Experimental study of water transport mechanisms and two-phase pressure drop in a simulated polymer electrolyte membrane fuel cell cathode gas channel

John Borrelli

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EXPERIMENTAL STUDY OF WATER TRANSPORT MECHANISMS AND TWO-PHASE PRESSURE DROP IN A SIMULATED POLYMER ELECTROLYTE MEMBRANE FUEL CELL CATHODE GAS CHANNEL

by

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A Thesis Submitted in Partial Fulfillment of the Requirement for the MASTER OF SCIENCE IN MECHANICAL ENGINEERING

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ABSTRACT

Water management is one of the most important challenges in polymer electrolyte membrane fuel cell (PEMFC) development. Water is a product of the fuel cell reaction, and it can accumulate in the gas diffusion medium (GDM) adjacent to the air distribution channels of a cathode flow field plate. While some water retention is necessary for membrane hydration, the majority must be removed from the cathode flow field channels for optimal stack performance.

The experiments of the present work utilize high-speed digital images to analyze water as it flows through a GDM sample and into a 1.08 mm hydraulic diameter rectangular channel of flowing air. The 25-cm-long air channel is held horizontal with the GDM acting as the top wall of the channel.

Three GDM samples are tested under the same water and air flow rates, and high-speed videos are used to measure departure droplet diameter, advancing and receding contact angles, and to report general flow patterns that are observed.

Results show a general agreement between GDM Samples A and B with respect to departure droplet behavior, contact angle data, and general two-phase flow behavior across the test matrix, but the GDM Sample B data show greater spread than the GDM Sample A data for departure droplet diameter. GDM Sample C data show some droplet formation, but the departure droplet diameters are markedly larger than those of GDM Samples A and B. Furthermore, as the GDM Sample C testing progressed through the test matrix (from highest air flow rate to lowest), all droplet activity ceased. In general, the flow patterns for GDM Sample C were identical to the typical two-phase flow patterns observed in conventional minichannel flow visualization experiments. Experimental two-phase pressure drop measurements were found to be much higher for the GDM Sample B data than for the Sample C data, but existing theoretical two-phase pressure drop correlations were found to closely predict the experimental pressure drop data depending on the different flow conditions for Samples B and C.
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NOMENCLATURE
Symbols and Abbreviations

A  Constant in Lee and Lee (2001) correlation
A  Area of channel cross section (m²)
ACCM Actual cubic centimeters per minute
Adv. Advancing contact angle (Fig. 6.2)
AR Area ratio defined in Fig. 6.4
B  Coefficient used in Chisholm (1973) two-phase multiplier; bias in Eq. (4.3)
Bo Bond number, dimensionless = $g(\rho_L - \rho_0)((D_h/2)^2/\sigma)$
C  Chisholm (1967) dimensionless parameter
D  Diameter (m)
Dh Hydraulic diameter (m)
DP Differential pressure (transducer)
E  Friedel (1979) dimensionless parameter
e  Electron
F  Friedel (1979) dimensionless parameter
Fr Froude number = $G^2/(gD_h\rho_{TP}^2)$
f Friction factor (for laminar fully developed flow $f = (\text{constant})/Re$)
fps Frames per second
GDM Gas diffusion media (a.k.a. gas diffusion layer)
G  Mass flux (kg/m²s)
g Gravitational acceleration (m/s²)
H⁺ Proton (hydrogen)
h Head loss
j Superficial velocity ($=Q/A$) (m/s); $j_G + j_L$ in Lee and Lee (2001) correlation
K Expansion and contraction coefficient Eq. (2.29); velocity ratio Eq. (2.32)
K(∞) Hagenbach factor
L Length (m)
MPL Micro-porous layer
$m$ Mass flow rate (kg/s)
mL Milliliter
\(N\) \hspace{1cm} \text{Number of measurements in uncertainty equation}
\(n\) \hspace{1cm} \text{Chisholm (1973) correlation from exponent Re is raised to in Blasius relation}
\(P\) \hspace{1cm} \text{Pressure (transducer)}
\(p\) \hspace{1cm} \text{Pressure (Pa)}
\(\text{PEMFC}\) \hspace{1cm} \text{Polymer electrolyte membrane fuel cell (a.k.a. proton exchange membrane...)}
\(p_g\) \hspace{1cm} \text{Gauge pressure (Pa)}
\(\text{PTFE}\) \hspace{1cm} \text{Polytetrafluoroethylene}
\(Q\) \hspace{1cm} \text{Volumetric flow rate (m}^3/\text{s)}
\(q\) \hspace{1cm} \text{Exponent in Lee and Lee (2001) correlation}
\(R\) \hspace{1cm} \text{Radius (m)}
\(r\) \hspace{1cm} \text{Exponent in Lee and Lee (2001) correlation}
\(r\) \hspace{1cm} \text{Radial axis in cylindrical coordinate system}
\(\text{Re}\) \hspace{1cm} \text{Reynolds number}
\(\text{Re}_L\) \hspace{1cm} \text{Liquid Reynolds number } = \frac{(1-x)GD_h}{\mu_L}
\(\text{Re}_L^0\) \hspace{1cm} \text{All mixture flowing as liquid Reynolds number } = \frac{GD_h}{\mu_L}
\(\text{Re}_G\) \hspace{1cm} \text{Gas Reynolds number } = \frac{xGD_h}{\mu_G}
\(\text{Re}_G^0\) \hspace{1cm} \text{All mixture flowing as gas Reynolds number } = \frac{GD_h}{\mu_G}
\(\text{Rec.}\) \hspace{1cm} \text{Receding contact angle (Fig. 6.2)}
\(s\) \hspace{1cm} \text{Exponent in Lee and Lee (2001) correlation}
\(\text{SCCM}\) \hspace{1cm} \text{Standard cubic centimeters per minute}
\(\text{SLPM}\) \hspace{1cm} \text{Standard liters per minute}
\(t\) \hspace{1cm} \text{time (sec.)}
\(U\) \hspace{1cm} \text{Uncertainty related to measurements}
\(\bar{V}\) \hspace{1cm} \text{Mean fluid velocity (m/s)}
\(v\) \hspace{1cm} \text{Velocity component}
\(\text{We}\) \hspace{1cm} \text{Weber number } = \frac{(G^2D_h)/(\sigma \rho_{rp})}
\(X\) \hspace{1cm} \text{Martinelli (1949) parameter, } X^2 = \text{ratio of liquid/gas pressure drop}
\(x\) \hspace{1cm} \text{Vapor mass fraction or quality } ( = \frac{\dot{m}_G}{(\dot{m}_L + \dot{m}_G)} )
\(Y\) \hspace{1cm} \text{Chisholm (1973) parameter, } Y^2 = \text{ratio of gas only/liquid only pressure drop}
\(z\) \hspace{1cm} \text{Length axis}
Greek

\( \alpha \)  
Kinetic energy coefficient (Eq. (6.3))

\( \alpha' \)  
Channel aspect ratio defined by Kakac et al. (1987) (Eq. (6.19))

\( \alpha_c \)  
Channel aspect ratio (Eq. (6.24))

\( \Delta \)  
Change in (e.g. change in time = \( \Delta t \))

\( \phi^2 \)  
Pressure drop multiplier

\( \lambda \)  
Dimensionless parameter in Lee and Lee (2001) correlation = \( \mu L^2/\left( \rho L \sigma D_h \right) \)

\( \mu \)  
Dynamic viscosity (N-s/m\(^2\))

\( \theta \)  
Contact angle (degrees); Angular axis in cylindrical coordinate system

\( \rho \)  
Density (kg/m\(^3\))

\( \sigma \)  
Surface tension (N/m); standard deviation in Eq. (4.3)

\( \nu \)  
Specific volume (m\(^3\)/kg)

\( \nu_e \)  
Momentum (effective) specific volume (=1/\( \rho_e \))

\( \Omega \)  
Modifier to Friedel (1979) correlation

\( \psi \)  
Dimensionless parameter in Lee and Lee (2001) correlation = \( \mu_L \left[ j_G + j_L \right]/\sigma \)

Subscripts

\( c \)  
Contraction (Eq. (2.12)); channel (Eq. (6.24))

\( e \)  
Expansion (Eq. (2.12)); effective (Eqs. (2.13 and 2.14))

\( F \)  
Fanning friction factor

\( G \)  
Gas (air)

\( g \)  
Gauge (pressure)

\( GO \)  
All flow as gas (air)

\( L \)  
Liquid (water)

\( LO \)  
All flow as Liquid (water)

\( r \)  
r-component: cylindrical coordinate system

\( S \)  
Standard

\( TP \)  
Two-Phase

\( z \)  
z-component: cylindrical coordinate system

\( \theta \)  
\( \theta \)-component: cylindrical coordinate system
1. INTRODUCTION

Fuel cells are electrical power generating devices. Polymer electrolyte membrane fuel cells (also called proton exchange membrane fuel cells or PEMFC) produce electricity by reacting hydrogen and oxygen in the presence of an electrolyte to form water and heat. As the reaction occurs, hydrogen gas is ionized at the anode side of the cell into protons and electrons as given by the reaction

\[ 2H_2 \rightarrow 4H^+ + 4e^- \]  \hspace{1cm} (1.1)

The polymer electrolyte membrane only allows the hydrogen ions (H\(^+\)) to move through it to the cathode side forcing the freed electrons to move through an external circuit in order to complete the reaction

\[ O_2 + 4e^- + 4H^+ \rightarrow 2H_2O \]  \hspace{1cm} (1.2)

The schematic representation of the electrochemical reaction described above is presented for a single cell in Figure 1.1.

