rangle / \max(|\langle K_c \rangle |)$) of the dye saturated substrate bottom indicates a loosely symmetric profile with the kinetic energy varying across the width of the flow chamber. The AHAM, EMPA221 and Terry substrate have two different conditions occurring for the short term concentration condition. The Bottom and Level2 laser positions indicate a maximum condition occurring the negative $z/H_y$ location. The kinetic energy then reduces toward the center of the flow chamber and then slightly increases again at the positive $z/H_y$ location. Level3 and Level4 laser position on the other hand indicates a uniform but varying profile across the width of the flow chamber with a slight decreasing trend at the negative $z/H_y$ location. In comparing the short run case to the ensemble average of the 2000 picture pairs it can be seen that Level2, Level4 and Level4
have similar trends for the AHAM, EMPA221 and Terry cases respectively. Generally the short run profiles have significant more variation than the larger averaging curves as expected. Furthermore, the short run profiles indicate the kinetic energy concentration profiles are similar regardless of substrate type or laser position and have similar shapes that indicate that the square of the velocity fluctuations occur generally across the width of the flow chamber compared to the 2000 pair averages that tend to average to one. Figure 90 shows the overall short run average for all three substrates.

In Figure 91 the short run ensemble average of the vertical normalized concentration kinetic energy profile \( \langle K_{12} \rangle / \max(\langle K_{12} \rangle) \) of the short run dye saturated substrate bottom shows a general similar trend as with the 2000 picture pair results with the maximum square of the velocity fluctuations in the x and y –directions occurring for AHAM and Terry at \( y/H_y = 0.2 \) and for EMPA at \( y/H_y = 0.1 \). The trends gradually reduce to zero moving toward the top of the flow chamber. The short run kinetic energy has more signal variation as expected.

6.2.6 Horizontal and Vertical Normalized Dye Reynolds Stress

The ensemble average of 2000 dye picture pairs for the normalized Reynolds stress and the profiles for four horizontal and one vertical laser planes are shown in the following figures. The maximum normalized Reynolds stress multiplied by the fluid density for creating the normalized horizontal AHAM substrate profile for the Bottom, Level2, Level3 and Level4 laser levels are -0.919, -1.93, -76.7 and -258 kg/m\(^3\) respectively. The maximum normalized kinetic energy for creating the horizontal EMPA221 substrate profile for the Bottom, Level2, Level3 and Level4 laser levels are 1.43, -222, -46.4 and -2.21 kg/m\(^3\) respectively. The maximum normalized kinetic energy for creating the horizontal Terry substrate profile for the Bottom, Level2, Level3
and Level4 laser levels are -3198, -689, -3.38 and -1.73 kg/m³ respectively. The maximum normalized Reynolds stress multiplied by the fluid density for the vertical AHAM, EMPA and Terry substrate profile are -1.79, -0.910 and -1.63 kg/m³ respectively.

Figure 92: Normalized Reynolds stress profile for a dyed AHAM substrate bottom, using Bottom, Level2, Level3 and Level4 horizontal laser position, ensemble average of 2000 picture pair runs.
Figure 93: Normalized Reynolds stress profile for a dyed EMPA221 substrate bottom, using Bottom, Level2, Level3 and Level4 horizontal laser position, ensemble average of 2000 picture pair runs.

Figure 94: Normalized Reynolds stress profile for a dyed Terry substrate bottom, using Bottom, Level2, Level3 and Level4 horizontal laser position, ensemble average of 2000 picture pair runs.
Figure 95: Average normalized Reynolds stress profiles of average dyed AHAM, EMPA221, and Terry substrate using Bottom, Level2, Level3 and Level4 horizontal laser positions, ensemble average of 2000 picture pair runs.

Figure 96: Normalized Reynolds stress profile for a dyed AHAM, EMPA221 and Terry substrate using Middle vertical laser position, ensemble average of 2000 picture pair runs.
As shown in Figure 92 through Figure 94 above, the ensemble average normalized horizontal Reynolds stress profile in the \(x\)-direction (\(\langle \tau_{13} \rangle / \max(|\langle \tau_{13} \rangle|)\)) of the dye saturated substrate bottom and indicates a generally similar behavior across the different horizontal laser positions. The AHAM substrate for Level2, Level3 and Level4 laser location shows Reynolds stress increasing from the side of the flow chamber to a local maximum that peaks at the negative \(z/H_y\) location between -1 and -0.5. The Reynolds stress becomes zero moving close to the center of the flow chamber and then decreases to a local minimum at the positive \(z/H_y\) location between 0.75 and 1.2. The Reynolds stress is generally the same for the different laser positions. For the EMPA221 substrate case, Level2, Level3 and Level4 laser positions have a generally the same similar profile with the normalized Reynolds stress increasing from the side of the flow chamber and peaking at the negative \(z/H_y\) region between -1.2 and -0.4. The signal then reduces to zero at the center of the flow chamber and decreases at the positive \(z/H_y\) region and peaking between 1 and 1.3. The Level2 profile is unique in that the local maximum occurs very close to the side of the flow chamber and then gradually decreases and remains mostly positive across the width of the flow chamber. When the signal begins to reach the opposite side of the flow chamber the signal oscillates becoming both negative and positive. The Bottom laser position has a more oscillating profile and maintains a generally positive normalized Reynolds stress condition across the width of the flow chamber with several local maxima and minima. For the Terry substrate case, Level2, Level3 and Level4 laser position have similar trends with the profiles increase from the side of the flow chamber to a maxima at \(z/H_y = -0.75\) for the Level3 and Level4 laser position. The Level2 maxima occurs at approximately \(z/H_y = -0.25\). The signal then decreases becoming zero at approximately \(z/H_y = 0.5\) and further decreases to a
local minima occurring between \( z/H_y = 1 \) and 1.25 for all four laser positions. The Bottom laser position has a more constant normalized Reynolds stress that occurs between \( z/H_y = -1 \) to 0.5 before it decreases significantly similar to the other laser position signals. The Reynolds stress indicated in these curves shown general similarities to the base flow however the signals extend further in the positive \( z/H_y \) region. Figure 95 shows the overall short run average for all three substrates.

In Figure 96 the vertical ensemble average of the normalized Reynolds stress along the \( x \)-direction \( \langle \tau_{12} \rangle / \max(\langle |\tau_{12}| \rangle) \) of the dye saturated substrate bottom and indicates a somewhat symmetric but similar curvature between the different substrates and base flow conditions. The three substrate signals generally follow the base flow Reynolds stress with some exceptions. The AHAM and EMPA221 substrates decrease instead of increase from the flow chamber bottom to a global and local minima respectively at approximately at \( y/H_y = 0.11 \) which is unique. The immediate signal reduction indicates greater shear stresses occurring close to the flow chamber bottom for these two substrates. The signals then increase past zero to a local and global maximum respectively at approximately \( y/H_y = 0.23 \). The EMPA221 substrate signal decreases to the lowest global minima of the three substrates occurring at \( y/H_y = 0.62 \) showing a similar base flow trend. The AHAM substrate also decrease from a global maxima and gradually decreases to a global minima at the same \( y/H_y \) location showing a different profile than the base flow. The Terry substrate with the highest asperities increases to a global maximum similar to the base flow but at a lower value of \( y/H_y = 0.23 \) and then decreases past zero to a global minima occurring at \( y/H_y = 0.59 \). The global minima is small compared to the other
substrates. This indicates that AHAM and Terry have minimal shear stress toward the top of the flow chamber compared to the base flow and the EMPA221 substrate. These vertical curves show loose similarities to the base flow Reynolds stress profiles.

6.2.7 Horizontal and Vertical Normalized Concentration Mass Flux x-direction

The ensemble average of 2000 dye picture pairs for the horizontal normalized concentration mass flux and the profiles for four horizontal and one vertical laser planes are shown in the following figures. The maximum normalized concentration mass flux in the x-direction for creating the normalized horizontal AHAM substrate profile for the Bottom, Level2, Level3 and Level4 laser levels are -30.6, -4.41e-04, -1.77 and -4.96 respectively. The maximum normalized kinetic energy for creating the horizontal EMPA221 substrate profile for the Bottom, Level2, Level3 and Level4 laser levels are -1.61e-04, -4.51, -1.35 and -2.23e-04 respectively. The maximum normalized kinetic energy for creating the horizontal Terry substrate profile for the Bottom, Level2, Level3 and Level4 laser levels are -18.0, -8.99, -0.100 and -4.8867e-04 respectively. The maximum normalized concentration mass flux for the vertical AHAM, EMPA and Terry substrate profile are -5.1193e-04, -2.514e-04 and -2.14 respectively.
Figure 97: Normalized x-direction concentration mass flux profile for a dyed AHAM substrate bottom, using Bottom, Level2, Level3 and Level4 horizontal laser position, ensemble average of 2000 picture pair runs.

Figure 98: Normalized x-direction concentration mass flux profile for a dyed EMPA221 substrate bottom, using Bottom, Level2, Level3 and Level4 horizontal laser position, ensemble average of 2000 picture pair runs.
Figure 99: Normalized x-direction concentration mass flux profile for a dyed Terry substrate bottom, using Bottom, Level2, Level3 and Level4 horizontal laser position, ensemble average of 2000 picture pair runs.

Figure 100: Average normalized concentration mass flux profiles of average dyed AHAM, EMPA221, and Terry substrate using Bottom, Level2, Level3 and Level4 horizontal laser positions, ensemble average of 2000 picture pair runs.
As shown in Figure 97 through Figure 99 above, the ensemble average normalized horizontal concentration mass flux profile in the \( x \)-direction (\( \langle \tau_{c1} \rangle / \max(|\langle \tau_{c1} \rangle|) \)) of the dye saturated substrate bottom and indicates an unique behavior in one horizontal laser positions. The AHAM substrate for the Bottom, Level3 and Level4 laser position shows the mass flux increasing from the side of the flow chamber to a local minimum that peaks close to the flow chamber center. The Level2 laser position is unique in that the signal quickly decreases to a local minimum then increases to a local maximum and then decreases again to a local minimum toward the side of the flow chamber. Thus the local minimums occur near the sides of the flow chamber (approximately \( z / H_y = -1.25 \) and \( 1.25 \)) instead of the center and the local maximum occurs at the close to the center of the flow chamber indicating that unique flow velocity fluctuations and dye concentration fluctuations are occurring at different flow chamber levels. For the EMPA221 substrate case a similar condition occurs with the Level4 laser position.

Figure 101: Normalized x-direction concentration mass flux profile for a dyed AHAM, EMPA221 and Terry substrate using Middle vertical laser position, ensemble average of 2000 picture pair runs.
showing local minimums at the sides of the flow chamber with a local maximum at the center of the flow chamber. The Bottom laser position in this case also has a somewhat unique profile with the Reynolds stress being slightly at the negative $z/H_y$ region and then decreases to a local minimum at the positive $z/H_y$ region with some signal variation occurring. Again the substrate with the lowest asperities and minimal thickness seems to have the most unique differences in flow fluctuations. For the Terry substrate case, the Bottom, Level2, and Level3 laser position have similar parabolic profiles as shown in the other substrate profiles. The Level4 position shows a similar unique signal trend described by the AHAM Level2 position. This indicates that the mass flux can be unique and almost invert across certain horizontal layers residing within the flow chamber.

In Figure 101 the vertical ensemble average of the normalized concentration mass flux along the $x$-direction ($\langle \tau_{ct} \rangle / \max(\langle \tau_{ct} \rangle)$ of the dye saturated substrate bottom and indicates a non-symmetric and different curvature between the different substrates. For the AHAM substrate case the normalized concentration mass flux has global minimum occurring at approximately $y/H_y = 0.28$. The signal gradually increases to a global maximum toward the top of the flow chamber. The Terry substrate gradually increases to a global maxima passing several local maxima and minima and reduces again. The EMPA221 substrate increases to a global maxima at $y/H_y = 0.2$ and then gradually decreases to a global minima towards the flow chamber top at $y/H_y = 0.75$. This indicates that three different substrates have unique vertical mass flux conditions with the AHAM substrate being negative, the EMPA221 being positive and Terry being slightly positive between $y/H_y = 0.18$ through 0.3.
6.2.8 Horizontal and Vertical Normalized Concentration Mass Flux in z and y-direction

The ensemble average of 2000 dye picture pairs where taken and the normalized concentration mass flux in the z and y – direction are shown in the following figures for four horizontal and one vertical laser planes respectively shown in the following figures. The maximum normalized concentration mass flux for creating the normalized horizontal AHAM substrate profile for the Bottom, Level2, Level3 and Level4 laser levels are -1.38, -1.7139e-04, -0.131 and -0.385 respectively. The maximum normalized kinetic energy for creating the horizontal EMPA221 substrate profile for the Bottom, Level2, Level3 and Level4 laser levels are -9.68e-05, -0.529, -0.104 and -1.06e-04 respectively. The maximum normalized kinetic energy for creating the horizontal Terry substrate profile for the Bottom, Level2, Level3 and Level4 laser levels are -1.35, -0.476, -7.98e-03 and -8.63e-05 respectively. The maximum normalized concentration mass flux for the vertical AHAM, EMPA and Terry substrate profile are -1.24e-04, -2.51e-04, -9.59e-05 respectively.

Figure 102: Normalized z-direction mass flux concentration profile for a dyed AHAM substrate bottom, using Bottom, Level2, Level3 and Level4 horizontal laser position, ensemble average of 2000 picture pair runs.
Figure 103: Normalized z-direction mass flux concentration profile for a dyed EMPA221 substrate bottom, using Bottom, Level2, Level3 and Level4 horizontal laser position, ensemble average of 2000 picture pair runs.

Figure 104: Normalized z-direction mass flux concentration profile for a dyed Terry substrate bottom, using Bottom, Level2, Level3 and Level4 horizontal laser position, ensemble average of 2000 picture pair runs.
Figure 105: Average of normalized z-direction mass flux concentration profiles of average dyed AHAM, EMPA221, and Terry substrate using Bottom, Level2, Level3 and Level4 horizontal laser positions, ensemble average of 2000 picture pair runs.

Figure 106: Normalized y-direction mass flux concentration profile for a dyed AHAM, EMPA221 and Terry substrate using Middle vertical laser position, ensemble average of 2000 picture pair runs.
As shown in Figure 102 through Figure 104 above, the ensemble average normalized horizontal concentration mass flux profile in the \( z \)-direction (\( \langle \tau_{z} \rangle / \max(\| \langle \tau_{z} \rangle \|) \)) of the dye saturated substrate bottom and indicates an unique behavior in some horizontal laser positions. The AHAM substrate Level3 and Level4 laser position have similar shapes with the shows the concentration mass flux maximized near the side of the flow chamber at the positive \( z/H_y \) region and then decreases to zero near the center of the flow chamber. The concentration mass flux continues to decrease further in the negative \( z/H_y \) region with the minimum occurring near the opposite flow chamber wall. The Bottom laser position shows an almost sinusoidal profile with the global maximum and minimum occurring near the flow chamber walls. The local minimum occurs at approximately \( z/H_y = -1.5 \) then decreases to a local minimum at \( z/H_y = -1.0 \) where it then slightly increases toward the flow chamber to a local maximum at approximately \( z/H_y = 0.9 \) where it decreases again to a global minima close the flow chamber wall at \( z/H_y = 1.5 \). The Level2 laser position demonstrates an almost condition from the Bottom laser position. The global minimum are located near the negative \( z/H_y \) flow chamber wall at approximately \( z/H_y = -1.5 \). The signal then increases to a local maximum and decreases again to a local minimum where the signal then slightly increases to a local maximum and a local minimum. The signal then increases to a global maximum at approximately \( z/H_y = 1.4 \) and decreases again. This indicates that concentration mass flux in the \( z \)-direction can have unique conditions moving from the bottom of the flow chamber near the substrate to the top of the flow chamber. For the EMPA221 substrate the different laser position are somewhat similar. The Bottom and Level4 laser position show similar profiles with two global maximums and two local
minimums at the positive and negative $z/H_y$ regions near the flow chamber walls. These signals tend to zero toward the center of the flow chamber with general local minima and maxima signals occurring at the negative and positive $z/H_y$ region respectively. The Level2 and Level3 laser position are somewhat unique from each other with the Level2 having a global maximum and the Level3 having a global minima near the side of the flow chamber in the negative $z/H_y$ region. The Level2 profile increases and becomes generally flat and uniform across the flow chamber middle. The signal then becomes negative as it approaches the flow chamber side at the positive $z/H_y$ region. The Level3 profile increase from its global minima to a maximum and then decrease through the center of the flow chamber to a local minimum at the positive $z/H_y$ region. The signal then increases and abruptly and surprisingly decreases again. It was expected that since the signal had a strong negative value at the negative $z/H_y$ side of the flow chamber, it would comply to the other laser positions and have a positive value at the positive side of flow chamber. Instead the signal became negative. This provides more evidence that the concentration mass flux is different within different horizontal laser positions moving from the bottom to the top of the flow chamber. For the Terry substrate the concentration mass flux indicates that three out of the four laser positions show a similar trend. The Bottom, Level2 and Level3 laser positions show a general signal decrease from a global maximum and then eventually tends decreases move through the flow chamber center to the positive $z/H_y$ region. The signals come together to a global minimum at the side of the flow chamber. The highest laser position, Level4, shows an opposite condition where the signal begins at a global minima next to side of the flow chamber and then increases to a global maximum next to the opposite side of the flow chamber with various local maxima and minima
in between. Again, this indicates unique conditions that exist at different laser levels within the flow chamber.

In Figure 106 the vertical ensemble average of the normalized concentration mass flux along the y-direction \( \langle \tau_{c2} \rangle / \max(\langle \tau_{c2} \rangle) \) of the dye saturated substrate bottom and indicates a non-symmetric but similar curvature between the AHAM and EMPA221 substrates. These two signals begin at zero and moving higher oscillates back and forth moving to the top of the flow chamber with the global minimum occurring at \( y/H_y = 0.08 \) and 0.22 and the global maximum occurring at \( y/H_y = 0.19 \) and 0.11 respectively. The Terry substrate moves in an opposite direction from the bottom of the flow chamber where the signal decrease to a global minimum at \( y/H_y = 0.19 \) and after a quick back and forth oscillation the signal increases to a local maximum at \( y/H_y = 0.55 \) and then decreases again. This indicates, as expected, unique concentration mass flux signals that occur for the different substrate surfaces.

6.2.9 Short Run Horizontal and Vertical Normalized Concentration Mass Flux x-direction

The short run ensemble average of 10 dye picture pairs for the horizontal normalized concentration mass flux and the profiles in the x-direction for four horizontal and one vertical laser planes are shown in the following figures. The maximum short run normalized concentration mass flux for creating the normalized horizontal AHAM substrate profile in the x-direction for the Bottom, Level2, Level3 and Level4 laser levels are -1.96e-04, -2.16e-04, -2.28e-04 and -15.5 respectively. The maximum short run normalized concentration mass flux for the horizontal EMPA221 substrate profile in the x-direction for the Bottom, Level2, Level3 and Level4 laser levels are -1.10e-04, -1.22e-04, -1.13e-04 and -6.70 respectively. The maximum short run normalized concentration mass flux for creating the horizontal Terry substrate profile
in the x – direction for the Bottom, Level2, Level3 and Level4 laser levels are $-9.20e-05$, $-1.33$, $-1.73$ and $-18.53$ respectively. The maximum short run normalized concentration mass flux for the vertical AHAM, EMPA and Terry substrate profile are $3.77e-04$, $-8.41e-05$, $-1.30$ respectively.

Figure 107: Short run normalized x-direction mass flux concentration profile of a dyed AHAM substrate bottom using Bottom, Level2, Level3 and Level4 horizontal laser positions, ensemble average of 10 picture pair runs.
Figure 108: Short run normalized x-direction mass flux concentration profile for a dyed EMPA221 substrate bottom using Bottom, Level2, Level3 and Level4 horizontal laser positions, ensemble average of 10 picture pair runs.

Figure 109: Short run normalized x-direction mass flux concentration profile of a dyed Terry substrate bottom using Bottom, Level2, Level3 and Level4 horizontal laser positions, ensemble average of 10 picture pair runs.
Figure 110: Average of short run normalized x-direction mass flux concentration profiles of average dyed AHAM, EMPA221, and Terry substrate using Bottom, Level2, Level3 and Level4 horizontal laser positions, ensemble average of 10 picture pair runs.

Figure 111: Short run normalized x-direction mass flux concentration profile of a dyed AHAM, EMPA and Terry substrate bottom using Middle vertical laser position, ensemble average of 10 picture pair runs.
As shown in Figure 107 through Figure 109 above, the short run ensemble average normalized horizontal concentration mass flux profile in the $x$-direction ($\langle \tau_{ci} \rangle / \max(\langle \tau_{ci} \rangle)$ of the dye saturated substrate bottom and indicates a erratic and variable behavior in both the substrate and laser positions. The AHAM, EMPA221 and Terry substrate for the Bottom, Level2, Level3 and Level4 laser location shows the short run mass flux having significant variation ranging across the flow chamber width. For the AHAM substrate the Bottom and the Level2 laser position indicate a more positive signal condition. The Level3 and Level4 laser position on the other hand show a more negative signal trend. For the EMPA221 substrate the indicate that all four laser positions are a more negative signal condition. Only the Bottom and Level4 a positive laser position. For the Terry substrate the short run Reynolds stress have a more negative signal with the Bottom and Level2 laser position showing some positive signal condition. In general the concentration mass flux profiles are erratic and randomly uniform and show very little semblance of the smooth parabolic profiles previously indicated 2000 picture pair ensemble average for these same cases.

In Figure 111 the vertical short run ensemble average of the normalized concentration mass flux along the $x$-direction ($\langle \tau_{ci} \rangle / \max(\langle \tau_{ci} \rangle)$ of the dye saturated substrate bottom and indicates a non-symmetric but generally similar curvature for the AHAM, EMPA221 and Terry substrates. These signals generally start at zero at the flow chamber bottom and decrease to a global minimum and then increase to a global maximum moving upward with the signals decreasing again toward the top. These short run signals have minimum variation compared to
the horizontal laser position previously discussed and indicates significantly more concentration mass flux occurring in the horizontal plane.

### 6.2.10 Short Run Horizontal and Vertical Normalized Concentration Mass Flux z and y-direction

The short run ensemble average of 10 dye picture pairs where taken and the normalized concentration mass flux in the z and y – direction are shown in the following figures for four horizontal and one vertical laser planes in the y-direction are shown in the following figures. The maximum short run normalized concentration mass flux for creating the normalized horizontal AHAM substrate profile in the z–direction for the Bottom, Level2, Level3 and Level4 laser positions are -8.07e-05, -7.89e-05, -3.78e-05 and -4.16 respectively. The maximum short run normalized concentration mass flux for the horizontal EMPA221 substrate profile z-direction for the Bottom, Level2, Level3 and Level4 laser positions are -6.52e-05, -4.64e-05, -4.13e-05 and -5.78 respectively. The maximum short run normalized concentration mass flux for the horizontal Terry substrate profile in the z–direction for the Bottom, Level2, Level3 and Level4 laser positions are -3.90e-05, -4.73e-05, -4.86e-05 and -6.01 respectively. The maximum short run normalized concentration mass flux for the vertical AHAM, EMPA and Terry substrate profile in the y-direction for the Middle laser position are -1.908e-04, -1.09e-04 and -3.75e-05 respectively.
Figure 112: Short run normalized z-direction concentration mass flux profile of a dyed AHAM substrate bottom using Bottom, Level2, Level3 and Level4 horizontal laser positions, ensemble average of 10 picture pair runs.

Figure 113: Short run normalized z-direction concentration mass flux profile of a dyed EMPA221 substrate bottom using Bottom, Level2, Level3 and Level4 horizontal laser positions, ensemble average of 10 picture pair runs.
Figure 114: Short run normalized z-direction concentration mass flux profile for a dyed Terry substrate bottom using Bottom, Level2, Level3 and Level4 horizontal laser positions, ensemble average of 10 picture pair runs.

Figure 115: Average of short run normalized z-direction mass flux concentration profiles of average dyed AHAM, EMPA221, and Terry substrate using Bottom, Level2, Level3 and Level4 horizontal laser positions, ensemble average of 10 picture pair runs.
Figure 116: Short run normalized y-direction concentration mass flux profile for a dyed AHAM, EMPA221 and Terry substrate bottom using Middle vertical laser positions, ensemble average of 10 picture pair runs.

As shown in Figure 112 through Figure 114 above, the short run ensemble average normalized horizontal concentration mass flux profile in the z-direction ($\langle \tau_{c3} \rangle / \max(\langle | \tau_{c3} | \rangle)$) of the dye saturated substrate bottom and indicates a variable behavior in both the substrate and laser positions as was shown in the short run $\langle \tau_{c3} \rangle / \max(\langle | \tau_{c3} | \rangle)$ case above. Furthermore, the AHAM, EMPA221 and Terry substrate for the Bottom, Level2, Level3 and Level4 laser location shows a similar condition for short run Reynolds stress having significant variation ranging across the flow chamber width. The AHAM substrate case show a generally positive trend across the width of the flow chamber. The EMPA221 substrate case showed a generally negative trend at the negative $z/H_y$ location and a generally positive signals trends at the positive $z/H_y$ location along the flow chamber. The Terry substrate case showed a generally negative trend at the flow chamber center and positive trend at both the negative and positive
location. The signals are erratic and randomly uniform across the flow chamber width and show very little semblance of the smooth parabolic profiles previously discussed in the above 2000 picture pair ensemble average for these same cases.

In Figure 116 the vertical short run ensemble average of the normalized concentration mass flux along the y-direction \( \langle \tau_{c2} \rangle / \max(\langle \tau_{c2} \rangle) \) of the dye saturated substrate bottom and indicates a non-symmetric but generally similar curvature for the AHAM, EMPA221 and Terry substrates. The AHAM and EMPA221 substrate generally have the same similar trends with the signal increasing from zero at the bottom of the flow chamber and increasing to a global maximum at \( y/H_y = 0.1 \) then decreasing to a global minima at approximately \( y/H_y = 0.26 \) and 0.2 respectively. The signal then slightly increases to a local maximum and then decreases to zero moving higher up the flow chamber. Again, these relatively smooth cures indicate that the horizontal laser planes measure significant more mass flux than the vertical laser planes.

6.2.11 Normalized Dye Turbulent Production Profile

The ensemble average of 2000 dye picture pairs for the horizontal normalized turbulent production and the profiles for four horizontal and one vertical laser planes are shown in the following figures. The maximum normalized turbulent production for creating the normalized horizontal AHAM substrate profile for the Bottom, Level2, Level3 and Level4 laser levels are -1.42e-05, -3.47e-05, -5.13e-03 and -0.051 respectively. The maximum normalized turbulent production for creating the horizontal EMPA221 substrate profile for the Bottom, Level2, Level3 and Level4 laser levels are -2.42e-05, -0.039, -1.09e-03 and -4.61e-05 respectively. The maximum normalized turbulent production for creating the horizontal Terry substrate profile for the Bottom, Level2, Level3 and Level4 laser levels are -0.893, -0.109, -6.51e-05 and -2.29e-05 respectively. The maximum normalized concentration turbulent production for the vertical
AHAM, EMPA and Terry substrate profile are -1.6005e-04, -4.28e-05 and -9.96e-05 respectively.

Figure 117: Normalized turbulent production profile for a dyed AHAM substrate bottom using Bottom, Level2, Level3 and Level4 horizontal laser positions, ensemble average of 2000 picture pair runs.
Figure 118: Normalized turbulent production profile for a dyed EMPA221 substrate bottom using Bottom, Level2, Level3 and Level4 horizontal laser positions, ensemble average of 2000 picture pair runs.