![Figure 1.1. Electrode reactions and charge flow for PEMFC (Larminie and Dicks (2003)).](image)

Minichannels (Kandlikar and Grande (2003)) are typically employed on both the cathode and the anode side of a PEMFC in order to evenly distribute the reactant gasses to the active area of the fuel cell. The channel wall adjacent to the polymer electrolyte
membrane is made of carbon paper or carbon cloth. This gas-permeable medium (commonly referred to as the gas diffusion medium, GDM) serves to diffuse the reactant gasses to ensure a more even distribution to the catalyst sites at the membrane. On the cathode side, reaction product water forms at the catalyst sites in the electrode layer and flows through the GDM toward the gas channel where it collects and is eventually removed by the flowing air stream. The region of interest for the present work is marked by the dashed circle shown on the physical representation of a PEM fuel cell cross-section in Figure 1.2.

Visualization of water behavior in operating PEM fuel cells has been employed as a tool for qualifying and quantifying water behavior by several investigators. The typical methodology undertaken in previous work is to mill a pocket from the backside of a flow field plate to the depth of the flow field gas distribution channels and insert an optically transparent window so that the air channel/GDM interface is visible. Alternatively, the entire plate can be constructed of an optically transparent material (e.g. Lexan, glass, etc.) with conductive ribs acting as the gas minichannels. These methods have the advantage of revealing actual operating conditions with respect to water management, but there are limitations if the goal is to measure departure droplet diameters or advancing and receding contact angles. These limitations are related to the nature of the view and include depth of focus limitations, channel water obstructions and the fact that the contact angles at the GDM surface cannot be seen.

The depth of focus limitation is related to the droplets growing towards the camera. Attempts to focus on a growing droplet can be difficult when trying to capture the instance of droplet departure, and a reasonably good focus is necessary in order to measure the droplet departure diameter. Furthermore, water slugs and/or films frequently flow on the channel bottom wall, which is the line-of-site wall for this type of view. These obstructions distort the droplet images to varying degrees making a consistent measurement scheme impossible. Finally, this view does not allow for the observation of contact angles at the GDM surface. For this, a different observation scheme is needed.
Figure 1.2. Schematic of a PEMFC single repeating unit cross-section. The membrane, catalyst layer and GDM are not shown to scale.
Side-view images of droplets shearing from the GDM are required in order to more accurately measure departure droplet diameters and are absolutely necessary for obtaining any information on contact angles. While this could also be accomplished by inserting an optically transparent window into a channel sidewall, it must be noted that this technique has some extreme limitations in that observations are restricted to outermost channels. Furthermore, depending on the flow field design, the available outer-wall channels may include the inlet and outlet regions where there could be less than ideal operating conditions – too wet or too dry.

The ideal case would be to examine an interior channel, but it is not possible to obtain a side view image from the interior of a flow-field plate channel in an operating PEMFC. For this reason it was necessary to design and fabricate a mockup of a cathode flow-field gas channel.

A single minichannel assembly was fabricated in order to simulate water transport through a GDM in an operating PEMFC. This gas channel has transparent bottom and sidewalls through which high-speed videos were obtained. However, it was found early in the experimental program that water flowing in the channel frequently obscured and distorted droplet activity at the GDM surface when viewed through the channel bottom wall. Furthermore, no information on contact angles could be obtained from the bottom view images. For this reason, bottom view images were not acquired. The departure droplet diameter data and contact angle data are taken from high-speed side-view images. A detailed description of the minichannel assembly is presented in the Experimental Setup section.
2. LITERATURE REVIEW

PEM fuel cells are increasingly being presented as a long-term solution to the world’s energy needs with the major application targeted at the transportation industry. Many of the major automakers are promising affordable fuel cell cars by 2010, thereby driving the need for fuel cell optimization (Hoogers (2003)). The published research related to visualization of air-water flows in operating fuel cells is limited; however, some relevant experiments that give insight into the water transport behavior in an operating PEM fuel cell are presented below.

2.1 PEM Fuel Cell History

In the 1960s a solid polymer electrolyte membrane fuel cell system manufactured by the General Electric Company was the first major application of a fuel cell system. NASA chose these fuel cell systems for use as auxiliary power sources on the Gemini Program space vehicles. Fuel cells were an attractive choice for space applications due to their high gravimetric power density, and the product water generated by the fuel cell reaction could be used for drinking water by the astronauts (Kordesch and Simader (1996)). However, these fuel cells had a short operating lifetime of approximately 500 hours, and even with continued development and performance improvements gained by the addition of a Nafion® membrane in 1967, the PEMFC was dropped by NASA due to water management problems. NASA chose a different type of fuel cell for the Apollo space vehicles, and even General Electric chose to abandon commercial development of the PEMFC. Research and development of PEM fuel cells essentially ceased throughout the 1970s and mid 1980s when it was revived by Ballard Power Systems and the Los Alamos National Laboratory (Larminie and Dicks (2003)).

Since the mid 1980s and early 1990s, further developments have led to major reductions in cost per kW of power and improved power density, which in turn have made the PEMFC the fuel cell of choice for its versatility and portability. PEM fuel cell development now dominates in many areas including passenger cars and public transportation, portable and stationary power units, and they have even once again become NASA’s fuel cell of choice for the space shuttle orbiters (Larminie and Dicks (2003)).
2.2 Water Production

Water management is still one of the most important challenges in PEMFC development. Water is a product of the fuel cell reaction, and it forms in the GDM adjacent to the air distribution channels of a cathode flow field plate. While some water retention is necessary for membrane hydration, the majority must be removed from the cathode flow field channels for optimal stack performance. Most of the product water is typically removed from the cathode electrode by the excess airflow and eventually purged from the cell through the gas channels (Kordesch and Simader (1996)).

The fairly linear region of the curve shown in Figure 2.1 begins with a rapid initial fall in voltage at low current density and ends with an increasingly faster voltage drop at higher current density - this end of the linear region represents the onset of gas transport losses which are ascribed to several limitations, one being the blockage of gas access to the catalyst sites by water droplets formed in the flow field channels or inside the GDM (Hoogers (2003)).

![Figure 2.1. Polarization curve for a typical PEMFC (Larminie and Dicks (2003)).](image)

Nam and Kaviany (2003) investigated the formation and distribution of condensed water in the gas diffusion media of PEM fuel cells. For the cathode GDM, they describe product water as flowing towards the cathode gas distribution channels through gas-phase
diffusion or liquid-phase motion. The case of liquid-phase motion occurs at higher current densities, and if the gas channel is at the local vapor saturation conditions then liquid water flows out of the GDM forming water droplets on the GDM surface adjacent to the cathode gas channel. Furthermore, their work covers water transport modeling in hydrophobic GDM that leads to the concept of a branching micro to macro water transport.

In this model, condensed water from near the catalyst sites flows from micro drops to macro drops as the product water moves toward the gas channel. As this occurs, the many connected macro droplets preferentially select larger pores due to lower capillary pressure and flow resistance. A schematic of the branching micro to macro water transport concept in a PEMFC cathode electrode is shown in Figure 2.2.

![Schematic of branching micro to macro water transport](image)

**Figure 2.2. Schematic of branching micro to macro water transport (Nam and Kaviany (2003)).**

### 2.3 Water Transport in Operating PEMFC Cathode Channels

Visualization of water behavior in operating PEM fuel cells has been employed as a tool for qualifying and quantifying water transport by several investigators. The following review examines flow visualization experiments that are focused on water transport through GDM viewed through the “bottom” wall of a cathode gas channel.

Tuber et al. (2003) performed visualization experiments of water buildup in the cathode of a transparent PEMFC. The cathode channel dimensions used for their experiment were 1.5 mm wide by 1 mm deep with a length of 50 mm, and they used standard Toray carbon paper (TGPH-090) treated with a PTFE coating (weight content absorbed: 25 wt%).
Their work showed randomly distributed water droplets and formations, droplet growth and droplet movement due to the kinetic energy of the airflow. However, no departure droplet diameter or contact angle data were presented. The transparent PEMFC was operated with an air flow rate of 225 CCM, and it was shown that the pores of the GDM and the entire cathode channel become filled with liquid water at high current densities.

Figure 2.3 shows three images taken from the visualization experiment of Tuber et al. (2003) for a hydrophobic carbon paper. The first image is taken after five minutes of constant voltage discharge (500 mV) operation when the current density has stabilized at about 200 mA/cm². Randomly distributed small droplets can be seen permeating the GDM. The second image is taken after 25 minutes at the same operating conditions. Here it is seen that water formations have grown due to increased product water, and it is also reported that droplets moved due to the force of the air flow. The third image, taken after 30 minutes, shows even more product water in the channels and even shows a water slug completely blocking one of the parallel gas channels.

Figure 2.3. Visualization of PEMFC cathode gas channels with hydrophobic GDM (Tuber et al. (2003)).

Yang et al. (2004) investigated the mechanics of water transport using a PEMFC with an optically transparent cathode plate. Seven 1-mm square by 100-mm long minichannels were created in a stainless-steel current collector plate with the land between channels
measuring 1 mm wide. Adding an optically clear polycarbonate plate to the outside of the stainless steel current collectors formed the bottom of the cathode gas channels.

For their experiment, pure hydrogen and air were used as the fuel and oxidant with the air flow rate set at 0.505 SLPM. The cell operating pressure was 2 atm (absolute) for both the anode and cathode, and the operating temperature was 70 °C. The GDM used in their experiment was Toray carbon paper (TGPH-090) with a 20-wt % PTFE loading.