Figure 119: Normalized turbulent production profile for a dyed Terry substrate bottom using Bottom, Level2, Level3 and Level4 horizontal laser positions, ensemble average of 2000 picture pair runs.
Figure 120: Average turbulent production profiles of average dyed AHAM, EMPA221, and Terry substrate using Bottom, Level2, Level3 and Level4 horizontal laser positions, ensemble average of 2000 picture pair runs.

Figure 121: Normalized turbulent production profile for a dyed AHAM, EMPA221 and Terry substrate bottom using Middle vertical laser positions, ensemble average of 2000 picture pair runs.
As shown in Figure 117 through Figure 119 above, the ensemble average normalized horizontal turbulent production profile in the x and z-direction \( \langle P_{ij} \rangle / \max(\langle P_{ij} \rangle) \) of the dye saturated substrate bottom and indicates a surprisingly non-consistent behaviors for each of the different laser positions even though it has the smallest asperities of three substrates. The AHAM substrate Bottom and Level2 laser position have the same similar profile shapes which the signal starting close to zero and shows the turbulent production quickly reaching both a global and local minima near either side of the flow chamber. The signal then increases rapidly to a global and local maximum at approximately \( z/H_y = -0.75 \) and 1.25. The Bottom laser position shows significantly more variation than the other laser position levels. The turbulent production for these two levels generally goes to zero close to the center of the flow chamber at \( z/H_y = 0 \). The Level3 and Level4 laser position have an opposite effect close to the sides of the flow chamber where the signal increases instead of decreases rapidly from zero from both sides of the flow chamber where it reaches a global and local maximums. The signals then decrease gradually to zero at the center of the flow chamber indicating a more a reduced but constant turbulent production condition compared to the Bottom and Level2 laser position. For the EMPA221 substrate all four curves are unique with the Bottom laser position showing only one significant turbulent production signal on the positive \( z/H_y \) side of the flow chamber (The negative side of the flow chamber shows an almost zero turbulent production signal). Moving from the negative side of the flow chamber the Bottom laser position signal increases to a local maxima at approximately \( z/H_y = -0.75 \). The signal then decrease to zero toward the center and continues to decrease to a local minima at \( z/H_y = 0.4 \). The signal increases again to zero and then abruptly decrease to a global minima. The Level2 laser position increases abruptly to a
global maxima close to the negative side of the flow chamber. The signal then abruptly decrease close to zero and maintains a minimal turbulent production signal along the width of the flow chamber. At the positive side of the flow chamber the signal abruptly decreases to a global minima and abruptly increases again to a local minima. The Level3 laser position abruptly decreases to a global minima close to the negative side of the flow chamber and abruptly increases to a local maximum at approximately $z/H_y = -1.1$. The signal then gradually decrease to zero toward the center of the flow chamber and then increases again to a global maximum at $z/H_y = 1.1$. The signal decrease abruptly to a local minima and then increase to a local maximum close to the positive side of the flow chamber. The Level4 laser position shows a gradual increase from the negative side of the flow chamber to two different local maxima. The signal then decreases to zero at the flow chamber center and then increase again to a global maxima close to the positive side of the flow chamber. The signal then reduce to approximately zero at the positive side of the flow chamber. For the Terry substrate the signals are similar with abrupt signal increase from zero at the negative side of the flow chamber to global and local maxima at approximately $z/H_y = -1.25$. The signals gradual decrease to zero at the center of the flow chamber and then the signal increases again to a global and local maxima towards the positive side of the flow chamber at $z/H_y = 1.25$. The signal then reduces to approximately zero at the positive side of the flow chamber with some oscillation. The Level3 and Level4 laser positions show more signal variation compared to the Bottom and Level2 laser position with the signals having a local maximum at approximately $z/H_y = -0.6$. The Level4 laser position also shows negative turbulent production at about the same location compared to the other laser positions toward the positive side of the flow chamber. Upon evaluating all four laser positions it can be seen that the turbulent production is generally largest against the sides of the flow
chamber in either the positive or negative directions and generally smallest at the center of the flow chamber. The positive and negative directions obviously change moving from the bottom to the top of the flow chamber with the Bottom and Level2 yielding a negative turbulent production and Level3 and Level4 yielding a positive turbulent production signal. The area between the flow chamber side and center region show some fluctuations where the different laser positions a signal increase whereas the remaining signals do not and seems to be dependent on the different substrate surfaces. This indicates that different surface roughness change how turbulent production are generated within the flow chamber. Furthermore the substrate signals show in general a bimodal or multimodal turbulent production signals that occur mostly at the sides of the flow chamber. The substrate signals are loosely similar to the base flow conditions in the negative $z/H_y$ region except of course the negative signals that are shown next to the sides of the flow chamber. In the positive $z/H_y$ side of the flow chamber the substrate signal generally increases whereas the base flow signal remains close to zero. This indicates differences between the base flow and dye measurements where the dye seems to have more sensitivity to turbulent production as it is expected to have turbulent production signals close to the sides of the flow chamber.

In Figure 121 the vertical ensemble average of the normalized turbulent production along the x and y-direction ($\langle P_{t,z} \rangle / \max(|\langle P_{t,z} \rangle|)$ of the dye saturated substrate bottom and indicates a non-symmetric but similar curvature between the AHAM, EMPA221 and Terry substrates. The AHAM and EMPA221 signals show an abrupt signal decrease to a global minima at $z/H_y = 0.11$. The signal then increases to a global maximum at $z/H_y = 2.2$. The signal then decreases to approximately zero $z/H_y = 0.5$ and 0.45 respectively and increase again to a local maxima at
\[ z / H_y = 0.65 \text{ and } 0.68 \text{ respectively. The signal reduces to approximately zero again at the flow chamber top. The Terry substrate on the other hand increases from zero to a global maximum at the same global maximum location as the other substrates. The signal also decreases to zero but increases again to a local maximum at } z / H_y = 0.56. \text{ The signal then reduces to zero similarly at the top of the flow chamber. This indicates again that the substrate roughness can reduce minimize or eliminate negative turbulent production behavior close to the substrate surfaces. The turbulent production layers are formed at generally the same location within the flow chamber but the layer separation increases moving to the flow chamber top. These signals somewhat mimic the base flow conditions (except for the initial negative signals at the flow chamber bottom) with two the maxima and one minima turbulent production nodes moving from the flow chamber bottom. } 

6.2.12 Normalized Concentration Turbulent Fluctuation Profile

The ensemble average of 2000 dye concentration picture pairs for the horizontal normalized turbulent production and the profiles for four horizontal and one vertical laser planes are shown in the following figures. The maximum normalized turbulent production for creating the normalized horizontal AHAM substrate profile for the Bottom, Level2, Level3 and Level4 laser levels are $6.21 \times 10^{-5}$, $1.24 \times 10^{-11}$, $5.78 \times 10^{-8}$ and $5.89 \times 10^{-7}$ \(m^2/s^2\) respectively. The maximum normalized turbulent production for creating the horizontal EMPA221 substrate profile for the Bottom, Level2, Level3 and Level4 laser levels are $4.24 \times 10^{-9}$, $1.59 \times 10^{-4}$, $1.53 \times 10^{-6}$ and $3.94 \times 10^{-10}$ \(m^2/s^2\) respectively. The maximum normalized turbulent production for creating the horizontal Terry substrate profile for the Bottom, Level2, Level3 and Level4 laser levels are $3.93 \times 10^{-10}$, $5.23 \times 10^{-10}$, $5.32 \times 10^{-10}$ and $5.48 \times 10^{-10}$ \(m^2/s^2\) respectively. The maximum normalized concentration
turbulent production for the vertical AHAM, EMPA and Terry substrate profile are $1.26 \times 10^{-17}$, $3.75 \times 10^{-17}$ and $1.54 \times 10^{-17} \text{ m}^2 / \text{s}^2$ respectively.

Figure 122: Normalized horizontal concentration turbulent fluctuation profile for a dyed AHAM substrate bottom using Bottom, Level2, Level3 and Level4 horizontal laser positions, ensemble average of 2000 picture pair runs.

Figure 123: Normalized horizontal concentration turbulent fluctuation profile for a dyed EMPA221 substrate bottom using Bottom, Level2, Level3 and Level4 horizontal laser positions, ensemble average of 2000 picture pair runs.
Figure 124: Normalized horizontal concentration turbulent fluctuation profile for a dyed Terry substrate bottom using Bottom, Level2, Level3 and Level4 horizontal laser positions, ensemble average of 2000 picture pair runs.

Figure 125: Average normalized horizontal concentration turbulent fluctuation profiles of average dyed AHAM, EMPA221, and Terry substrate using Bottom, Level2, Level3 and Level4 horizontal laser positions, ensemble average of 2000 picture pair runs.
As shown in Figure 122 through Figure 124 above, the ensemble average normalized horizontal concentration turbulent production profile in the x-direction ($\langle P_{tc1} \rangle / \max(\langle |P_{tc1}| \rangle)$) of the dye saturated substrate bottom and indicates a generally consistent behaviors for each of the different laser positions. The AHAM substrate Bottom, Level3 and Level4 laser positions have the same similar shapes which the concentration turbulent production signal starting close to zero and abruptly increasing against both sides of the flow chamber to a global maximum. The signal then decreases rapidly to the center of the flow chamber and gradually decreases to a global minimum close to the center of the flow chamber. The Level2 laser position is unique in that the signal starts close to zero and instead of abruptly increasing it abruptly decreases to a global minima and local minima at the negative and positive side of the flow chamber respectively. The signal then abruptly increases to zero with some variation and settle to zero and remains that
way throughout most of the flow chamber width. This indicates that concentration turbulent production occurs mostly against the sides of the flow chamber. The Bottom, Level3 and Level4 shows an increase in negative concentration turbulent production across the width of the flow chamber. The Level2 laser position shows almost no concentration turbulent production along the flow chamber width. For the EMPA221 substrate the Bottom and Level3 signals start close to zero and abruptly decrease to a local and global minima respectively. The signal then increases rapidly to a positive global and local maxima respectively. Both signals then decrease to zero. The Level2 laser position is unique in that the signal gradually decreases from zero to a local minima and then gradually increases again until the signal becomes zero again close to the positive side of the flow chamber. The signal then abruptly increases to a global maxima and abruptly decrease again to zero. The Bottom laser position once it reaches zero remains that way along the width of the flow chamber. When the signal approaches the positive side of the flow chamber the signal decreases rapidly to a global minima. The Level4 laser position minimally oscillates close to the negative side of the flow chamber and then goes to zero and remains at zero along the width of the flow chamber. As this signal approaches the positive side of the flow chamber the signal abruptly decreases to a global minimum. The Level2 laser position increases abruptly from zero at the negative side of the flow chamber to a global maxima. The signal then decreases to zero and remains zero along the width of the flow chamber. As it approaches the positive side of the flow chamber the signal increases to a local maximum and then decrease to zero. These signals indicate that the concentration turbulent production occurs considerably more at the sides of the flow chamber. The Bottom, Level2 and Level4 signal of the EMPA221 substrate tends to have almost no concentration turbulent production that occurs along the width of the flow chamber. The Level3 laser position shows a considerable increase in negative
concentration turbulent production occurring across the width of the flow chamber. For the Terry substrate the Bottom laser position the signal at the negative side of the flow chamber abruptly decreases then increases to a local minimum and maximum respectively. Once the signal reaches zero it oscillates and gradually decreases in a parabolic fashion along the width of the flow chamber to a local minima and then gradually increases again. When the signal reaches the positive side of the flow chamber the signal increases and then abruptly decreases, then increases twice with the second signal increase and decrease closest to the flow chamber side becoming the global minima and maximum respectively before it terminates at the flow chamber side. The Leve2 laser position the signal increases abruptly from negative side of the flow chamber and then decreases and oscillates around zero along the width of the flow chamber with no parabolic shape. As the signal approaches the positive side of the flow chamber the decreases to a global minimum and then begins to increase the closer it gets to the side of the flow chamber. The signal then abruptly increases and decreases twice with the first becoming a global maximum. The Level3 laser position does not have an abrupt signal change close to the negative side of the flow chamber but instead slightly oscillates across the flow chamber width with a slight parabolic decrease to a global minima where it then increases and oscillates around zero. As the signal approaches the positive side of the flow chamber the signal abruptly increases to a global maximum and then decreases and increases again. The Level4 laser position is unique in that the signal abruptly decreases instead of increasing from the negative side of the flow chamber. The signal then increases to approximately zero where it remain constant along the width of the flow chamber. When the signal approaches the positive side of the flow chamber the signal oscillates and then abruptly decreases to a global minima where it terminates. These signals indicate that the concentration turbulent production occurs
considerably more at the sides of the flow chamber. The Bottom signal of the Terry substrate tends to have the greatest concentration turbulent production. Signal oscillation across the width of the signal tends to decrease moving upward from the bottom of the flow chamber. In general the concentration turbulent production magnitude is greatest very close the flow chamber sides with mostly minimal signal increase along the flow chamber center.

In Figure 126 the vertical ensemble average of the normalized concentration turbulent production along the x and y-direction $(\langle P_{c1} \rangle / \max(|\langle P_{c1} \rangle|)$ of the dye saturated substrate bottom and indicates a non-symmetric curvature between the AHAM, EMPA221 and Terry substrates. All three substrates show an abrupt signal increase to a global maximum from the flow chamber bottom at approximately $z / H_y = 0.08$ to 0.1. The AHAM signal remains positive with an abrupt signal decrease and then increase to a local minima and maxima. The signal then gradually decreases to zero and continues to decrease to a global minima as it moves toward the top of the flow chamber. The signal then increases again to zero at the top of the flow chamber. For the EMPA221 substrate, the signal decreases from the global maximum to zero and generally remains at zero as it moves to the top of the flow chamber. The Terry substrate signal decreases form its global maximum past zero and becomes negative to a global minima. The signal then gradually increases moving toward the top of the flow chamber. The signal increases past zero where it reaches a local maxima and then decreases again toward the flow chamber top. This indicates that concentration turbulent production is greatest toward the substrate bottom. The Terry and AHAM substrate with the largest asperities show more signal concentration turbulent production fluctuation toward the bottom surface. The EMPA221 with the smallest asperities show less concentration turbulent production variation and minimal production signal after $y / H_y = 0.2$ compared to the other substrates.
6.2.13 Short Run Normalized Concentration Turbulent Fluctuation Profile

The ensemble average of 10 dye concentration picture pairs for the horizontal normalized turbulent production and the profiles for four horizontal and one vertical laser planes are shown in the following figures. The maximum normalized turbulent production for creating the normalized horizontal AHAM substrate profile for the Bottom, Level2, Level3 and Level4 laser levels are 2.25e-09, 4.65e-09, 5.15e-10 and 3.16e-10 $m^2/s^2$ respectively. The maximum normalized turbulent production for creating the horizontal EMPA221 substrate profile for the Bottom, Level2, Level3 and Level4 laser levels are 1.91e-09, 3.51e-09, 8.27e-10 and 8.35e-10 $m^2/s^2$ respectively. The maximum normalized turbulent production for creating the horizontal Terry substrate profile for the Bottom, Level2, Level3 and Level4 laser levels are 2.7454e-05, 2.2148e-06, 1.5369e-09 and 2.0107e-11 $m^2/s^2$ respectively. The maximum normalized concentration turbulent production for the vertical AHAM, EMPA and Terry substrate profile are 1.12e-08, 1.34e-08 and 2.06e-09 $m^2/s^2$ respectively.

![Figure 127: Short run normalized horizontal concentration turbulent fluctuation profile for a dyed AHAM substrate bottom using Bottom, Level2, Level3 and Level4 horizontal laser positions, ensemble average of 10 picture pair runs.](image)

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Figure 128: Short run normalized horizontal concentration turbulent fluctuation profile for a dyed EMPA221 substrate bottom using Bottom, Level2, Level3 and Level4 horizontal laser positions, ensemble average of 10 picture pair runs.

Figure 129: Short run normalized horizontal concentration turbulent fluctuation profile for a dyed Terry substrate bottom using Bottom, Level2, Level3 and Level4 horizontal laser positions, ensemble average of 10 picture pair runs.
Figure 130: Average of short run normalized horizontal concentration turbulent fluctuation profiles of average dyed AHAM, EMPA221, and Terry substrate using Bottom, Level2, Level3 and Level4 horizontal laser positions, ensemble average of 10 picture pair runs.

Figure 131: Short run normalized vertical concentration turbulent fluctuation profile for a dyed AHAM, EMPA221 and Terry substrate bottom using Middle vertical laser positions, ensemble average of 10 picture pair runs.
As shown in Figure 127 through Figure 129 above, the short run ensemble average normalized horizontal concentration turbulent production profile in the x-direction \( \langle P_{nci} \rangle / \max(\langle P_{nci} \rangle) \) of the concentration dye saturated substrate bottom and indicates a significantly variable signal. The AHAM substrate Bottom, Level2, Level3 and Level4 laser positions have the same similar variable signal that are mostly positive with most of the higher signals occurring at the negative section of the flow chamber. The EMPA221 substrate laser positions show a similar variable but signal as what was shown in the AHAM substrate. However the Level4 laser position has significantly more variability at the positive section of the flow chamber. The Terry substrate shows again a variable and generally positive signal across the width of the flow chamber. This indicates that the short run concentration averages have significant signal variation but a generally positive concentration turbulent production across the flow chamber width turbulent.

In Figure 131 the vertical short run ensemble average of the normalized concentration turbulent production along the x-direction \( \langle P_{nci} \rangle / \max(\langle P_{nci} \rangle) \) of the dye saturated substrate bottom and indicates a non-symmetric curvature between the AHAM, EMPA221 and Terry substrates. All three substrates show a slight signal oscillation at the flow chamber bottom with an abrupt signal increase to a global maximum at approximately \( z / H_y = 0.1 \). The AHAM and Terry substrate signals then decrease to zero at \( z / H_y = 0.2 \) and generally remain there as the signal approaches the top of the flow chamber. The Terry substrate is the exception with the signal decreasing toward zero but then gradually decreases to zero as it approach the top of the flow chamber. This indicates that a majority of the short run concentration turbulent production.
occurs about ten percent from the flow chamber bottom and the dissipates at approximately 20 percent of the flow chamber width.

6.2.14 Normalized Dye Vorticity Field Profile
The ensemble average of 2000 dye picture pairs for the horizontal normalized vorticity and the profiles for four horizontal and one vertical laser planes are shown in the following figures. The maximum normalized vorticity for creating the normalized horizontal AHAM substrate profile for the Bottom, Level2, Level3 and Level4 laser levels are 3.11e-04, 4.36e-04, 9.75e-04 and 1.77e-03 respectively. The maximum normalized turbulent production for creating the horizontal EMPA221 substrate profile for the Bottom, Level2, Level3 and Level4 laser levels are 2.98e-04, 1.65e-04, 8.65e-04 and 2.96e-04 respectively. The maximum normalized turbulent production for creating the horizontal Terry substrate profile for the Bottom, Level2, Level3 and Level4 laser levels are 4.52e-03, 3.19e-03, 5.29e-04 and 4.83e-04 respectively. The maximum normalized concentration turbulent production for the vertical AHAM, EMPA and Terry substrate profile are 7.68e-04, 5.94e-04 and 8.53e-04 respectively.
Figure 132: Normalized vorticity profile for a dyed AHAM substrate bottom using Bottom, Level2, Level3 and Level4 horizontal laser positions, ensemble average of 2000 picture pair runs.

Figure 133: Normalized vorticity profile for a dyed EMPA221 substrate bottom using Bottom, Level2, Level3 and Level4 horizontal laser positions, ensemble average of 2000 picture pair runs.
Figure 134: Normalized vorticity profile for a dyed Terry substrate bottom using Bottom, Level2, Level3 and Level4 horizontal laser positions, ensemble average of 2000 picture pair runs.

Figure 135: Average vorticity profiles of average dyed AHAM, EMPA221, and Terry substrate using Bottom, Level2, Level3 and Level4 horizontal laser positions, ensemble average of 2000 picture pair runs.
As shown in Figure 132 through Figure 134 above, the dye ensemble average normalized horizontal vorticity profile \( \frac{\langle \omega_3 \rangle}{\max(|\langle \omega_3 \rangle|)} \) of the dye saturated substrate bottom is shown and indicates a generally consistent behavior for each of the different laser positions. For all three AHAM, EMPA221 and Terry substrates the vorticity all four laser positions decreases from approximately zero at the negative side of the flow chamber to a global minima at approximately \( z/H_y \approx -1.4 \). The signal then increases gradually across the flow chamber width and becomes zero when it crosses the flow chamber center. The signal further increases until a global maximum is reached at \( z/H_y = 1.4 \). The signal then abruptly decreases to zero. However, the EMPA 221 substrate signal is significantly more variable across the flow chamber width than the other substrates. This indicates that the substrate with the least asperities (more smooth) than the other substrates cause greater vorticities across the flow chamber width. The vorticity signal is greatest at the flow chamber sides with negative and positive vorticity direction at the negative...
and positive $z/H_y$ locations with the reversing occurring at the flow chamber middle. Moreover, the vorticity profile of the three different substrates and corresponding laser positions are similar to the base flow profiles shown above.

In Figure 136 the vertical ensemble average of the normalized vorticity ($\langle \omega_z \rangle / \max(|\langle \omega_z \rangle|)$ of the dye saturated substrate bottom and indicates a generally symmetric curvature for all three substrates (AHAM, EMPA221 and Terry). The signal decreases from zero to a global minima at about approximately $y/H_y = 0.16$ regardless of the different substrates. The signal then increases through zero and continues to increase until a global maximum is reached. The global minima occurs at the same location $z/H_y = 0.16$ regardless of the substrate type. The global maximum is different for each of the different substrates with Terry having the lowest maxima occurring a $z/H_y = 0.54$, followed by AHAM at $z/H_y = 0.61$ and then EMPA221 at $z/H_y = 0.69$. It is interesting that the signal reversal does not occur at the flow chamber center but instead at approximately $z/H_y = 0.35$. These vorticity profiles of the three different substrates are also similar to the base flow profiles shown above.

6.2.15 Short Run Normalized Dye Vorticity Field Profile

The short run ensemble average of 10 dye picture pairs for the horizontal normalized vorticity and the profiles for four horizontal and one vertical laser planes are shown in the following figures. The maximum normalized vorticity for creating the normalized horizontal AHAM substrate profile for the Bottom, Level2, Level3 and Level4 laser levels are 0.011, 0.011, 0.012 and 0.010 respectively. The maximum normalized turbulent production for creating the horizontal EMPA221 substrate profile for the Bottom, Level2, Level3 and Level4 laser levels are 7.32e-03, 0.011, 8.92e-03 and 0.010 respectively. The maximum normalized turbulent
production for creating the horizontal Terry substrate profile for the Bottom, Level2, Level3 and Level4 laser levels are 8.79e-03, 0.011, 9.53e-03 and 0.011 respectively. The maximum normalized concentration turbulent production for the vertical AHAM, EMPA and Terry substrate profile are 9.52e-04 6.34e-04 9.55e-04 respectively.

Figure 137: Short run normalized vorticity profile for a dyed AHAM substrate bottom using Bottom, Level2, Level3 and Level4 horizontal laser positions, ensemble average of 10 picture pair runs.
Figure 138: Short run normalized vorticity profile for a dyed EMPA221 substrate bottom using Bottom, Level2, Level3 and Level4 horizontal laser positions, ensemble average of 10 picture pair runs.

Figure 139: Short run normalized vorticity profile for a dyed Terry substrate bottom using Bottom, Level2, Level3 and Level4 horizontal laser positions, ensemble average of 10 picture pair runs.
Figure 140: Average of short run normalized vorticity profiles of average dyed AHAM, EMPA221, and Terry substrate using Bottom, Level2, Level3 and Level4 horizontal laser positions, ensemble average of 10 picture pair runs.

Figure 141: Short run normalized vorticity profile for a dyed AHAM, EMPA221 and Terry substrate bottom using Middle vertical laser positions, ensemble average of 10 picture pair runs.
As shown in Figure 137 through Figure 139 above, the short run ensemble average normalized horizontal vorticity profile \( \langle \omega_z \rangle / \max(\langle \omega_z \rangle) \) of the dye saturated substrate bottom is shown and indicates a generally consistent behavior as was previously shown for the 2000 picture pair ensemble average. All three AHAM, EMPA221 and Terry substrates the vorticity all four laser positions decreases from approximately zero at the negative side of the flow chamber to a global minima at approximately \( z / H_y = -1.4 \). The signal then increases gradually across the flow chamber width and crosses zero and further increases until a global maximum is reached at \( z / H_y = 1.4 \). The signal then abruptly decreases to zero. However, again, the EMPA221 substrate signal is significantly more variable across the flow chamber width than the other substrates especially the Level4 laser position. As with the 2000 ensemble average the vorticity occurs at the flow chamber sides with negative and positive vorticity direction at the negative and positive \( z / H_y \) locations with the reversing occurring at the flow chamber middle.

In Figure 141 the short run vertical ensemble average of the normalized vorticity \( \langle \omega_z \rangle / \max(|\langle \omega_z \rangle|) \) of the dye saturated substrate bottom and indicates as the 2000 ensemble average, a generally symmetric curvature for all three substrates (AHAM, EMPA221 and Terry). The signal decreases from zero to a global minima at about approximately \( y / H_y = 0.15 \) for AHAM and EMPA221 regardless of the different substrates. The Terry substrate global minim occurs at \( y / H_y = 0.19 \). All three signals then increases through zero and continues to increase until a global maximum is reached. The global maximum is different for each of the different substrates as with the 2000 ensemble average with Terry having the lowest maxima occurring at \( z / H_y = 0.546 \) followed by AHAM at \( z / H_y = 0.61 \) and then EMPA221 at \( z / H_y = 0.69 \).
Again, it is interesting that the signal reversal does not occur at the flow chamber center but instead at approximately \( z / H_y = 0.44 \).

7 QUANTIFYING OBSERVED STREAKY STRUCTURES

During flow chamber testing of dyed fabric substrate, streaky structures were readily observed and continued to form throughout the course of the 45 minute test when 2000 picture pairs were taken. However, when using typical ensemble metrics of multiple picture pairs, these observed streaky structures tended to be much less pronounced. This is due to the inherent irregularity and randomness of these structures that when averaged, they tend to blend within the space measured. In order to quantify these streaky structures, an instantaneous look at the field plots for eleven different normalized metrics (kinetic energy, concentration kinetic energy, Reynolds stress, mass flux in the x and z-direction, turbulent production, concentration turbulent production, concentration fluctuation, velocity fluctuation in the x and z-direction, and concentration transport by turbulent fluctuations) is provided and shown in the following figures for AHAM, EMPA221 and Terry fabric substrate for the bottom horizontal laser position at four different time intervals during the test (4.5, 14.6, 24.8 and 34.9 minute intervals). The instantaneous metrics are defined by taking the resulting metric of a single picture pair at the aforementioned time intervals and comparing it to the 2000 ensemble average. Thus the velocity and concentration fluctuations \( (u'_i = \langle U_i \rangle - u_i \text{ and } c' = \langle C \rangle - c) \) for a single picture pair condition are then used to create the instantaneous Reynolds stress \( \tau_{ij} \), mass flux \( \tau_{rj} \), kinetic energy \( K_{ij} \) and turbulent production \( P_{ij} \) terms defined by the following equations respectively

\[
\tau_{ij} = -\rho u'_i u'_j
\]
\[ \tau_{sci} = -2u_i c_i \]  

\[ K_{stij} = \frac{1}{2} \left( u_i u_j + u_j u_i \right) \]  

\[ K_{sc} = \frac{1}{2} (c c) \]  

\[ P_{stij} = -u_i u_j \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \]  

\[ P_{scij} = -2 \left( c u_i \frac{\partial c}{\partial x_j} + c u_j \frac{\partial c}{\partial x_i} \right) \]

Furthermore, a new metric is introduced called the concentration transport by turbulent fluctuations \( T_{sc} \) to quantify the instantaneous mass transport that occurs next to the fabric surface.