Water was seen as discrete droplets permeating the GDM at preferred locations and as lumps flowing on the channel walls. The mechanics of liquid water transport is described by Yang et al. (2004) as starting with droplet emergence on the GDM surface, continuing with droplet growth, and finally ending with droplet departure. Departure droplet sizes of up to 0.8 mm were reported, but no information about advancing and receding contact angles was given. Liquid film flow on the channel walls and water slugs completely blocking channels was also reported. Water droplets can be seen in Figure 2.4 below.

Figure 2.4. Visualization of PEMFC cathode gas channels with hydrophobic GDM (Yang et al. (2004)).
2.4 Two-Phase Flow and Pressure Drop in Minichannels

The two-phase flow observed in the minichannels used in the experiments of Tuber et al. (2003) and Yang et al. (2004) is not typical of the type of two-phase flow that has been historically studied. In air-water two-phase flow visualization experiments, the air and water are typically mixed before entering the test section as shown in Figure 2.5. Conversely, in liquid water and gaseous water two-phase flow visualization experiments, the phases are effectively mixed in the test section as water flowing in a small channel undergoes flow boiling. Published flow pattern maps, flow pattern drawings, and video images for this type of flow all pertain to moving air or gas and moving water. Some typical patterns related to this type of flow are presented in Figures 2.6-2.8 taken from the work of Kawaji and Chung (2003) and Coleman and Garimella (1999).

Figure 2.5. Typical air-water two-phase flow experimental loop (Coleman and Garimella (1999)).
Microchannels are defined by Kandlikar and Grande (2003) as channels having a hydraulic diameter in the range of 10 to 200 micrometers. The classification of minichannels refers to channels of hydraulic diameters larger than 200 micrometers up to 3 mm, and channels with hydraulic diameters greater than 3 mm are classified as conventional channels.
Figure 2.7. Two-phase flow patterns for horizontal microchannels (Kawaji and Chung (2003)).
In a PEMFC cathode gas channel, liquid water and air are “mixed” in the channel, and the entire channel is the region of interest with respect to water transport. Moreover, droplets emerging through the GDM and into the gas channel cannot move until they reach a critical departure diameter, get knocked off by another droplet, break against a channel sidewall, or get pulled into other water formations flowing through the channel. The reduction in channel cross-sectional area caused by a stationary droplet and its effect on two-phase pressure drop may not be adequately represented by the typical two-phase flow studies.
For two-phase flow, there are several correlations based on the separated flow model. One that is widely used is the Lockhart and Martinelli (1949) correlation. This correlation relates the pressure drop multiplier given by Equation (2.1) to the parameter $X^2$ defined in Equation (2.2).

$$
\phi_L^2 = \left[ \frac{dp_F}{dz} \right]_{TP} / \left[ \frac{dp_F}{dz} \right]_L
\tag{2.1}
$$

$$
X^2 = \left[ \frac{dp_F}{dz} \right]_L / \left[ \frac{dp_F}{dz} \right]_G
\tag{2.2}
$$

The single-phase pressure gradients given in Equation (2.2) are defined by Equations (2.3) and (2.4), where $x$ is the quality defined by Equation (2.5).

$$
- \left( \frac{dp_F}{dz} \right)_G = \frac{2f_G G^2 x^2}{D_h \rho_G}
\tag{2.3}
$$

$$
- \left( \frac{dp_F}{dz} \right)_L = \frac{2f_L G^2 (1-x)^2}{D_h \rho_L}
\tag{2.4}
$$

$$
x = \frac{\dot{m}_G}{\dot{m}_G + \dot{m}_L}
\tag{2.5}
$$

The friction factors $f_L$ and $f_G$ are related to the Reynolds numbers defined by Equations (2.6) and (2.7), where $G$ is the total mass flux of liquid and gas phases as given by Equation (2.8).

$$
Re_G = \frac{G x D_h}{\mu_G}
\tag{2.6}
$$

$$
Re_L = \frac{G (1-x) D_h}{\mu_L}
\tag{2.7}
$$
\[ G = \frac{\dot{m}_G + \dot{m}_L}{A} \]  \hspace{1cm} (2.8)

Chisholm (1967) fit curves to the graphical representation of the Lockhart and Martinelli correlation for pressure drop. The relationship is given by Equation (2.9), where \( C \) is a dimensionless parameter related to the nature of the two-phase flows. The suggested values for \( C \) are given in Table 2.1.

\[ \phi_L^2 = 1 + \frac{C}{X} + \frac{1}{X^2} \]  \hspace{1cm} (2.9)

<table>
<thead>
<tr>
<th>Liquid</th>
<th>Gas</th>
<th>( C )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laminar</td>
<td>Laminar</td>
<td>5</td>
</tr>
<tr>
<td>Turbulent</td>
<td>Laminar</td>
<td>10</td>
</tr>
<tr>
<td>Laminar</td>
<td>Turbulent</td>
<td>12</td>
</tr>
<tr>
<td>Turbulent</td>
<td>Turbulent</td>
<td>20</td>
</tr>
</tbody>
</table>

Table 2.1. Values of dimensionless parameter \( C \) suggested by Chisholm (1967).

Mishima and Hibiki (1996) modified the parameter \( C \) by relating it to the tube inner diameter. A new equation for \( C \) was developed for vertical and horizontal round tubes and rectangular ducts as given by Equation (2.10). It is important to note that the hydraulic diameter \( D_h \) must be in millimeters for use in this equation.

\[ C = 21 (1 - e^{-0.319D_h}) \]  \hspace{1cm} (2.10)

Through the work of Baroczy (1966), Chisholm (1973) modified the procedure for obtaining a two-phase multiplier in order to account for fluid properties, quality and mass flux. The correlation is given by Equation (2.11), where \( n \) is the exponent to which the Reynolds number is raised in the friction factor equation (Equation (6.16)), and \( B \) is a
coefficient based on the Baroczy (1966) correlation given by Chisholm (1973) in Table 2.2. For a Reynolds number, $Re_{LO}$, at or below 2100, $n = 1$, and for a liquid only Reynolds number above 2100 the value of $n$ is 0.25 as given by the Blasius correlation (Fox and McDonald (1998)) for turbulent flow in smooth pipes.

$$\phi_{LO}^2 = 1 + \left( Y^2 - 1 \right) \left[ Bx^{(2-n)/2} (1-x)^{(2-n)/2} + x^{2-n} \right]$$  \hspace{1cm} (2.11)

The $Y$ term in Equation (2.11) is the Chisholm parameter, and it is defined as the square root of the ratio of gas-only and liquid-only Reynolds numbers as given by Equations (2.12) – (2.14).

$$Y^2 = \frac{\frac{dp_F}{dz}_{GO}}{\frac{dp_F}{dz}_{LO}}$$  \hspace{1cm} (2.12)

$$-\left( \frac{dp_F}{dz} \right)_{GO} = \frac{2f_{GO}G^2}{D_h \rho_G}$$  \hspace{1cm} (2.13)

$$-\left( \frac{dp_F}{dz} \right)_{LO} = \frac{2f_{LO}G^2}{D_h \rho_L}$$  \hspace{1cm} (2.14)

<table>
<thead>
<tr>
<th>$Y$</th>
<th>$G$ (kg/m$^2$)</th>
<th>$B$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Y$</td>
<td></td>
<td>$\leq 500$</td>
</tr>
<tr>
<td>$\leq 9.5$</td>
<td>$500 &lt; G &lt; 1900$</td>
<td>$2400/G$</td>
</tr>
<tr>
<td>$\leq 9.5$</td>
<td>$\geq 1900$</td>
<td>$55/G^{0.5}$</td>
</tr>
<tr>
<td>$9.5 &lt; Y &lt; 28$</td>
<td>$\leq 600$</td>
<td>$520/(YG^{0.5})$</td>
</tr>
<tr>
<td>$9.5 &lt; Y &lt; 28$</td>
<td>$&gt; 600$</td>
<td>$21/Y$</td>
</tr>
<tr>
<td>$\geq 28$</td>
<td></td>
<td>$15000/(Y^2G^{0.5})$</td>
</tr>
</tbody>
</table>

Table 2.2. Values of $B$ given by Chisholm (1973) for smooth tubes.
For all combinations of experimental parameters in the current test program the total mass flux $G$ was less than 500 and the liquid-only Reynolds numbers were below 2100, so the values for $n$ and $B$ in Equation (2.11) were taken as 1 and 4.8, respectively.

Another correlation that is widely used is that of Friedel (1979). This correlation was developed for adiabatic flow through channels with diameters greater than 1 mm. The Friedel pressure drop multiplier is given by Equation (2.15), where the parameters $E$, $F$, and $H$ are defined by Equations (2.16) – (2.18), and the Froude number $Fr$ and the Weber number $We$ are defined by Equations (2.19) and (2.20), where $\rho_{TP}$ is defined by Equation (2.21), $g$ is the acceleration due to gravity, and $\sigma$ is the surface tension of the liquid phase.

$$\phi_{lo}^2 = E + \frac{0.324 F \cdot H}{Fr^{0.045} We^{0.035}}$$ \hspace{1cm} (2.15)

$$E = (1 - x)^2 + x^3 \frac{\rho_L f_{GO}}{\rho_G f_{LO}}$$ \hspace{1cm} (2.16)

$$F = x^{0.78} + (1 - x)^{0.24}$$ \hspace{1cm} (2.17)

$$H = \left( \frac{\rho_L}{\rho_G} \right)^{0.91} \left( \frac{\mu_G}{\mu_L} \right)^{0.19} \left( 1 - \frac{\mu_G}{\mu_L} \right)^{0.7}$$ \hspace{1cm} (2.18)

$$Fr = \frac{G^2}{gD_h \rho_{TP}^2}$$ \hspace{1cm} (2.19)

$$We = \frac{G^2 D_h}{\rho_{TP} \sigma}$$ \hspace{1cm} (2.20)

$$\rho_{TP} = \left( \frac{x}{\rho_G} + \frac{1 - x}{\rho_L} \right)^{-1}$$ \hspace{1cm} (2.21)
Although the Friedel correlation is recommended for $\mu_l/\mu_g < 1000$, which is the case for the present work, this correlation greatly over predicts the experimental pressure drop observations.