This transport equation is defined by the following equation [34]

\[ T_{sc} = \frac{\partial}{\partial x_i} u_i c_i = c \frac{\partial u_i}{\partial x_i} + u_i \frac{\partial c}{\partial x_i} \]

These different metrics are provided in the following sections as field plot to visually represent what is happening across the fabric substrate area over time.

### 7.1 Instantaneous Kinetic Energy

The instantaneous kinetic energy for three different substrates and four different times with corresponding zoomed in regions are shown in Figure 142 through Figure 145 for AHAM, Figure 146 through Figure 149 for EMPA and Figure 150 through Figure 153 for Terry fabric substrates. The time differences of these four figures generally indicates an increased kinetic energy toward the second half of the flow chamber compared to the first half. The instantaneous kinetic energy is shown to be lower at the 4.5 minute mark with mostly localized low kinetic
energy regions with some localized higher kinetic energy regions. The AHAM fabric shows the least amount of these localized higher kinetic energy regions followed by the EMPA221 with the Terry substrate showing the most localized higher kinetic energy regions. Over time the AHAM and EMPA221 substrate show a column of high kinetic energy that forms within the first half of the flow chamber and then gradually fans out within the second half. The Terry substrate maintains a more uniform kinetic energy signal across the width of both sides of the flow chamber. The overall kinetic energy intensity is generally uniform for the AHAM and Terry substrate but seem to favor the positive $z/H_y$ side for the EMPA221 substrate. Kinetic energy significantly increases from the 4.5 minute to the 14.6 minute mark and again at 24.75 minutes for the AHAM and EMPA221 substrate. The kinetic energy for Terry does not increase after the 14.6 minute mark but instead increases in overall area. At the 34.9 minute mark the AHAM and EMPA221 kinetic energy declines to approximately the 14.6 minute levels. The Terry kinetic energy increases again at the 34.9 minute mark. The aforementioned dead zone prevalent at the 4.5 minute mark showed significant higher kinetic energy that was maintained during the remaining time of the test. In contrast, the higher initial kinetic energy regions shown became a dead zone comparatively as time progressed. These figures indicate a time varying condition exist for kinetic energy as it increases and then decrease toward the end of the test. Furthermore, kinetic energy regions builds up locally over time while at the same time higher initial kinetic energy regions can reduce and remain reduced over that same time period.
7.1.1 Instantaneous AHAM Kinetic Energy Figures

Figure 142: a) Instantaneous (one-run) normalized kinetic energy field plot for AHAM substrate at Bottom horizontal laser position at approximately 4.5 min. b) corresponding zoomed in view of latter half of flow chamber.

Figure 143: a) Instantaneous (one-run) normalized kinetic energy field plot for AHAM substrate at Bottom horizontal laser position at approximately 14.6 min. b) corresponding zoomed in view of latter half of flow chamber.
Figure 144: a) Instantaneous (one-run) normalized kinetic energy field plot for AHAM substrate at Bottom horizontal laser position at approximately 24.8 min. b) corresponding zoomed in view of latter half of flow chamber.

Figure 145: a) Instantaneous (one-run) normalized kinetic energy field plot for AHAM substrate at Bottom horizontal laser position at approximately 34.9 min. b) corresponding zoomed in view of latter half of flow chamber.
7.1.2 Instantaneous EMPA221 Kinetic Energy Figures

Figure 146: a) Instantaneous (one-run) normalized kinetic energy field plot for EMPA221 substrate at Bottom horizontal laser position at approximately 4.5 min. b) corresponding zoomed in view of latter half of flow chamber.

Figure 147: a) Instantaneous (one-run) normalized kinetic energy field plot for EMPA221 substrate at Bottom horizontal laser position at approximately 14.6 min. b) corresponding zoomed in view of latter half of flow chamber.
Figure 148: a) Instantaneous (one-run) normalized kinetic energy field plot for EMPA221 substrate at Bottom horizontal laser position at approximately 24.8 min. b) corresponding zoomed in view of latter half of flow chamber.

Figure 149: a) Instantaneous (one-run) normalized kinetic energy field plot for EMPA221 substrate at Bottom horizontal laser position at approximately 34.9 min. b) corresponding zoomed in view of latter half of flow chamber.
7.1.3 Instantaneous Terry Kinetic Energy Figures

Figure 150: a) Instantaneous (one-run) normalized kinetic energy field plot for Terry substrate at Bottom horizontal laser position at approximately 4.5 min. b) corresponding zoomed in view of latter half of flow chamber.
Figure 151: a) Instantaneous (one-run) normalized kinetic energy field plot for Terry substrate at Bottom horizontal laser position at approximately 14.6 min. b) corresponding zoomed in view of latter half of flow chamber.

Figure 152: a) Instantaneous (one-run) normalized kinetic energy field plot for Terry substrate at Bottom horizontal laser position at approximately 24.8 min. b) corresponding zoomed in view of latter half of flow chamber.

Figure 153: a) Instantaneous (one-run) normalized kinetic energy field plot for Terry substrate at Bottom horizontal laser position at approximately 34.9 min. b) corresponding zoomed in view of latter half of flow chamber.
7.2 Instantaneous Concentration Kinetic Energy

The instantaneous kinetic energy for three different substrates and four different times with corresponding zoomed in regions are shown in Figure 154 through Figure 157 for AHAM, Figure 158 through Figure 161 for EMPA and Figure 162 through Figure 165 for Terry fabric substrates. The time differences of these four figures generally indicates a uniformly distributed concentration kinetic energy along the length of the flow chamber. The EMPA221 figures show a plume structure from the fluid coming into the flow chamber. This is not prevalent in the other substrates. The instantaneous concentration kinetic energy is shown to be lower for the AHAM and EMPA221 substrates at the 4.5 minute mark and gradually increase until the 24.8 minute mark. These two substrates then decrease slightly at the 34.9 minute mark. The Terry substrate has the highest concentration kinetic energy at the 4.5 minute mark then the signal significantly decreases at the 14.6 minute mark and then slightly increases until the 34.9 minute mark. Each substrate has a unique streaky structure pattern represented with the concentration kinetic energy. The AHAM substrate shows long connected structures with greater intensity highlighted at the negative $z/H$ side of the flow chamber. This is due to the higher mass being expelled from the substrate against the intensity of the laser sheet emitting from that side of the flow chamber. The AHAM substrate shows a longer narrower streaky structure that increases and becomes more uniform over time. However, the Terry substrate shows the initial streaky structure development but then over time these structures reduce to multiple uniform points within the flow chamber. Overall these figures indicate a time varying condition that exists for concentration kinetic energy. Each substrate has a unique kinetic energy pattern due to the substrate differences.
7.2.1 Instantaneous AHAM Concentration Kinetic Energy Figures

Figure 154: a) Instantaneous (one-run) normalized concentration kinetic energy field plot for AHAM substrate at Bottom horizontal laser position at approximately 4.5 min. b) corresponding zoomed in view of latter half of flow chamber.

Figure 155: a) Instantaneous (one-run) normalized concentration kinetic energy field plot for AHAM substrate at Bottom horizontal laser position at approximately 14.62 min. b) corresponding zoomed in view of latter half of flow chamber.
Figure 156: a) Instantaneous (one-run) normalized concentration kinetic energy field plot for AHAM substrate at Bottom horizontal laser position at approximately 24.8 min. b) corresponding zoomed in view of latter half of flow chamber.

Figure 157: a) Instantaneous (one-run) normalized concentration kinetic energy field plot for AHAM substrate at Bottom horizontal laser position at approximately 34.9 min. b) corresponding zoomed in view of latter half of flow chamber.
7.2.2 Instantaneous EMPA221 Concentration Kinetic Energy Figures

Figure 158: a) Instantaneous (one-run) normalized concentration kinetic energy field plot for EMPA221 substrate at Bottom horizontal laser position at approximately 4.5 min. b) corresponding zoomed in view of latter half of flow chamber.

Figure 159: a) Instantaneous (one-run) normalized concentration kinetic energy field plot for EMPA221 substrate at Bottom horizontal laser position at approximately 14.6 min. b) corresponding zoomed in view of latter half of flow chamber.
Figure 160: a) Instantaneous (one-run) normalized concentration kinetic energy field plot for EMPA221 substrate at Bottom horizontal laser position at approximately 24.8 min. b) corresponding zoomed in view of latter half of flow chamber.

Figure 161: a) Instantaneous (one-run) normalized concentration kinetic energy field plot for EMPA221 substrate at Bottom horizontal laser position at approximately 34.9 min. b) corresponding zoomed in view of latter half of flow chamber.
7.2.3 Instantaneous Terry Concentration Kinetic Energy Figures

Figure 162: a) Instantaneous (one-run) normalized concentration kinetic energy field plot for Terry substrate at Bottom horizontal laser position at approximately 4.5 min. b) corresponding zoomed in view of latter half of flow chamber.

Figure 163: a) Instantaneous (one-run) normalized concentration kinetic energy field plot for Terry substrate at Bottom horizontal laser position at approximately 14.6 min. b) corresponding zoomed in view of latter half of flow chamber.
Figure 164: a) Instantaneous (one-run) normalized concentration kinetic energy field plot for Terry substrate at Bottom horizontal laser position at approximately 4.5 min. b) corresponding zoomed in view of latter half of flow chamber.

Figure 165: a) Instantaneous (one-run) normalized concentration kinetic energy field plot for Terry substrate at Bottom horizontal laser position at approximately 34.9 min. b) corresponding zoomed in view of latter half of flow chamber.
7.3 Instantaneous Reynolds Stress

The instantaneous Reynolds stress for three different substrates and four different time states with corresponding zoomed in regions are shown in Figure 166 through Figure 169 for AHAM, Figure 170 through Figure 173 for EMPA and Figure 174 through Figure 177 for Terry fabric substrates. The time differences of these four figures generally indicates a uniformly distributed Reynolds stress along the length of the flow chamber except for the AHAM substrate where it shows a slight gradual increase in Reynolds stress. The instantaneous Reynolds stress is shown to be lower for all three substrates at the 4.5 minute mark and significantly increase at the 14.6 minute mark. The Reynolds stress magnitude generally increases at the 24.8 and 34.9 minute mark. All three substrates have the same overall magnitude for each time step. Each substrate has a unique Reynolds stress signature within the flow chamber. The first half of the flow chamber generally shows a negative Reynolds stress region along the aforementioned plume area. The AHAM substrate shows general positive background at the 4.5 minute time step. The Reynolds stress then transitions to a negative background for the 14.6 and 24.8 minute mark. At the 34.9 minute mark the background transitions again to a positive condition. The background of the other substrates shows a more balanced condition. The regions of high and low magnitudes are random across the flow chamber area and change over time for all three substrates. Overall these figures indicate a time varying condition that exists for Reynolds stress. Each substrate has a unique Reynolds stress pattern due to the substrate differences.
7.3.1 Instantaneous AHAM Reynolds Stress Figures

Figure 166: a) Instantaneous (one-run) normalized Reynolds stress field plot for AHAM substrate at Bottom horizontal laser position at approximately 4.5 min. b) corresponding zoomed in view of latter half of flow chamber.

Figure 167: a) Instantaneous (one-run) normalized Reynolds stress field plot for AHAM substrate at Bottom horizontal laser position at approximately 14.6 min. b) corresponding zoomed in view of latter half of flow chamber.
Figure 168: a) Instantaneous (one-run) normalized Reynolds stress field plot for AHAM substrate at Bottom horizontal laser position at approximately 24.8 min. b) corresponding zoomed in view of latter half of flow chamber.

Figure 169: a) Instantaneous (one-run) normalized Reynolds stress field plot for AHAM substrate at Bottom horizontal laser position at approximately 34.9 min. b) corresponding zoomed in view of latter half of flow chamber.
7.3.2 Instantaneous EMPA221 Reynolds Stress Figures

Figure 170: a) Instantaneous (one-run) normalized Reynolds stress field plot for EMPA221 substrate at Bottom horizontal laser position at approximately 4.5 min. b) corresponding zoomed in view of latter half of flow chamber.

Figure 171: a) Instantaneous (one-run) normalized Reynolds stress field plot for EMPA221 substrate at Bottom horizontal laser position at approximately 14.6 min. b) corresponding zoomed in view of latter half of flow chamber.
Figure 172: a) Instantaneous (one-run) normalized Reynolds stress field plot for EMPA221 substrate at Bottom horizontal laser position at approximately 24.8 min. b) corresponding zoomed in view of latter half of flow chamber.

Figure 173: a) Instantaneous (one-run) normalized Reynolds stress field plot for EMPA221 substrate at Bottom horizontal laser position at approximately 34.9 min. b) corresponding zoomed in view of latter half of flow chamber.
7.3.3 Instantaneous Terry Reynolds Stress Figures

Figure 174: a) Instantaneous (one-run) normalized Reynolds stress field plot for Terry substrate at Bottom horizontal laser position at approximately 4.5 min. b) corresponding zoomed in view of latter half of flow chamber.

Figure 175: a) Instantaneous (one-run) normalized Reynolds stress field plot for Terry substrate at Bottom horizontal laser position at approximately 14.6 min. b) corresponding zoomed in view of latter half of flow chamber.
Figure 176: a) Instantaneous (one-run) normalized Reynolds stress field plot for Terry substrate at Bottom horizontal laser position at approximately 24.8 min. b) corresponding zoomed in view of latter half of flow chamber.

Figure 177: a) Instantaneous (one-run) normalized Reynolds stress field plot for Terry substrate at Bottom horizontal laser position at approximately 34.9 min. b) corresponding zoomed in view of latter half of flow chamber.
7.4 Instantaneous Mass Flux in x-direction

The instantaneous mass flux in the x-direction for three different substrates and four different times with corresponding zoomed in regions are shown in Figure 178 through Figure 181 for AHAM, Figure 182 through Figure 185 for EMPA and Figure 186 through Figure 189 for Terry fabric substrates. The time differences of these four figures generally indicates a uniformly distributed x-directional mass flux along the length of the flow chamber. The instantaneous mass flux in the x-direction is shown to vary across different substrates at the 4.5 minute mark. The mass flux in the x-direction for the AHAM substrate shows a lower value at the 4.5 minute mark which then increases significantly at the 14.6 minute mark. The magnitude then decreases slightly at the 24.8 minute mark and increases again at the 34.9 minute mark. At the initial time step a unique round or “C” shape structure appears and perhaps indicates a formation of a mass flux region. This round or “C” shape region is not prevalent in the other given time conditions. The pockets of mass flux are generally large but less prevalent initially. As time increases these pockets become smaller but more elongated. The intensity of the mass flux in the x-direction favors the negative $z/H_y$ region. At the 24.8 minute time region the formations of an erratic linear streaks mostly positive mass flux are seen moving towards the flow chamber exit. For the EMPA221 substrate, the mass flux starts out high at the 4.5 minute time step and continues to reduces at consecutive time step. Initially, the pockets of mass flux in the x-direction are sparse and elongated. Over time these pockets increase and are equally distributed across the flow chamber regions. Negative mass flux regions are more prevalent in the downstream side of the flow chamber. For the Terry substrate, the mass flux in the x-direction starts out low at the 4.5 minute time step and decreases further at the 14.6 min time step
and continues to decreases for the other time steps. The Terry substrate initially shows round or “C” shape formations similar to the AHAM substrate with sparse but relatively large pockets of x-direction mass flux. However, over time these pockets become less negative, smaller, more prevalent and distributed across the flow chamber area. Overall these figures indicate a time varying conditions that exists for x-direction mass flux with each substrate having a unique mass flux patterns due to the substrate differences.

7.4.1 Instantaneous AHAM Mass Flux in x-direction Figures

![Figure 178](image)

Figure 178: a) Instantaneous (one-run) normalized mass flux field plot in x-direction for AHAM substrate at Bottom horizontal laser position at approximately 4.5 min. b) corresponding zoomed in view of latter half of flow chamber.
Figure 179: a) Instantaneous (one-run) normalized mass flux field plot in x-direction for AHAM substrate at Bottom horizontal laser position at approximately 14.6 min. b) corresponding zoomed in view of latter half of flow chamber.

Figure 180: a) Instantaneous (one-run) normalized mass flux field plot in x-direction for AHAM substrate at Bottom horizontal laser position at approximately 24.75 min. b) corresponding zoomed in view of latter half of flow chamber.
7.4.2 Instantaneous EMPA221 Mass Flux x-direction Figures

Figure 182: a) Instantaneous (one-run) normalized mass flux field plot for EMPA221 substrate in x-direction at Bottom horizontal laser position at approximately 4.5 min. b) corresponding zoomed in view of latter half of flow chamber.
Figure 183: a) Instantaneous (one-run) normalized mass flux field plot for EMPA221 substrate in x-direction at Bottom horizontal laser position at approximately 14.6 min. b) corresponding zoomed in view of latter half of flow chamber.

Figure 184: a) Instantaneous (one-run) normalized mass flux field plot for EMPA221 substrate in x-direction at Bottom horizontal laser position at approximately 24.8 min. b) corresponding zoomed in view of latter half of flow chamber.
Figure 185: a) Instantaneous (one-run) normalized mass flux field plot for EMPA221 substrate in x-direction at Bottom horizontal laser position at approximately 34.9 min. b) corresponding zoomed in view of latter half of flow chamber.

7.4.3 Instantaneous Terry Mass Flux x-direction Figures

Figure 186: a) Instantaneous (one-run) normalized mass flux field plot for Terry substrate in x-direction at Bottom horizontal laser position at approximately 4.5 min. b) corresponding zoomed in view of latter half of flow chamber.
Figure 187: a) Instantaneous (one-run) normalized mass flux field plot for Terry substrate in x-direction at Bottom horizontal laser position at approximately 14.6 min. b) corresponding zoomed in view of latter half of flow chamber.

Figure 188: a) Instantaneous (one-run) normalized mass flux field plot for Terry substrate in x-direction at Bottom horizontal laser position at approximately 24.8 min. b) corresponding zoomed in view of latter half of flow chamber.
7.5 Instantaneous Mass Flux in the z-direction

The instantaneous mass flux in the z-direction for three different substrates and four different times with corresponding zoomed in regions are shown in Figure 190 through Figure 193 for AHAM, Figure 194 through Figure 197 for EMPA and Figure 198 through Figure 201 for Terry fabric substrates. The time differences of these four figures generally indicates a uniformly distributed z-directional mass flux along the length of the flow chamber. The instantaneous mass flux in the x-direction is shown to vary across different substrates at the 4.5 minute mark. The mass flux in the z-direction for the AHAM substrate shows a lower value at the 4.5 minute mark which then increases significantly at the 14.6 minute mark. The magnitude then decreases slightly at the 24.8 minute mark and increases again at the 34.9 minute mark. At the initial time step the pockets of mass flux vary in size and shape and are somewhat sparse.
across the flow chamber area. As time increases these pockets become generally smaller and connected in varying degrees. At the 4.5 and 14.6 minute mark, the intensity of the mass flux in the x-direction favors the negative $z/H_y$ side of the flow chamber similar to the x-direction mass flux metric above. Over time these mass flux pockets migrate toward the positive $z/H_y$ side of the flow chamber where full distribution is realized. The intense negative mass flux regions still seems to favor the negative $z/H_y$ flow chamber region. For the EMPA221 substrate, the mass flux starts out high at the 4.5 minute time step and continues to reduces at each consecutive time step. Initially, the pockets mass flux in the x-direction are sparse and elongated. Over time the pockets of mass flux increase and are equally distributed across the flow chamber area regions. The back ground is more positive for the 4.5 and 14.6 minute time steps. The background then becomes negative at the 24.8 and 34.9 minute time steps. For the Terry substrate, the mass flux in the x-direction starts out low at the 4.5 minute time step and decreases further at the 14.6 minute mark and then slightly increases at 24.8 minute mark and then slightly decreases at the 34.9 minute mark. The Terry substrate initially shows “C” and linear shape formations similar to the x-direction mass flux above with sparse but relatively large pockets of z-direction mass flux. However, over time these pockets become more prevalent and distributed across the flow chamber area. At the final time step the pockets tend to become larger and more intense. Overall these figures indicate a time varying conditions that exists for z-direction mass flux with each substrate having a unique mass flux patterns due to the substrate differences.
7.5.1 Instantaneous AHAM Mass Flux z-direction Figures

Figure 190: a) Instantaneous (one-run) normalized mass flux field plot in z-direction for AHAM substrate at Bottom horizontal laser position at approximately 4.5 min. b) corresponding zoomed in view of latter half of flow chamber.

Figure 191: a) Instantaneous (one-run) normalized mass flux field plot in z-direction for AHAM substrate at Bottom horizontal laser position at approximately 14.6 min. b) corresponding zoomed in view of latter half of flow chamber.
Figure 192: a) Instantaneous (one-run) normalized mass flux field plot in z-direction for AHAM substrate at Bottom horizontal laser position at approximately 24.75 min. b) corresponding zoomed in view of latter half of flow chamber.

Figure 193: a) Instantaneous (one-run) normalized mass flux field plot in z-direction for AHAM substrate at Bottom horizontal laser position at approximately 34.9 min. b) corresponding zoomed in view of latter half of flow chamber.
7.5.2 Instantaneous EMPA221 Mass Flux z-direction Figures

Figure 194: a) Instantaneous (one-run) normalized mass flux field plot for EMPA221 substrate in z-direction at Bottom horizontal laser position at approximately 4.5 min. b) corresponding zoomed in view of latter half of flow chamber.

Figure 195: a) Instantaneous (one-run) normalized mass flux field plot for EMPA221 substrate in z-direction at Bottom horizontal laser position at approximately 14.6 min. b) corresponding zoomed in view of latter half of flow chamber.
Figure 196: a) Instantaneous (one-run) normalized mass flux field plot for EMPA221 substrate in z-direction at Bottom horizontal laser position at approximately 24.8 min. b) corresponding zoomed in view of latter half of flow chamber.

Figure 197: a) Instantaneous (one-run) normalized mass flux field plot for EMPA221 substrate in z-direction at Bottom horizontal laser position at approximately 34.9 min. b) corresponding zoomed in view of latter half of flow chamber.
7.5.3 Instantaneous Terry Mass Flux z-direction Figures

Figure 198: a) Instantaneous (one-run) normalized mass flux field plot for Terry substrate in z-direction at Bottom horizontal laser position at approximately 4.5 min. b) corresponding zoomed in view of latter half of flow chamber.

Figure 199: a) Instantaneous (one-run) normalized mass flux field plot for Terry substrate in z-direction at Bottom horizontal laser position at approximately 14.6 min. b) corresponding zoomed in view of latter half of flow chamber.
Figure 200: a) Instantaneous (one-run) normalized mass flux field plot for Terry substrate in \( z \)-direction at Bottom horizontal laser position at approximately 24.8 min. b) corresponding zoomed in view of latter half of flow chamber.

Figure 201: a) Instantaneous (one-run) normalized mass flux field plot for Terry substrate in \( z \)-direction at Bottom horizontal laser position at approximately 34.9 min. b) corresponding zoomed in view of latter half of flow chamber.
7.6 Instantaneous Turbulent Production

The instantaneous turbulent production for three different substrates and four different times with corresponding zoomed in regions are shown in Figure 202 through Figure 205 for AHAM, Figure 206 through Figure 209 for EMPA and Figure 210 through Figure 213 for Terry fabric substrates. The time differences of these four figures generally indicates a uniformly distributed turbulent production across the length of the flow chamber except for the initial time step at the 4.5 minute mark where turbulent production is shown to be present only against the sides of the flow chamber. The turbulent production for the AHAM substrate shows the turbulent production increasing to the 24.8 minute mark and then a significant decrease occurs at the 34.9 minute mark. The figures indicate a sparse localized instantaneous turbulent production pockets somewhat elongated and round across the flow chamber area. Generally production tends to be more pronounced along the flow chamber sides. As time increases some of these pockets of production, both negative and positive, do not change location only in magnitude. For the EMPA221 substrate, the instantaneous turbulent production magnitude is generally maintained throughout the time steps. The pockets of production are generally elongated, “C” shaped and round. At the 34.9 minute mark the production pockets become more elongated. Similar to the AHAM substrate, production tends to be more pronounced along the flow chamber sides and as time increases some of these pockets of production, both negative and positive, do not change location only in magnitude. For the Terry substrate, the instantaneous turbulent production slightly increases from the initial time step of 4.5 minute until the 34.9 minute mark. No real noticeable geometric patterns are present with the terry substrate. It is interesting that at location $z/H_y = 0$ and $x/H_y = 14$ this localized production point is negative, then becomes almost zero and then become negative again. This indicates again that certain regions are prone
to producing turbulent production zones or pockets regardless of time. Overall these figures indicate a time varying conditions that exists for instantaneous turbulent production. Furthermore, overall the sides of the substrate tend to have the greatest turbulent production magnitude.

7.6.1 Instantaneous AHAM Turbulent Production Figures

Figure 202: a) Instantaneous (one-run) normalized turbulent production field plot for AHAM substrate at Bottom horizontal laser position at approximately 4.5 min. b) corresponding zoomed in view of latter half of flow chamber.
Figure 203: a) Instantaneous (one-run) normalized turbulent production field plot for AHAM substrate at Bottom horizontal laser position at approximately 14.6 min. b) Corresponding zoomed in view of latter half of flow chamber.

Figure 204: a) Instantaneous (one-run) normalized turbulent production field plot for AHAM substrate at Bottom horizontal laser position at approximately 24.8 min. b) Corresponding zoomed in view of latter half of flow chamber.
Figure 205: a) Instantaneous (one-run) normalized turbulent production field plot for AHAM substrate at Bottom horizontal laser position at approximately 34.9 min. b) corresponding zoomed in view of latter half of flow chamber.

7.6.2 Instantaneous EMPA221 Turbulent Production Figures

Figure 206: a) Instantaneous (one-run) normalized turbulent production field plot for EMPA221 substrate at Bottom horizontal laser position at approximately 4.5 min. b) corresponding zoomed in view of latter half of flow chamber.
Figure 207: a) Instantaneous (one-run) normalized turbulent production field plot for EMPA221 substrate at Bottom horizontal laser position at approximately 14.6 min. b) corresponding zoomed in view of latter half of flow chamber.

Figure 208: a) Instantaneous (one-run) normalized turbulent production field plot for EMPA221 substrate at Bottom horizontal laser position at approximately 24.8 min. b) corresponding zoomed in view of latter half of flow chamber.
7.6.3 Instantaneous Terry Turbulent Production Figures

Figure 210: a) Instantaneous (one-run) normalized turbulent production field plot for Terry substrate at Bottom horizontal laser position at approximately 4.5 min. b) Corresponding zoomed view of latter half of flow chamber.
Figure 211: a) Instantaneous (one-run) normalized turbulent production field plot for Terry substrate at Bottom horizontal laser position at approximately 14.6 min. b) Corresponding zoomed in view of latter half of flow chamber.

Figure 212: a) Instantaneous (one-run) normalized turbulent production field plot for Terry substrate at Bottom horizontal laser position at approximately 24.8 min. b) Corresponding zoomed in view of latter half of flow chamber.
7.7 Instantaneous Concentration Turbulent Production

The instantaneous concentration turbulent production for three different substrates and four different times with corresponding zoomed in regions are shown in Figure 214 through Figure 217 for AHAM, Figure 218 through Figure 221 for EMPA and Figure 222 through Figure 225 for Terry fabric substrates. These figures are significantly different than the previous turbulent production metrics and tend to show significantly more detail in terms of concentration production. The time differences of these four figures generally indicates a uniformly distributed concentration turbulent production across the length of the flow chamber except for the AHAM substrate were the concentration turbulent production is skewed toward the negative $z/H_y$ region. It should also be stated that at the final time step the AHAM concentration production eventually become more uniform across the flow chamber. At the 4.5 minute mark, the figures
show the beginnings of multiple interconnected structures which increase significantly over time and fill the entire flow chamber area. These intense positive signals are coupled with adjacent negative signals and indicates that instantaneous concentration production occurs in closely packed conditions across the flow chamber surface. The AHAM substrate shows more of a smattering of the concentration production structure. Whereas the EMPA221 substrate shows a more elongated concentration production structure and the Terry substrate shows a short “C” structures across the flow chamber surface. Again, these figures indicate a time varying conditions that exists for instantaneous concentration turbulent production. Furthermore, overall the flow chamber area is generally densely populated with these concentration production structures.