Chen et al. (2001) conducted air-water tests at room temperature for tubes with diameters of less than 10 mm. A modification was made to the Friedel (1979) correlation by the theory that the surface tension effects are underemphasized and the gravity effects are over emphasized for two-phase flow in small tubes. The Chen et al. (2001) modification takes the form of a multiplier that is used with the two-phase pressure drop predicted by the Friedel correlation (1979) as given by Equation (2.22).

$$\left( \frac{dp_F}{dz} \right)_{TP} = \left( \frac{dp_F}{dz} \right)_{\text{Friedel}} \Omega \quad (2.22)$$

The $\Omega$ term in Equation (2.22) is defined by Equation (2.23), where the Bond number $Bo$ is given by Equation (2.24). For the present work, the Bond number is less than 2.5.

$$\Omega = \begin{cases} 
\frac{0.0333\text{Re}_{\text{LO}}^{0.45}}{\text{Re}_G^{0.09} (1 + 0.4 \exp[-Bo])} & Bo < 2.5 \\
\frac{We^{0.2}}{(2.5 + 0.06Bo)} & Bo \geq 2.5 
\end{cases} \quad (2.23)$$

$$Bo = g (\rho_L - \rho_G) \left( \frac{D_h/2}{\sigma} \right)^2 \quad (2.24)$$

Lee and Lee (2001) proposed a different value for $C$ in Chisholm’s correlation in order to account for the channel gap size as well as the interaction between the two phases. They theorized that surface tension effects increase as channel size decreases, and through the work of Suo and Griffith (1964), they identified the important dimensionless parameters for two-phase flow as given by Equations (2.25) and (2.26). It is important to note that Lee and Lee (2001) report the use of hydraulic diameter $D_h$ for use in Equation (2.25), but Suo
and Griffith (1964) reported the tube radius $D_h/2$ for use in Equation (2.25) in their original work. The difference in the theoretical two-phase frictional pressure drop is that of a slightly higher prediction when the hydraulic diameter is used.

$$\lambda = \frac{\mu_i^2}{\rho_i \sigma D_h}$$  \hspace{1cm} (2.25)

$$\psi = \frac{\mu_L (j_o + j_L)}{\sigma}$$  \hspace{1cm} (2.26)

Based on their experimental data, Lee and Lee (2001) proposed the form of the parameter $C$ given by Equation (2.27), with the constants $A$, $q$, $r$, and $s$ given in Table 2.3 for the different laminar-turbulent flow conditions.

$$C = A \lambda^q \psi^r \text{Re}_L^s$$  \hspace{1cm} (2.27)

<table>
<thead>
<tr>
<th>Flow Regime</th>
<th>Liquid</th>
<th>Gas</th>
<th>$A$</th>
<th>$q$</th>
<th>$r$</th>
<th>$s$</th>
<th>Range of $X$</th>
<th>Range of $\text{Re}_L$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laminar</td>
<td>Laminar</td>
<td>6.833 $\times 10^{-8}$</td>
<td>-1.317</td>
<td>0.719</td>
<td>0.557</td>
<td>0.776-14.176</td>
<td>175-1480</td>
<td></td>
</tr>
<tr>
<td>Laminar</td>
<td>Turbulent</td>
<td>6.185 $\times 10^{-2}$</td>
<td>0</td>
<td>0</td>
<td>0.726</td>
<td>0.303-1.426</td>
<td>293-1506</td>
<td></td>
</tr>
<tr>
<td>Turbulent</td>
<td>Laminar</td>
<td>3.627</td>
<td>0</td>
<td>0</td>
<td>0.174</td>
<td>3.276-79.415</td>
<td>2606-17642</td>
<td></td>
</tr>
<tr>
<td>Turbulent</td>
<td>Turbulent</td>
<td>0.408</td>
<td>0</td>
<td>0</td>
<td>0.451</td>
<td>1.309-14.781</td>
<td>2675-17757</td>
<td></td>
</tr>
</tbody>
</table>

Equations (2.1) through (2.27) are used to obtain theoretical two-phase frictional pressure drops for the flow conditions in the present work, and the experimental two-phase pressure drop measurements are compared to these correlations in Section 7.
Measured pressure drop for horizontal two-phase minichannel flow can be described as the total pressure loss due to wall friction, contraction and expansion at the channel entrance and exit plenums, and momentum changes in the flow as shown by Equation (2.28). Subtracting the momentum and contraction estimations from the measured pressure drop isolates the two-phase frictional pressure drop. This loss due to friction is compared to two-phase pressure drop correlations that use experimentally derived pressure drop multipliers.

\[
\Delta p_{\text{measured}} = \Delta p_{\text{friction}} + \Delta p_{\text{contraction}} + \Delta p_{\text{momentum}}
\]  
(2.28)

The change in pressure due to the contraction and expansion at the minichannel entrance and exit is referred to as a minor loss. The relation used for determining the minor losses is given by Equation (2.29), where the \(K_{c,e}\) terms are found through experimental data to be \(K_c = 0.5\) for the contraction and \(K_e = 0.97\) for the expansion (Fox and McDonald (1998)).

\[
\Delta p_{\text{contraction}} = \rho K_{c,e} \frac{V^2}{2}
\]  
(2.29)

The pressure loss due to momentum is given by Chisholm (1983) as shown in Equation (2.30). This model is used to represent water condensing on the inner wall of a tube of flowing steam, and it was selected due to the similarities of water droplets forming on a solid tube wall and water droplets emerging through a GDM wall.

\[
\Delta p_{\text{momentum}} = G^2 \nu_L \left[ \frac{\nu_G}{\nu_L} - \frac{\nu_e}{\nu_L} \right]
\]  
(2.30)

In Equation (2.30), \(G\) is the total mass flux and \(\nu_G\) and \(\nu_L\) are the specific volumes of the air and water, respectively. The ratio of \(\nu_e/\nu_L\) is given by Equation (2.31), where \(x\) is the quality and \(K\) is defined by Equation (2.32).
\[
\frac{v_x}{v_L} = \left[ x \left( \frac{v_G}{v_L} \right) + K (1-x) \right] \left[ x + \frac{1-x}{K} \right]
\]
(2.31)

\[
K = \left[ \left( \frac{v_G}{v_L} \right)^{1/4} \right]^{0.28}
\]
(2.32)

The contraction and momentum terms are subtracted from the total measured pressure drop in order to isolate the frictional pressure drop and compare it with theoretical predictions.

A plot of pressure drop as a function of superficial gas velocity for each water flow rate is presented in the Results and Discussion section. Since the two phases are not mixed before entering the test section minichannel, half of the water flow rate is used to calculate the quality \( x \) used in the frictional pressure drop calculations. However, the exit quality is used in Equation (2.31), as specified by Chisholm (1983), so the full water flow rate is used in calculating the quality for the pressure drop due to momentum flux.
3. OBJECTIVES

The objectives of the present work are to create a model of an operating PEMFC cathode gas channel in order to:

- Obtain side-view images of departing water droplets in order to understand the droplet departure phenomenon
- Measure departure droplet diameters and contact angles to determine water shedding performance of different GDM samples
- Investigate and detail two-phase flow patterns for the specific flow present in these experiments
- Measure two-phase pressure drop for the flows observed in these experiments and compare the experimental results to existing two-phase frictional pressure drop correlations
4. EXPERIMENTAL SETUP

The experimental setup is described in this section. Three different GDM samples were examined with the test section positioned horizontally and the GDM acting as the top wall of the channel. High-speed digital video of liquid water as it emerged from the GDM and flowed in the gas channel was taken at 1000 frames per second (fps).

4.1 Test Section

In order for the water transport to be visualized, it was necessary to construct a minichannel with transparent walls. This was accomplished by assembling three separate Lexan blocks together as shown in Figure 4.1, where the dashed lines indicate the water-clear Lexan surfaces. End blocks were added to provide for the channel inlet and exit, and the top surface of the minichannel block was machined after all five blocks were glued together in order to create a uniform seating and sealing surface for the GDM sample and Teflon gasket. The solid arrows on the assembled cross section show the lines of sight through which high-speed images were taken.

![Figure 4.1. Air channel plate construction. Dashed lines indicate water-clear surfaces. The thin solid arrows define side and bottom views.](image)

Water delivery was realized by creating a top cover plate for the air channel plate. This top plate is made from one solid piece of Lexan with a 1-mm square water channel milled into it. The water channel is lined up with the air channel when the test section is assembled and compressed. Figure 4.2 shows each channel plate.
4.2 GDM Samples

Three GDM samples were compared using the test section described above. The samples are referred to as GDM Sample A, GDM Sample B, and GDM Sample C from this point on.

Early on, experiments revealed that water was flowing in plane in the GDM and down the air-channel sidewalls, so the GDM samples were treated by baking a polymer film (Kynar) into them or by masking them off with tape except at the center (~1mm wide) as shown in Figure 4.3.
The center strip was left untreated so that water could still flow through plane but be inhibited from flowing in plane to the channel corners. Furthermore, the sealing surfaces of the test section were coated with the hydrophobic solution FluoroPel (PFC 1602A) in order to keep water away from the channel corners. The assembly was compressed with the Kynar or tape adjacent to the sealing surface of the air channel as shown in Figure 4.4. This resulted in several more water droplets flowing through the GDM plane, and into the air channel, than locations where water just drained down the sidewalls. Details about the treatment of each GDM sample and test section treatment are presented in Table 4.1.