7.7.1 Instantaneous AHAM Concentration Turbulent Production Figures

![Figure 214](image)

Figure 214: a) Instantaneous (one-run) normalized concentration turbulent production field plot for AHAM substrate at Bottom horizontal laser position at approximately 4.5 min. b) corresponding zoomed in view of latter half of flow chamber.
Figure 215: a) Instantaneous (one-run) normalized concentration turbulent production field plot for AHAM substrate at Bottom horizontal laser position at approximately 14.6 min. b) corresponding zoomed in view of latter half of flow chamber.

Figure 216: a) Instantaneous (one-run) normalized concentration turbulent production field plot for AHAM substrate at Bottom horizontal laser position at approximately 24.8 min. b) corresponding zoomed in view of latter half of flow chamber.
Figure 217: a) Instantaneous (one-run) normalized concentration turbulent production field plot for AHAM substrate at Bottom horizontal laser position at approximately 34.9 min. b) corresponding zoomed in view of latter half of flow chamber.

7.7.2 Instantaneous EMPA221 Concentration Production Figures

Figure 218: a) Instantaneous (one-run) normalized concentration production field plot for EMPA221 substrate at Bottom horizontal laser position at approximately 4.5 min. b) corresponding zoomed in view of latter half of flow chamber.
Figure 219: a) Instantaneous (one-run) normalized concentration production field plot for EMPA221 substrate at Bottom horizontal laser position at approximately 14.6 min. b) corresponding zoomed in view of latter half of flow chamber.

Figure 220: a) Instantaneous (one-run) normalized concentration production field plot for EMPA221 substrate at Bottom horizontal laser position at approximately 24.8 min. b) corresponding zoomed in view of latter half of flow chamber.
7.7.3 Instantaneous Terry Concentration Production Figures

Figure 221: a) Instantaneous (one-run) normalized concentration production field plot for EMPA221 substrate at Bottom horizontal laser position at approximately 34.9 min. b) corresponding zoomed in view of latter half of flow chamber.

Figure 222: a) Instantaneous (one-run) normalized concentration production field plot for Terry substrate at Bottom horizontal laser position at approximately 4.5 min. b) corresponding zoomed in view of latter half of flow chamber.
Figure 223: a) Instantaneous (one-run) normalized concentration production field plot for Terry substrate at Bottom horizontal laser position at approximately 14.6 min. b) corresponding zoomed in view of latter half of flow chamber.

Figure 224: a) Instantaneous (one-run) normalized concentration production field plot for Terry substrate at Bottom horizontal laser position at approximately 24.8 min. b) corresponding zoomed in view of latter half of flow chamber.
Figure 225: a) Instantaneous (one-run) normalized concentration production field plot for Terry substrate at Bottom horizontal laser position at approximately 34.9 min. b) corresponding zoomed in view of latter half of flow chamber.

7.8 Instantaneous Concentration Fluctuations

The instantaneous concentration fluctuations for three different substrates and four different times with corresponding zoomed in regions are shown in Figure 226 through Figure 229 for AHAM, Figure 230 through Figure 233 for EMPA and Figure 234 through Figure 237 for Terry fabric substrates. These figures show the observed streaky structures that were inherently present during the entirety of the test and is preserved in this instantaneous analysis. The magnitudes of the instantaneous concentration fluctuations change minimally over time for all three substrates. For the AHAM substrate both positive and negative “C” shape and elongated medium structures can be seen in an almost broken wave formation and change over time. These structures are generally equally distributed throughout the flow chamber area. The intensity increases in the downstream half of the flow chamber. The EMPA221 substrate shows
a more fine and elongated structure configuration that is parallel to the length of the flow chamber and equally distributed throughout the flow chamber. The structure intensity is also equally distributed throughout the flow chamber but changes over time. The Terry substrate shows significant and contrasting “C” shape and curling structures especially at the 4.5 and 14.6 minute mark. At the 24.8 minute mark the structures have less contrasting structures and are less pronounced with similar but reduced “C” shape and curling structures as before. At the 34.9 minute mark these pronounced “C” and curling are reduced further with localized regions of odd shape structures. The intensity and contrasting differences also slightly increases at the downstream side of the flow chamber at this time. Overall these figures show significant time varying conditions that are preserved using the instantaneous concentration fluctuation metric presented here.

7.8.1 Instantaneous AHAM Concentration Fluctuation Figures

Figure 226: a) Instantaneous (one-run) normalized concentration fluctuation field plot for AHAM substrate at Bottom horizontal laser position at approximately 4.5 min. b) corresponding zoomed in view of latter half of flow chamber.
Figure 227: a) Instantaneous (one-run) normalized concentration fluctuation field plot for AHAM substrate at Bottom horizontal laser position at approximately 14.6 min. b) Corresponding zoomed in view of latter half of flow chamber.

Figure 228: a) Instantaneous (one-run) normalized concentration fluctuation field plot for AHAM substrate at Bottom horizontal laser position at approximately 24.8 min. b) Corresponding zoomed in view of latter half of flow chamber.
Figure 229: a) Instantaneous (one-run) normalized concentration fluctuation field plot for AHAM substrate at Bottom horizontal laser position at approximately 34.9 min. b) corresponding zoomed in view of latter half of flow chamber.

7.8.2 Instantaneous EMPA221 Concentration Fluctuation Figures

Figure 230: a) Instantaneous (one-run) normalized concentration fluctuation field plot for EMPA221 substrate at Bottom horizontal laser position at approximately 4.5 min. b) corresponding zoomed in view of latter half of flow chamber.
Figure 231: a) Instantaneous (one-run) normalized concentration fluctuation field plot for EMPA221 substrate at Bottom horizontal laser position at approximately 14.63 min. b) corresponding zoomed in view of latter half of flow chamber.

Figure 232: a) Instantaneous (one-run) normalized concentration fluctuation field plot for EMPA221 substrate at Bottom horizontal laser position at approximately 24.8 min. b) corresponding zoomed in view of latter half of flow chamber.
Figure 233: a) Instantaneous (one-run) normalized concentration fluctuation field plot for EMPA221 substrate at Bottom horizontal laser position at approximately 34.9 min. b) corresponding zoomed in view of latter half of flow chamber.

7.8.3 Instantaneous Terry Concentration Fluctuation Figures

Figure 234: a) Instantaneous (one-run) normalized concentration fluctuation field plot for Terry substrate at Bottom horizontal laser position at approximately 4.5 min. b) corresponding zoomed in view of latter half of flow chamber.
Figure 235: a) Instantaneous (one-run) normalized concentration fluctuation field plot for Terry substrate at Bottom horizontal laser position at approximately 14.6 min. b) Corresponding zoomed in view of latter half of flow chamber.

Figure 236: a) Instantaneous (one-run) normalized concentration fluctuation field plot for Terry substrate at Bottom horizontal laser position at approximately 24.8 min. b) Corresponding zoomed in view of latter half of flow chamber.
Figure 237: a) Instantaneous (one-run) normalized concentration fluctuation field plot for Terry substrate at Bottom horizontal laser position at approximately 34.9 min. b) corresponding zoomed in view of latter half of flow chamber.

7.9 Instantaneous Velocity Fluctuation in the x-direction

The instantaneous velocity fluctuation in the x-direction ($u'$) for three different substrates and four different times with corresponding zoomed in regions are shown in Figure 238 through Figure 241 for AHAM, Figure 242 through Figure 245 for EMPA and Figure 246 through Figure 249 for Terry fabric substrates. The time differences of these four figures generally indicates a decrease in magnitude moving from the 4.5 min mark to the 14.6 minute mark and continues to slightly decrease until the 34.9 minute mark. The decrease in x-direction magnitude is shown to be predominated in the downstream half of the flow chamber and continues to decrease until the last time step. The signal magnitude is approximately the same for all three substrates and show an initial uniformly distributed x-directional fluctuation regions or zones across the flow chamber surface. As time increases, negative fluctuation regions increase significantly.
especially at the downstream half of the flow chamber. The upstream half also shows a negative fluctuation regions but with less overall affected area. This is due to the flow backing up as it pushes through a smaller exit orifice. The upstream half also shows a slight skewing to the positive $y/H_y$ side of the flow chamber. This is somewhat corrected over time as shown in the figures below. This skewing is due to the fluid entering the flow chamber in this way despite previous efforts to do otherwise. These figures indicate a time varying condition exists for $x$-direction fluctuation. Furthermore, negative fluctuations regions increase significantly over time especially in the downstream half of the flow chamber.

### 7.9.1 Instantaneous AHAM Velocity Fluctuation x-direction Figures

Figure 238: a) Instantaneous (one-run) normalized velocity fluctuation field plot in $x$-direction for AHAM substrate at Bottom horizontal laser position at approximately 4.5 min. b) corresponding zoomed in view of latter half of flow chamber.
Figure 239: a) Instantaneous (one-run) normalized velocity fluctuation field plot in x-direction for AHAM substrate at Bottom horizontal laser position at approximately 14.6 min. b) corresponding zoomed in view of latter half of flow chamber.

Figure 240: a) Instantaneous (one-run) normalized velocity fluctuation field plot in x-direction for AHAM substrate at Bottom horizontal laser position at approximately 24.8 min. b) corresponding zoomed in view of latter half of flow chamber.
Figure 241: a) Instantaneous (one-run) normalized velocity fluctuation field plot in x-direction for AHAM substrate at Bottom horizontal laser position at approximately 34.9 min. b) corresponding zoomed in view of latter half of flow chamber.
7.9.2 Instantaneous EMPA221 Velocity Fluctuation in x-direction Figures

Figure 242: a) Instantaneous (one-run) normalized velocity fluctuation field plot for EMPA221 substrate in x-direction at Bottom horizontal laser position at approximately 4.5 min. b) corresponding zoomed in view of latter half of flow chamber.

Figure 243: a) Instantaneous (one-run) normalized velocity fluctuation field plot for EMPA221 substrate in x-direction at Bottom horizontal laser position at approximately 14.6 min. b) corresponding zoomed in view of latter half of flow chamber.
Figure 244: a) Instantaneous (one-run) normalized velocity fluctuation field plot for EMPA221 substrate in x-direction at Bottom horizontal laser position at approximately 24.8 min. b) corresponding zoomed in view of latter half of flow chamber.

Figure 245: a) Instantaneous (one-run) normalized velocity fluctuation field plot for EMPA221 substrate in x-direction at Bottom horizontal laser position at approximately 34.9 min. b) corresponding zoomed in view of latter half of flow chamber.
7.9.3 Instantaneous Terry Velocity Fluctuation in x-direction Figures

Figure 246: a) Instantaneous (one-run) normalized velocity fluctuation field plot for Terry substrate in x-direction at Bottom horizontal laser position at approximately 4.5 min. b) corresponding zoomed in view of latter half of flow chamber.

Figure 247: a) Instantaneous (one-run) normalized velocity fluctuation field plot for Terry substrate in x-direction at Bottom horizontal laser position at approximately 14.6 min. b) corresponding zoomed in view of latter half of flow chamber.
Figure 248: a) Instantaneous (one-run) normalized velocity fluctuation field plot for Terry substrate in x-direction at bottom horizontal laser position at approximately 24.8 min. b) corresponding zoomed in view of latter half of flow chamber.

Figure 249: a) Instantaneous (one-run) normalized velocity fluctuation field plot for Terry substrate in x-direction at bottom horizontal laser position at approximately 34.9 min. b) corresponding zoomed in view of latter half of flow chamber.
7.10 Instantaneous Velocity Fluctuation in z-direction

The instantaneous velocity fluctuation in the z-direction ($u'_z$) for three different substrates and four different times with corresponding zoomed in regions are shown in Figure 250 through Figure 253 for AHAM, Figure 254 through Figure 257 for EMPA and Figure 258 through Figure 261 for Terry fabric substrates. The magnitudes for all three substrates are generally the same and do not change in time. The z-direction fluctuations are uniformly distributed across the flow chamber surface. The AHAM and Terry substrates show that the z-direction fluctuations move from a positive background condition to a more negative background condition. The EMPA221 substrate background generally does not change and stays the same over time. The AHAM and Terry substrate also shows a significant negative and positive z-direction intensity against the flow chamber sides respectively. These figures indicate a time varying condition exists for z-direction fluctuation and the z-direction fluctuation regions are generally evenly distributed across the flow chamber surface over time. However the AHAM and Terry substrates show a general increase in negative z-direction fluctuations as time increases.
7.10.1 Instantaneous AHAM Velocity Fluctuation in z-direction Figures

Figure 250: a) Instantaneous (one-run) normalized velocity fluctuation field plot in z-direction for AHAM substrate at Bottom horizontal laser position at approximately 4.5 min. b) corresponding zoomed in view of latter half of flow chamber.

Figure 251: a) Instantaneous (one-run) normalized velocity fluctuation field plot in z-direction for AHAM substrate at Bottom horizontal laser position at approximately 14.6 min. b) corresponding zoomed in view of latter half of flow chamber.
Figure 252: a) Instantaneous (one-run) normalized velocity fluctuation field plot in z-direction for AHAM substrate at Bottom horizontal laser position at approximately 24.8 min. b) corresponding zoomed in view of latter half of flow chamber.

Figure 253: a) Instantaneous (one-run) normalized velocity fluctuation field plot in z-direction for AHAM substrate at Bottom horizontal laser position at approximately 34.9 min. b) corresponding zoomed in view of latter half of flow chamber.
7.10.2 Instantaneous EMPA221 Velocity Fluctuation in z-direction Figures

Figure 254: a) Instantaneous (one-run) normalized velocity fluctuation field plot for EMPA221 substrate in z-direction at Bottom horizontal laser position at approximately 4.5 min. b) corresponding zoomed in view of latter half of flow chamber.