Table 4.1. GDM sample details.

<table>
<thead>
<tr>
<th>GDM Sample</th>
<th>FluoroPel Test Section Surface</th>
<th>Tape/Kynar</th>
<th>MPL</th>
<th>Gasket Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Air surface only</td>
<td>Kynar</td>
<td>no</td>
<td>8 mil</td>
</tr>
<tr>
<td>B</td>
<td>Both</td>
<td>Tape</td>
<td>yes</td>
<td>10 mil</td>
</tr>
<tr>
<td>C</td>
<td>Both</td>
<td>Kynar</td>
<td>no</td>
<td>8 mil</td>
</tr>
</tbody>
</table>

4.3 Test Section Compression Fixture

A compression fixture was fabricated so that a GDM sample could be evenly compressed and sealed between the two Lexan plates. A slightly exploded view is given in Figure 4.4, and a picture of this fixture with the test section under compression is shown in Figure 4.5. With the test section plate dimensions giving a surface area of 10.87 in$^2$ (70.13 cm$^2$), the GDM sample was compressed to approximately 260 psi at 1.4 tons in the compression fixture, with a Teflon gasket used as the seal between the air channel and water channel plates.
Figure 4.4. Exploded cross-sectional view of compression fixture assembly with test section, GDM and seal in compression position (side plates not shown).

Figure 4.5. Picture of compression fixture with test section compressed inside. The viewing windows through which the high-speed videos were taken can be seen in the visible side plate.
4.4 Air Supply Loop

A compressed gas cylinder provided the airflow. Air was regulated at the cylinder and adjusted until a pressure transducer located at the inlet of the bank of rotameters read 7 psig. The system line pressure $p_g$ was used to correct the calibrated flow rate using Equation (4.1), where the Calibrated Flow Rate is obtained from the flow meter manufacturer’s calibration charts for a given flow setting, and the pressure drop was measured across the air channel as shown in Figure 4.6. Ultra zero grade air was used throughout the experiment.

\[
\text{Flow Rate} = \sqrt{\frac{14.7 + p_g}{14.7}} \times \text{Calibrated Flow Rate} \tag{4.1}
\]

Figure 4.6. Air supply loop.
4.5 Water Supply Loop

Water flow was provided through the use of two synchronized syringe pumps. While one syringe infused water into the test section water chamber, the other syringe withdrew a fresh supply of water from a reservoir. The syringe-pump system provided a continuous, pulse-free flow except at the time when the pumps switched directions. Care was taken not to collect data directly after the pumps switched directions. Ultra filtered deionized water was used throughout the experiment.

![Water supply loop diagram]

Figure 4.7. Water supply loop.

4.6 High-Speed Video System

The high-speed video system used in the present work is comprised of a digital high-speed camera, high-speed processor, lenses and video capture and processing software. The digital camera is a Photron brand Fastcam Ultima APX, model 120K. The camera is capable of capturing images at frame rates of up to 120,000 fps. This high maximum frame rate allows for images to be taken at much slower frame rates with reasonable lighting. The recording rate used for a majority of the video data collected during this experiment is 1000 fps. The resolution was set to 1024 × 256, and the shutter speed was set at 1/6000.

Three lens setups were used at various times during the data collection; however, a majority of the video data were taken with a Nikon NIKKOR lens with a 2X teleplus extender. A microscopic lens was also used for a few images, and some of the data was
collected using the Nikon NIKKOR lens without the teleplus extender. The exact lens details are given along with the other details for each experimental run in the data-sheet Appendices.

4.7 Experimental Parameters and Uncertainties

The experimental parameters used in the present work were initially chosen to simulate the conditions in an operating PEMFC cathode gas channel. Water flow rates were found to be inadequate for use with the experimental facility so they were increased until water flow through the GDM was achieved.

The accuracy of the water flow rate set at the pump was examined by calibrating the syringe pump at the 0.28 mL/min, 0.56 mL/min and 1.12 mL/min settings. The results of the pump calibration are given in Table 4.2 with the uncertainty taken as three standard deviations. A statistical analysis of the pump calibration data is given in Appendix B.

<table>
<thead>
<tr>
<th>Pump Setting</th>
<th>Calculated Mean</th>
<th>Uncertainty (+/-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.28 mL/min</td>
<td>0.281 mL/min</td>
<td>0.003 mL/min</td>
</tr>
<tr>
<td>0.56 mL/min</td>
<td>0.563 mL/min</td>
<td>0.006 mL/min</td>
</tr>
<tr>
<td>1.12 mL/min</td>
<td>1.127 mL/min</td>
<td>0.009 mL/min</td>
</tr>
</tbody>
</table>

High air flow rates cause too much interference with the water in the water chamber plate as air was seen to diffuse into the water. The initial air flow rates were scaled down slightly in order to get the model to more closely resemble the operating PEMFC water transport seen in visualization experiments described above. The air flow rates used in the experiments of the present work are given in standard and actual flow rate along with their associated uncertainties in Table 4.3. The equation for converting between the actual flow rates (ACCM) and the standard flow rates (SCCM) with absolute pressures and temperatures is given by Equation (4.2) (United States EPA (2004)) where standard temperature and pressure are taken as 1 atm and 25°C.

$$\text{ACCM} = \left( \frac{T_{act}}{T_s} \right) \left( \frac{P_s}{P_{act}} \right) \times \text{SCCM}$$  

(4.2)
Table 4.3. Air flow rates and uncertainties.

<table>
<thead>
<tr>
<th>Standard Flow Rate</th>
<th>Actual Flow Rate</th>
<th>Uncertainty (+/-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>49 SCCM</td>
<td>48 CCM</td>
<td>5.1 CCM</td>
</tr>
<tr>
<td>90 SCCM</td>
<td>88 CCM</td>
<td>5.1 CCM</td>
</tr>
<tr>
<td>180 SCCM</td>
<td>175 CCM</td>
<td>5.1 CCM</td>
</tr>
<tr>
<td>366 SCCM</td>
<td>351 CCM</td>
<td>5.1 CCM</td>
</tr>
<tr>
<td>757 SCCM</td>
<td>714 CCM</td>
<td>46.4 CCM</td>
</tr>
</tbody>
</table>

The transducers were calibrated with an Omega DPI 610 pressure calibrator. A voltage output was recorded for 16 pressure settings, and a linear regression was performed in order to obtain an equation for pressure as a function of voltage. This process resulted in a pressure reading that was within +/- 207 Pa (± 0.03 psi) of the calibrator setting.

Measurement uncertainty associated with departure droplet diameters and contact angles, as presented in Table 4.4, are explained in detail in the Data Reduction section related to image analysis.

Table 4.4. Measurement uncertainties for droplet diameter and contact angles.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>GDM Sample A</th>
<th>GDM Sample B</th>
<th>GDM Sample C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Departure Droplet Diameter</td>
<td>±0.05 mm</td>
<td>±0.03 mm</td>
<td>±0.03 mm</td>
</tr>
<tr>
<td>Contact Angle</td>
<td>± 2 deg.</td>
<td>± 2 deg.</td>
<td>± 2 deg.</td>
</tr>
</tbody>
</table>

The channel width was measured at a low end of 1.02 mm up to a high end of 1.09 mm, and the channel depth was measured at 1.1 mm. The channel length is 25 cm. The uncertainties associated with these measurements are obtained using Equation (4.3), where $B$ is the bias error, $\sigma$ is the standard deviation and $N$ is the number of measurements.

$$ U = 2 \sqrt{\left(\frac{B}{2}\right)^2 + \left(\frac{\sigma}{\sqrt{N}}\right)^2} $$

(4.3)

The uncertainty associated with the channel width and depth measurements is ± 0.03 mm, and the uncertainty for the channel length measurement is ± 0.05 mm.
5. EXPERIMENTAL PROCEDURE

After the test section is assembled, the system is run near the highest water flow rate and at the desired air flow rate for two hours before the start of data collection. After this time, active locations are identified by eye and then examined more closely with the high-speed camera and high-intensity halogen lighting. Each viewing window is scanned for droplet activity, and digital image sequences are recorded at 1000 fps. This frame rate allows for a maximum recording time of approximately eight seconds.

Pressure data are recorded continuously between video data collections so that the system pressure can be monitored. After a video is captured, the pressure data collection is stopped and saved with the time indicated on the pressure data collection computer noted. A new pressure data file is then started for use with the next video.
6. DATA REDUCTION AND ANALYSIS

A description of how the high-speed video images are used to obtain data is presented in this section. The methods of determining the uncertainty related to departure droplet diameters and contact angles are also discussed, and an analysis of test section validation for pressure drop measurement is presented.

6.1 Image Analysis

The high-speed video images were used to obtain information about the water transport behavior in the simulated cathode gas channel. Several two-phase flow patterns and two-phase interactions were observed for the different air and water flow rates, and discrete droplets were seen shearing from the GDM surface due the air flow. The flow patterns and interactions ascertained from high-speed video images are described in the Results and Discussion section. Departure droplet diameter and contact angle data are also presented in the Results and Discussion section, and is obtained by making measurements on the high-speed video image of a droplet at the onset of departure. Figure 6.1 shows a schematic of a typical video image at the onset of droplet departure.