Figure 255: a) Instantaneous (one-run) normalized velocity fluctuation field plot for EMPA221 substrate in z-direction at Bottom horizontal laser position at approximately 14.6 min. b) corresponding zoomed in view of latter half of flow chamber.
Figure 256: a) Instantaneous (one-run) normalized velocity fluctuation field plot for EMPA221 substrate in z-direction at Bottom horizontal laser position at approximately 24.8 min. b) Corresponding zoomed in view of latter half of flow chamber.

Figure 257: a) Instantaneous (one-run) normalized velocity fluctuation field plot for EMPA221 substrate in z-direction at Bottom horizontal laser position at approximately 34.9 min. b) Corresponding zoomed in view of latter half of flow chamber.
7.10.3 Instantaneous Terry Velocity Fluctuation in z-direction Figures

Figure 258: a) Instantaneous (one-run) normalized velocity fluctuation field plot for Terry substrate in z-direction at Bottom horizontal laser position at approximately 4.5 min. b) corresponding zoomed in view of latter half of flow chamber.

Figure 259: a) Instantaneous (one-run) normalized velocity fluctuation field plot for Terry substrate in z-direction at Bottom horizontal laser position at approximately 14.6 min. b) corresponding zoomed in view of latter half of flow chamber.
Figure 260: a) Instantaneous (one-run) normalized velocity fluctuation field plot for Terry substrate in z-direction at Bottom horizontal laser position at approximately 24.8 min. b) corresponding zoomed in view of latter half of flow chamber.

Figure 261: a) Instantaneous (one-run) normalized velocity fluctuation field plot for Terry substrate in z-direction at Bottom horizontal laser position at approximately 34.9 min. b) corresponding zoomed in view of latter half of flow chamber.
7.11 Instantaneous x-direction Concentration Transport by Turbulent Production

The instantaneous x-direction concentration transport by turbulent production for three different substrates and four different times with corresponding zoomed in regions are shown in Figure 262 through Figure 265 for AHAM, Figure 266 through Figure 269 for EMPA and Figure 270 through Figure 273 for Terry fabric substrates. These figures show the observed concentration transport to be an intersecting crosshatch structure. The pattern of which vary depending on the different fabric types. For the AHAM substrate, concentration transport increases significantly from the 4.5 minute mark to the 14.6 minute mark and slightly increases as time progresses. Round or “C” structures are integrated with the crosshatching structures for both the initial and final time steps indicating that concentration transport occurs over and over again in generally the same structural fashion. The concentration transport signal is initially uniformly distributed across the length of the flow chamber and then favors the downstream half of the flow chamber as time progresses. For the EMPA221 substrate, concentration transport increases significantly from the 4.5 minute mark to the 14.6 minute mark and slightly increases as time progresses to the 24.8 minute mark. At 34.9 minute mark the magnitude decreases slightly. Mostly intersecting crosshatching patterns are shown and are slightly longer and thinner than the previous AHAM substrate. The concentration transport magnitude is generally uniformly distributed across the length of the flow chamber. For the Terry substrate, the magnitudes slightly increases over time. The concentration transport signal shows a round and “C” shape structures integrated with small intersecting crosshatch structures. As time progresses, these round and “C” shape structures seem to disappear leaving only the intersecting crosshatch structures. Overall these figures indicate that concentration transport occurs generally in the
form of a crosshatching like structure. Time varying conditions are also preserved using the instantaneous concentration transport by turbulent production metric presented here.

### 7.11.1 Instantaneous AHAM x-direction Concentration Transport by Turbulent Production Figures

**Figure 262:** a) Instantaneous (one-run) normalized transport of concentration by turbulent fluctuation field plot for AHAM substrate at Bottom horizontal laser position at approximately 4.5 min. b) corresponding zoomed in view of latter half of flow chamber.
Figure 263: a) Instantaneous (one-run) normalized transport of concentration by turbulent fluctuation field plot for AHAM substrate at Bottom horizontal laser position at approximately 14.6 min. b) corresponding zoomed in view of latter half of flow chamber.

Figure 264: a) Instantaneous (one-run) normalized transport of concentration by turbulent fluctuation field plot for AHAM substrate at Bottom horizontal laser position at approximately 24.8 min. b) corresponding zoomed in view of latter half of flow chamber.
Figure 265: a) Instantaneous (one-run) normalized transport of concentration by turbulent fluctuation field plot for AHAM substrate at Bottom horizontal laser position at approximately 34.9 min. b) corresponding zoomed in view of latter half of flow chamber.
7.11.2 Instantaneous EMPA221 x-direction Concentration Transport by Turbulent Production Figures

Figure 266: a) Instantaneous (one-run) normalized transport of concentration by turbulent fluctuation field plot for EMPA221 substrate at Bottom horizontal laser position at approximately 4.5 min. b) corresponding zoomed in view of latter half of flow chamber.

Figure 267: a) Instantaneous (one-run) normalized transport of concentration by turbulent fluctuation field plot for EMPA221 substrate at Bottom horizontal laser position at approximately 14.6 min. b) corresponding zoomed in view of latter half of flow chamber.
Figure 268: a) Instantaneous (one-run) normalized transport of concentration by turbulent fluctuation field plot for EMPA221 substrate at Bottom horizontal laser position at approximately 24.8 min. b) corresponding zoomed in view of latter half of flow chamber.

Figure 269: a) Instantaneous (one-run) normalized transport of concentration by turbulent fluctuation field plot for EMPA221 substrate at Bottom horizontal laser position at approximately 34.9 min. b) corresponding zoomed in view of latter half of flow chamber.
7.11.3 Instantaneous Terry x-direction Concentration Transport by Turbulent Production

Figures

Figure 270: a) Instantaneous (one-run) normalized transport of concentration by turbulent fluctuation field plot for Terry substrate in z-direction at Bottom horizontal laser position at approximately 4.5 min. b) corresponding zoomed in view of latter half of flow chamber.

Figure 271: a) Instantaneous (one-run) normalized transport of concentration by turbulent fluctuation field plot for Terry substrate in z-direction at Bottom horizontal laser position at approximately 14.6 min. b) corresponding zoomed in view of latter half of flow chamber.
Figure 272: a) Instantaneous (one-run) normalized transport of concentration by turbulent fluctuation field plot for Terry substrate in $z$-direction at Bottom horizontal laser position at approximately 24.8 min. b) corresponding zoomed in view of latter half of flow chamber.

Figure 273: a) Instantaneous (one-run) normalized transport of concentration by turbulent fluctuation field plot for Terry substrate in $z$-direction at Bottom horizontal laser position at approximately 34.9 min. b) corresponding zoomed in view of latter half of flow chamber.
8 CONCLUSION

Optical flow methods were used to develop specific flow metrics within a flow chamber. Measurement of velocity, vorticity, kinetic energy, Reynolds stress, turbulent production, mass flux and concentration fluctuations where taken using 2000 pictures pair averages which can be applied to the governing flow equations. Base flow measurements using laser sheet illuminated glass beads for both the horizontal and vertical directions were taken at the Bottom, Middle and Top and Middle horizontal laser positions within the flow chamber. Similar measurements with four different laser positions were taken with three different dye impregnated fabric substrates. Correlating the dye mass concentration with dye intensity enabled the development of concentration kinetic energy, mass flux and concentration fluctuations metrics. Short run averages with only 10 picture pair averages also taken and similar metrics where developed to compare the unique difference with the 2000 picture pair averages. By combining the different base flow metrics together direct similarities with Pope and Perot’s DNS flow data can be seen. The base flow metrics were then compared with each of the dye metrics and indicated general similarities in the velocity, vorticity, kinetic energy and Reynolds stress profiles. However, significant differences were shown in the turbulent production and concentrations profiles metrics. Instantaneous field plot measurements for kinetic energy, concentration kinetic energy, Reynolds stress, x-direction mass flux, z-direction mass flux, turbulent production, concentration turbulent production, concentration fluctuation, x-direction velocity fluctuation, z-direction velocity fluctuation and x-direction concentration transport by turbulent production were taken for three different substrates and shown for four different equally divided times. These field
plots indicated unique structural differences for each metric and corresponding substrates especially the streaky structures observed throughout the testing.

In comparing the different normalized base flow (glass beads) profiles with the normalized dye impregnated substrates the profiles show slight differences in velocity. It can be seen that the different substrates cause the profile to be more rounded indicating a more overall turbulent condition occurring within the flow chamber. For the vertical velocity profile the profile for the different substrates is generally similar to the base flow with the different substrates showing a more narrower profile. For normalized horizontal kinetic energy profiles, the base flow profiles show loose similarities to the substrate flow profiles. However the maximum kinetic energy for the base flow condition is shown to be in the negative $z/H_y$ region whereas in almost every case the substrate maximum kinetic energy is in the positive $z/H_y$ region. The vertical normalized kinetic energy profiles show significant differences with the maximum kinetic energy of the base flow being uniform and flat across the center of the flow chamber whereas the substrate flow condition shows the maximum kinetic energy occurring toward the bottom third of the flow chamber and dissipating to zero as it moves to the top of the flow chamber. The normalized horizontal concentration kinetic energy substrate profiles generally average to one. However, each individual substrate has a specific horizontal laser position that shows unique profiles that increases from the sides of the flow chamber and oscillate with values less than one within the flow chamber center. This indicates certain vertical distances within the flow chamber have unique concentration kinetic energy and change depending on the substrate type. The vertical concentration kinetic energy profile is loosely similar to the dyed substrate curve but shows that EMPA221 substrate (with least asperities) has a more concave curve moving to the top of the flow chamber.
The short run horizontal concentration kinetic energy provides a more expected profile with the signal increasing from zero at the sides of the flow chamber and oscillating within the flow chamber center and gives a clear picture of concentration kinetic energy occurring within the flow chamber. The short run vertical concentration kinetic energy profile is similar to the 2000 picture pair profile above but with slightly more variation as expected. The base flow and dye normalized horizontal Reynolds stress is loosely similar to each other. However the dyed substrate shows a greater negative signal extending into the positive $z/H_y$ region for the different substrates. Some laser positions of the EMPA221 fabric substrate is significantly more variable and does not conform to the expected Reynolds stress profile. The base flow and dye impregnated normalized vertical Reynolds stress show loose similarities to each other. Horizontal concentration mass flux in the x-direction generally show a parabolic curvature and in every substrate condition a singular laser position is shown to have a significant deviation from these curves. Vertical concentration mass flux in the x-direction shows a large profile difference between the three different fabric substrates. The horizontal concentration mass flux in the $z$-direction indicate both similarities and differences between each of the fabric substrates. The vertical concentration mass flux in the y-direction again shows a large profile difference between the three substrates. Short run horizontal concentration mass flux in both the x and z – direction have significant signal noise and is difficult perceive any real pattern. Short run vertical concentration in the x and y-direction provide discernible profiles where the global maximum and minim occur at 10 to 25% from the flow chamber bottom. The horizontal dye turbulent production is similar to the base flow in the negative $z/H_y$ and different in the positive $z/H_y$ as the dye signal shows a signal increase or decrease close to the flow chamber wall indicating a greater signal sensitivity. Overall it demonstrates that turbulence production occurs close to the
flow chamber side walls. The vertical dye turbulent production loosely mimics the base flow but with a negative turbulent production occurring close to the flow chamber bottom by two of the three substrates. The horizontal concentration turbulent fluctuation profile occur directly against the side of the flow chamber with slight signal decrease in the flow chamber center. The vertical concentration turbulent fluctuation profile increases significantly close to the flow chamber bottom and uniquely reduces depending on the substrate type. The short run horizontal concentration turbulent fluctuation profile show significant indecipherable signal noise across the flow chamber center. Finally, The short run vertical concentration turbulent fluctuation profile show similarities to the larger average profile.

The instantaneous kinetic energy field plots shows an initial dead zone that then increases in intensity as time progresses for all three substrates. The instantaneous concentration kinetic energy clearly shows different types of streaky structures depending on the substrate. The Terry substrate shows a more uniform or blended configuration than the other two substrates. The instantaneous x-direction mass flux shows equally distributed pockets of high and low magnitudes that change over time. Negative mass flux regions are more prevalent in the downstream side of the flow chamber. The instantaneous mass flux in the z-direction generally shows equally distributed pockets of positive and negative magnitudes that slow change over time. At the final time step these pockets become larger and more intense. The instantaneous Reynolds stress shows a unique signature within the flow chamber for each substrate and the magnitudes are uniformly distributed across the flow chamber area regardless of time. The instantaneous mass flux in the x-direction initial show sparse pockets of intensity and over time these pockets increase and become less negative, smaller, more prevalent and equally distributed. The instantaneous mass flux in the z-direction show different pockets of intensity and become
more prevalent over time with slightly more occurrences in the downstream half of the flow chamber. The instantaneous turbulent production initially shows these signals close to the edge of the flow chamber with minimal signals occurring in the center. As time increases, production intensity also increases and tend to elongate. In the EMPA221 and Terry substrates the turbulent production remains intense both positive and negative against the edge of the flow chamber. The concentration turbulent production shows both short, long and “C” shape structures depending on the substrate type and are generally uniform and increase in visual density across the flow chamber area as time increases. The instantaneous concentration fluctuation show the streaky structures that were observed during the test. Surprisingly the overall magnitudes change very little over time. Unique streaky structure patterns are indicative of the substrate being tested with the EMPA221 substrate having a more elongated structure, the Terry substrate having a more curling structures and the AHAM substrate somewhere in between. These different structures also change as time progresses. The instantaneous velocity fluctuations in the x-direction and initially shows uniform pockets of intensity. However as time progresses negative fluctuation regions increase significantly especially at the downstream half of the flow chamber. The instantaneous velocity fluctuations in the z-direction show the same magnitudes regardless of the substrate. The signals change as time increases but they are always evenly distributed across the flow chamber. Finally, the instantaneous x-direction concentration transport by turbulent production shows an unique detailed crosshatching structure. The pattern of which depends on the substrate type and indicates how mass transported by that substrate.

9 REFERENCES