The onset of droplet departure is defined as the video image just before the tail seen in Figure 6.1 breaks free from the GDM surface. After the tail breaks free, the droplet diameters often become unstable making a consistent departure diameter measurement impossible. For this reason, the departure diameter was defined as shown in Figure 6.1.

![Figure 6.1. Schematic of the onset of droplet departure.](image)

A numeric value for the departure droplet diameter was obtained by using the known channel height of 1.1 mm. For the GDM Sample A data, a precision scale was used to
measure the channel height and the droplet diameter. The uncertainty associated with the on-screen scale measurements was derived by making a conservative error estimate of ± 0.050 inches (a ruler graduated in inches was used for this measurement). All on-screen measurements of the channel and water droplets were definitely within this uncertainty range, and a sample diameter calculation illustrates the effect on droplet dimension.

If the channel measured 1.65” ± 0.05” and the droplet measured 0.65” ± 0.05” then the nominal droplet diameter would be 0.43mm as given by Equation (6.1).

\[
0.65" \times \frac{1.1 \text{ mm}}{1.65"} = 0.43 \text{ mm}
\]  

(6.1)

The minimum value for the droplet occurs when the nominal drop diameter measurement low end (0.65” – 0.05”) is used with the nominal channel height measurement high end (1.65” + 0.05”). Similarly, the maximum value for the droplet diameter occurs when the nominal drop diameter measurement high end (0.65” + 0.05”) is used with the nominal channel height measurement low end (1.65” – 0.05”). For this case the calculated droplet diameter would be presented as 0.43 mm ± 0.05 mm.

For the GDM Sample B and C data, a different approach was used in an attempt to reduce the uncertainty. This method utilized a pixel selector tool available in the video capture and analysis software. The uncertainty associated with the on-screen pixel measurements was derived by edge determination. An image was magnified and an edge (channel or droplet) was focused on. The pixel selector was placed on the best guess of where the edge was and the pixel coordinate was recorded. The uncertainty was taken as one pixel above and below the best guess for a given edge. All possible combinations of measurements, with uncertainties, lead to a total uncertainty of ± 2 pixels from a nominal measurement. A sample diameter calculation illustrates the uncertainty effect on droplet dimension.

If the channel measured 126 pixels ± 2 pixels and the droplet diameter measured 82 pixels ± 2 pixels then the nominal droplet diameter would be 0.72 mm as given by Equation (6.2).
The minimum value for the droplet occurs when the nominal drop diameter measurement low end (82 pix - 2 pix) is used with the nominal channel height measurement high end (126 pix + 2 pix). Similarly, the maximum value for the droplet diameter occurs when the nominal drop diameter measurement high end (82 pix + 2 pix) is used with the nominal channel height measurement low end (126 pix - 2 pix). For this case the calculated droplet diameter would be 0.72 mm ± 0.03 mm, which is a slight improvement in uncertainty over the method used for GDM Sample A.

Advancing and receding contact angles were also measured on the onset of droplet departure video frames. Figure 6.2 shows the advancing and receding contact angle orientation. Contact angles are measured on high-quality color laser printouts of the high-speed video frames capturing the onset of droplet departure. The color laser printouts were made on an HP Color Laser Jet 4500N, and a transparent precision ruler/protractor was used to make angle measurements on contact angle lines drawn tangent to the water droplet at the air-water-GDM interface.

![Figure 6.2. Schematic of contact angle measurements.](image)

This method was validated for accuracy by taking a high-speed video of a known angle block and comparing the angle measurement from the color laser print out method to the actual angle. However, there is some subjectivity involved in drawing the three-phase contact angle line for a departure droplet so a conservative error estimate of ± 2 degrees was taken for this measurement procedure.
6.2 Frictional Pressure Drop

It is common practice to compare experimental pressure drop data against theoretical pressure drop correlations. This involves isolating only the frictional pressure drop component from the experimental pressure drop data, which for single-phase flow can include entrance and exit effects due to contraction and expansion at the test section inlet and outlet and developing flow region effects.

Single-phase pressure drop theory for fully developed, internal, steady flow begins with the energy balance given by Equation (6.3) where the $h_i$ term refers to the total energy loss per unit mass and the $\alpha$ terms refer to the kinetic energy coefficients (Fox and McDonald (1998)).

$$h_i = \left( \frac{p_1}{\rho} + \alpha_1 \frac{V_1^2}{2} + gz_1 \right) - \left( \frac{p_2}{\rho} + \alpha_2 \frac{V_2^2}{2} + gz_2 \right)$$  \hspace{1cm} (6.3)

In the case of a constant-area horizontal channel, $z_1 = z_2$ and $\alpha_1 V_1^2 / 2 = \alpha_2 V_2^2 / 2$ thereby reducing Equation (6.3) to the form of Equation (6.4).

$$h_i = \frac{\Delta p}{\rho}$$  \hspace{1cm} (6.4)

Equation (6.4) shows that major head loss can be expressed as pressure drop for fully developed constant internal flows in horizontal channels with constant cross sectional areas.

The pressure drop for fully developed laminar flow in a horizontal pipe can be derived from the equations of motion. The continuity equation in cylindrical coordinates is given by Equation (6.5).

$$\frac{1}{r} \frac{\partial}{\partial r} (rv_r) + \frac{1}{r} \frac{\partial}{\partial \theta} (v_\theta) + \frac{\partial}{\partial z} (v_z) = 0$$  \hspace{1cm} (6.5)
Figure 6.3. Schematic of a fully developed laminar velocity profile in a round tube (Schlichting (1979)).

Assuming a fully developed axis-symmetric velocity profile, as shown in Figure 6.3, the continuity equation reduces to Equation (6.6).

\[
\frac{\partial}{\partial z} (v_z) = 0
\]  

(6.6)

The Navier-Stokes equations are dynamic equations that describe fluid motion. In cylindrical coordinates they are written as shown in Equations (6.7) – (6.9) for constant density and viscosity.

\[
\rho \left( \frac{\partial v_r}{\partial t} + v_r \frac{\partial v_r}{\partial r} + v_\theta \frac{\partial v_r}{\partial \theta} \frac{v_\theta}{r} + v_z \frac{\partial v_r}{\partial z} \right) = \rho g_r - \frac{\partial p}{\partial r} + \mu \left\{ \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial v_r}{\partial r} \right) + \frac{1}{r^2} \frac{\partial^2 v_r}{\partial \theta^2} - \frac{2}{r^2} \frac{\partial v_\theta}{\partial \theta} + \frac{\partial^2 v_r}{\partial z^2} \right\}
\]

(6.7)

\[
\rho \left( \frac{\partial v_\theta}{\partial t} + v_r \frac{\partial v_\theta}{\partial r} + v_\theta \frac{\partial v_\theta}{\partial \theta} + v_z \frac{\partial v_\theta}{\partial z} \right) = \rho g_\theta - \frac{1}{r} \frac{\partial p}{\partial \theta} + \mu \left( \frac{1}{r^2} \frac{\partial}{\partial \theta} \left( r \frac{\partial v_\theta}{\partial r} \right) + \frac{1}{r^2} \frac{\partial^2 v_\theta}{\partial \theta^2} + \frac{2}{r^2} \frac{\partial v_r}{\partial \theta} + \frac{\partial^2 v_\theta}{\partial z^2} \right)
\]

(6.8)

\[
\rho \left( \frac{\partial v_z}{\partial t} + v_r \frac{\partial v_z}{\partial r} + v_\theta \frac{\partial v_z}{\partial \theta} + v_z \frac{\partial v_z}{\partial z} \right) = \rho g_z - \frac{\partial p}{\partial z} + \mu \left( \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial v_z}{\partial r} \right) + \frac{1}{r^2} \frac{\partial^2 v_z}{\partial \theta^2} + \frac{\partial^2 v_z}{\partial z^2} \right)
\]

(6.9)
Under the same fully developed axis-symmetric velocity profile assumption used to reduce the continuity equation, and by assuming steady-state flow and neglecting body forces, Equations (6.7) and (6.8) reduce to zero, and by using the result that these assumptions had on the continuity equation (Equation (6.6)), Equation (6.9) reduces to the form given by Equation (6.10). Therefore, the pressure drop is only a function of channel length, and the fluid velocity is only a function of the channel radius.

\[
0 = -\frac{dp}{dz} + \mu \left( \frac{1}{r} \frac{d}{dr} \left( r \frac{dv_z}{dr} \right) \right) \quad (6.10)
\]

Integrating this equation twice and using the boundary conditions given by Equations (6.11) and (6.12), the velocity profile is derived as given by Equation (6.13).

\[
\left. \frac{dv_z}{dr} \right|_{r=0} = 0 \quad (6.11)
\]
\[
v_z (r = R) = 0 \quad (6.12)
\]
\[
v_z (r) = \left( -\frac{dp}{dz} \right) \frac{1}{4\mu} \left( R^2 - r^2 \right) \quad (6.13)
\]

The maximum velocity in the channel occurs at the center of the channel where \( r = 0 \). The mean velocity is half the maximum velocity; therefore, a relation can be obtained between volumetric flow rate \( Q \) and pressure drop as follows. The volumetric flow rate is defined as the average velocity multiplied by the channel cross section \( A \) as given by Equation (6.14).

\[
Q = AV \Rightarrow \pi R^2 \bar{V} = \left( -\frac{dp}{dz} \right) \frac{\pi R^4}{8\mu} \quad (6.14)
\]

Since the pressure gradient is constant for fully developed flow, \( \frac{dp}{dz} = \frac{(p_2 - p_1)}{L} = -\frac{\Delta p}{L} \). Substituting this into Equation (6.14) and rewriting \( R^4 \) as \((D/2)^4\), the flow rate as a
function of pressure drop is obtained for laminar flow in a horizontal pipe as given by Equation (6.15).

\[ Q = \frac{\pi \Delta p D^4}{128 \mu L} \]  

(6.15)

Rearranging Equation (6.15) by solving for \( \Delta p \) and writing \( Q \) as \( \left( \pi \frac{D^2}{4} \right) \overline{V} \) and substituting into Equation (6.4) gives an expression for head loss with the Darcy friction factor \( f \) identified as the term in the parenthesis in Equation (6.16).

\[ h_f = \left( \frac{64}{Re} \right) \frac{L \overline{V}^2}{D/2} \]  

(6.16)

By combining Equations (6.4) and (6.16), the frictional pressure drop over a given length \( L \) for a horizontal internal pipe flow is given by Equation (6.17).

\[ \Delta p = f \rho \frac{L \overline{V}^2}{D/2} \]  

(6.17)

Since the present experimental work was carried out using a rectangular duct, the diameter \( D \) given in Equation (6.17) is replaced by the hydraulic diameter \( D_h \) defined by Equation (6.18) and the friction factor is defined by the relation given by Kakac et al. (1987) as shown in Equation (6.19) where the Reynolds number, \( Re \), is defined by Equation (6.20) as the ratio of the product of fluid density \( \rho \), average fluid velocity \( \overline{V} \), and hydraulic diameter \( D_h \) to the fluid viscosity \( \mu \).

\[ D_h = \frac{4ab}{2(a+b)} = \frac{2ab}{a+b} \]  

(6.18)

\[ f_f \ Re = 24 \left( 1-1.3553 \alpha^* + 1.9467 \alpha^{*2} - 1.7012 \alpha^{*3} + 0.9564 \alpha^{*4} - 0.2537 \alpha^{*5} \right) \]  

(6.19)
\[ \text{Re} = \frac{\rho \bar{V} D_h}{\mu} \] (6.20)

This form of the friction factor (Equation (6.19)) is known as the Fanning friction factor (1/4 of the Darcy friction factor) for laminar flow, and it is accurate to ± 0.05% and valid for \( 0 \leq \alpha^* \leq 1 \) where the \( \alpha^* \) term in Equation (6.19) is defined as

\[ \alpha^* = \frac{2b}{2a} \] (6.21)

and \( 2a \) and \( 2b \) are the channel height and width dimensions.

Entrance and exit effects at the test section inlet and outlet and developing flow region effects must be subtracted from the experimental pressure drop measurements. The channel length is 250 mm, and according to the hydrodynamic entrance length equation given by Equation (6.22), the flow is fully developed at the exit for the range of air flow rates examined in this experiment.

\[ L_h = 0.05 \text{Re} D_h \] (6.22)

According to Steinke and Kandlikar (2005), the apparent friction factor due to the developing flow region can be accounted for through the Hagenbach factor \( K(\infty) \). Since the flow is fully developed at the channel exit, the total pressure defect due to frictional pressure drop and the developing region is given by Equation (6.23) where the Hagenbach factor is defined by Equation (6.24). In Equation (6.24), the \( \alpha_c \) term is the ratio of the channel width and height with \( 0 \leq \alpha_c \leq 1 \).

\[ \Delta p = \frac{2(f \text{ Re}) \mu \bar{V} L}{D_h^2} + K(\infty) \frac{\rho \bar{V}^2}{2} \] (6.23)

\[ K(\infty) = 0.6796 + 1.2197\alpha_c + 3.3089\alpha_c^2 - 9.5921\alpha_c^3 + 8.9089\alpha_c^4 - 2.9959\alpha_c^5 \] (6.24)
When the expansion and contraction losses are considered, Equation (6.23) is expanded to the form given by Equation (6.25) where the contraction and expansion coefficients $K_c$ and $K_e$ are found through charts given by Fox and McDonald (1998) using the area ratio $AR$ as defined in Figure 6.4. The area ratio for the test section used in the present experiment is found to be $AR = 0.013$ with the large area equal to $\pi(8.73 \text{ mm}/2)^2$ and the small area equal to $\pi(1.0 \text{ mm}/2)^2$.

$$\Delta p = \frac{2(f_e \text{ Re}) \mu \bar{V} L}{D_h^2} + K(\infty) \frac{\rho \bar{V}^2}{2} + K_c \frac{\rho \bar{V}^2}{2} + K_e \frac{\rho \bar{V}^2}{2}$$  \hspace{1cm} (6.25)

![Diagram of area ratio for contractions and expansions](image)

Figure 6.4. Area ratio for contractions and expansions.

The above equations are used to validate the pressure measurement scheme by flowing only air through the minichannel and comparing the experimental pressure drop results to the theoretical predictions over the range of air flow rates used in this work. The experimental friction factor is plotted against the Reynolds number and compared to the theoretical prediction as shown in Figure 6.5. The form of the experimental Fanning friction factor presented in Figure 6.5 is given by Equation (6.26), and it is obtained by solving Equation (6.25) for $f_F \text{ Re}$. The experimental single-phase pressure drop data agrees with the
theoretical friction factor within the experimental uncertainty given by Equation (6.27) (Steinke and Kandlikar (2005)).

\[
f_{FR} \Re = \frac{D_h^2}{2LV \mu} \left( \Delta p - K(\infty) \frac{\rho \bar{V}^2}{2} - K_c \frac{\rho \bar{V}^2}{2} - K_e \frac{\rho \bar{V}^2}{2} \right)
\]

(6.26)

\[
\frac{U_{fRRe}}{f_{FR} \Re} = \left[ 2 \left( \frac{U_p}{\rho} \right)^2 + \frac{U_p}{\mu} \right]^2 + \frac{U_{bR}}{\Delta p} \left( \frac{U_p}{\mu} \right)^2 + 3 \left( \frac{U_Q}{Q} \right)^2 + 5 \left( \frac{U_a}{a} \right)^2 + 2 \left( \frac{U_b}{b} \right)^2 + 2 \left( \frac{U_a}{a+b} \right)^2 + 2 \left( \frac{U_b}{a+b} \right)^2 \right]^{1/2}
\]

(6.27)

Figure 6.5. Experimental friction factor vs. Reynolds number.
7. RESULTS AND DISCUSSION

The results obtained from examining the high-speed video images are presented in this section. A comparison of data taken under the same operating conditions is presented wherever possible for the three GDM samples. Two-phase flow patterns and observed water transport mechanisms and behaviors are explained.

In general, GDM Samples A and B both displayed liquid water transport in a discrete manner along the length of test section channel. The water moving through the GDM and into the air flow channel could be seen as either isolated droplets, or as water draining down a channel sidewall. On the other hand, the Sample C GDM showed much less identifiable water transport locations and two-phase flow patterns that more closely resembled the typical two-phase flow patterns described in Section 2.4.

An attempt was made to only use water droplets that were observed shearing from the GDM surface without touching other water formations or the channel walls for the departure droplet diameter calculations; however, for the case of very low air flow rate, a few departure diameters derived from droplets that grew into the sidewalls are used in order to get an idea of the upper limit of droplet departure diameters for the channel dimensions and air flow rates investigated in this experiment.

7.1 Departure Droplet Diameters

There appears to be a strong relationship between departure droplet diameter and air flow rate as can be seen in Figure 7.1. There is clearly a decreasing trend in departure diameter with increasing air flow rate.

The spread in the data is most likely the result of variable channel cross-section and/or airflow pattern variation due to water slug formation upstream and down stream of the droplet location. It is impossible to accurately monitor the entire channel length simultaneously as conditions in the air channel and droplet behavior change rapidly and in many cases occur faster than the unaided eye can see. Local GDM surface geometry or surface chemistry could also play a role in departure droplet diameter variation.

There were not many droplets formed on the Sample C GDM surface. Toward the beginning of testing, some droplets were observed near the test section inlet and test section
center, but they stopped altogether as the testing progressed. At the end of the test matrix, the initial test conditions were repeated and no droplets were seen.

The best droplet data was used to obtain departure droplet diameters for GDM Sample C. Figure 7.1 shows departure droplet diameters for all three GDM Samples as a function of actual air flow rate. Although there are limited data for GDM Sample C, the departure droplet diameter data show larger values than the GDM Sample A or B data at the 714 CCM and 351 CCM air flow rates. This could be an indication of a much wetter GDM, as it appears that the departure droplet diameter is also strongly influenced by local wetness around an active pore site.

![Graph showing departure droplet diameter vs. actual air flow rate.](image)

**Figure 7.1. Departure droplet diameter vs. actual air flow rate.**

The ranges of departure droplet diameters observed in the present work for the three GDM samples are given in Table 7.1.
Table 7.1. Range of departure droplet diameters (mm) categorized by air flow rate.

<table>
<thead>
<tr>
<th>GDM Sample</th>
<th>Air Flow (CCM)</th>
<th>48</th>
<th>88</th>
<th>175</th>
<th>351</th>
<th>714</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>no data</td>
<td>no data</td>
<td>0.62 – 0.88</td>
<td>0.46 – 0.76</td>
<td>0.3 – 0.56</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>0.63 – 0.94</td>
<td>0.51 – 0.75</td>
<td>0.55 – 0.85</td>
<td>0.38 – 0.77</td>
<td>0.27 – 0.53</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>no data</td>
<td>no data</td>
<td>no data</td>
<td>0.48 – 0.85</td>
<td>0.51 – 0.70</td>
<td></td>
</tr>
</tbody>
</table>

7.2 Contact Angles

Advancing and receding contact angles were observed in the high-speed, side-view images. The contact angle measurements are displayed as a function of departure droplet diameter in Figures 7.2 and 7.3 for the GDM Samples A and B. The data points have been sized to the height of the error bars.

Figure 7.2. Contact angle vs. departure droplet diameter. GDM Sample A.
Figure 7.3. Contact angle vs. departure droplet diameter. GDM Sample B.

The advancing contact angle appears to increase slightly as the departure droplet diameter increases for GDM Sample A, but over the larger range of departure droplet diameters in the GDM Sample B experiment, the advancing contact angle appears to remain constant. The receding contact angle shows the opposite behavior, as it appears to decrease with increasing diameter for both GDM samples for diameters below 0.75 mm. The larger diameters in the GDM Sample B data are due to the much lower airflow rates that the experiment for GDM Sample B covered which were not covered in the GDM Sample A experiment.
Figure 7.4. Contact angle vs. departure droplet diameter. GDM Sample C.

The GDM Sample C advancing contact angle data appear to increase slightly with increasing departure droplet diameter, and the receding contact angle data appears to decrease as the diameter increases up to approximately 0.65 mm and then increase again with increasing departure droplet diameter (Figure 7.4).

The spread in the contact angle data is a result of the spread in the departure droplet diameters due to local air velocity changes in the channel. Departure droplets with the same diameters can have greatly different receding contact angles due to the difference in air flow rate, but the advancing contact angles seem to be less affected by air flow rate. An example of the difference seen in receding contact angle for similar-sized departure droplet diameters is shown in Figure 7.5. The arrows on the images in Figure 7.5 indicate the edge view of the top channel wall (GDM edge).
Figure 7.5. Contact angle difference for similar-sized droplets.

A comparison of the mean contact angle as a function of superficial air velocity for the GDM Samples A, B and C shows that the Sample A GDM has a slightly smaller mean advancing contact angle than does GDM Sample B. However, there is no clear trend in the receding contact angle data as can be seen in Figure 7.6. The limited GDM Sample C advancing and receding contact angle data is also presented in Figure 7.6, and the mean contact angle for GDM Sample C falls between the GDM Sample A and B data at the 5 m/s superficial gas velocity for both the advancing and receding contact angles. At the 10 m/s condition, the GDM Sample C advancing contact angle is comparable to the GDM Sample B advancing contact angle, but the receding contact angle is much lower than the GDM Sample A and B receding contact angle. A summary of the range of advancing and receding contact angles observed in the present work are given in Tables 7.2 and 7.3.
Figure 7.6. Mean contact angle data as a function of superficial gas velocity.

Table 7.2. Range of advancing contact angles (degrees) by departure droplet diameter.

<table>
<thead>
<tr>
<th>GDM Sample</th>
<th>Departure Droplet Diameter (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$d &lt; 0.5$</td>
</tr>
<tr>
<td>A</td>
<td>108 - 140</td>
</tr>
<tr>
<td>B</td>
<td>120 - 145</td>
</tr>
<tr>
<td>C</td>
<td>no data</td>
</tr>
</tbody>
</table>
Table 7.3. Range of receding contact angles (degrees) by departure droplet diameter.

<table>
<thead>
<tr>
<th>GDM Sample</th>
<th>Departure Droplet Diameter (mm)</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>d &lt; 0.5</td>
<td>27 - 78</td>
<td>30 - 87</td>
</tr>
<tr>
<td>B</td>
<td>0.5 ≤ d ≤ 0.65</td>
<td>38 - 70</td>
<td>26 - 71</td>
</tr>
<tr>
<td>C</td>
<td>d &gt; 0.65</td>
<td>no data</td>
<td>40 - 90</td>
</tr>
</tbody>
</table>

7.3 Droplet/GDM Interactions

One of the droplet/GDM interactions observed may affect departure droplet diameter. In this interaction, a droplet is observed growing through a GDM sample and deforming under the influence of the airflow. As the droplet continues to grow, the advancing droplet edge breaks on the GDM surface, which increases the droplet/GDM contact area. The droplet continues to grow at this location and once again is deformed by the airflow until it reaches a critical diameter. The following image sequences show this behavior on both GDM Samples A and B, and although this effect appears to be subtle on the GDM Sample A departure droplet diameter (Figure 7.7), it is possible that the droplet on the GDM Sample B (Figure 7.8) would have sheared at a smaller departure diameter if the advancing edge of this droplet had not broken as the droplet was undergoing its initial shear deformation.
Figure 7.7. Advancing droplet edge breaking on the GDM Sample A surface. $\Delta t$ is the time elapsed between each frame. Video: 7_27\Run_6. Air: 714 CCM; Water: 0.56 mL/min.
Another typical behavior observed is that of a droplet growing to a certain size and moving downstream to another location on the GDM surface. Often the droplet only moves a short distance from the active pore site from which it first emanated, with the subsequent smaller droplets feeding it to critical size. This behavior is shown in Figure 7.9.
Figure 7.9. Feeder drop and main drop merging. GDM Sample A. Video: 7_26\Run_5. Air: 351 CCM; Water: 0.28 mL/min.

An extreme case of this behavior was observed for the GDM Sample C. In this case, a droplet appears to form on the GDM surface, and it moves relatively far downstream until it
gets stuck on a GDM location. As shown in Figure 7.10 it continues to grow to a critical size, but it appears that a droplet is feeding it from its initial emergence location through a long water film. The sequence of images that follows shows this behavior although it is difficult to discern the small droplet (white arrow in Frame 1212) feeding into the larger water formation from the still images.
At $\Delta t = 0.002$ sec; Frame 1299

At $\Delta t = 0.013$ sec; Frame 1312

At $\Delta t = 0.059$ sec; Frame 1371

At $\Delta t = 0.058$ sec; Frame 1429

Figure 7.10. Droplet departure near channel center. GDM Sample C.
Video: 3/25 Run 1. Air: 714 CCM; Water: 1.12 mL/min.

The next example is of a drop shearing from one location and then sliding along the GDM to another location where it becomes stuck. Also illustrated by this video is the effect of water slugs on departure diameter and water splashing back onto the GDM during water slug/droplet interactions.

First a droplet grows to a certain size at which time it shears off. This drop is large (Frame 2451) with respect to the channel cross section measuring 0.83 mm in diameter +/- 0.03 mm, and it only moves slightly down the channel before it collides with the wall. This process continues until a water slug forms underneath the active departure site effectively
reducing the channel height by half. The reduction in departure diameter is evident in the sequence of frames showing the departure, movement and droplet re-attachment (Frames 3932 to 4195). The drop at the re-attachment location does not grow but instead remains attached to the GDM until it is removed through channel-water/droplet interaction. The sequence of images in Figure 7.11 is taken from the video 8_26\Run_9 in which the air flow rate was 48 CCM and the water flow rate was 1.12 mL/min. A complete description of this video can be found in the Appendix under Sample B Datasheets (8/26/2004, Run 9).
Figure 7.11. Video of droplet shear and re-attachment. Video: 8_26\Run_9. $\Delta t$ is the time elapsed between each frame. Air: 48 CCM; Water: 1.12 mL/min.

Frame 5373 shows the same drop that is seen in Frame 4195. The increased size of the water slug pushes the drop to the right but doesn’t shear it off. Instead the drop is pulled
into the slug, and a small portion of it is splashed back onto the GDM as shown in the sequence of images in Figure 7.12. Note that this sequence starts from the last frame in Figure 7.11.
At \( \Delta t = 0.001 \) sec; Frame 5379

Figure 7.12. Water droplet splashing back onto GDM. Video: 8_26\Run_9. \( \Delta t \) is the time elapsed between each frame. Air: 48 CCM; Water: 1.12 mL/min.

A close examination of the GDM surface surrounding these locations is necessary in order to explain the reasons for such behavior.

7.4 Two-Phase Flow Pattern Comparisons

The flow patterns observed for the three GDM samples are presented in this section. The video images from similar channel locations and air and water flow rates are compared with a single frame from the high-speed videos selected for each GDM sample in order to illustrate differences or similarities in flow patterns for given flow conditions at a given channel location. The channel locations are given in centimeters from the inlet end of the test section. For all images, air flow is from left to right and gravity is in the plane of the page pointing down. The black arrows in the following figures indicate the edge-view of the GDM (which is the edge-view of the top channel wall).

Water droplets were observed for all three GDM samples at the air and water flow rates presented in Figure 7.13, but the Sample C GDM produced a much larger departure droplet diameter than did Sample A or B.
Figure 7.13. Air/Water flow patterns near channel entrance.
Sample A

6 cm; Air: 351 CCM; Water: 0.56 mL/min (7/26/04 Run 3)

Sample B

4 cm; Air: 351 CCM; Water: 0.56 mL/min (9/02/04 Run 1)

Sample C

4 cm; Air: 351 CCM; Water: 0.56 mL/min (3/29/05 Run 6)

**Figure 7.14. Air/Water flow patterns near channel entrance.**

In Figure 7.14, the GDM Sample A produces a droplet that grows to the size seen until it touches the channel sidewall. Although there is more water present in the figure for Sample B than that of Sample A, the Sample B GDM still produces isolated droplets on the GDM surface (the white arrows indicate an isolated droplet location). Sample C GDM shows a droplet sliding on the GDM surface. The white arrow in the Sample C image indicates the location where water is coming through the GDM. It is clear that this region is much less droplet shaped than the droplets in the other GDM sample images. This could be the result of several active pores in the same region.
Sample A

6 cm; Air: 351 CCM; Water: 0.28 mL/min (7/26/04 Run 12)

Sample B

3 cm; Air: 351 CCM; Water: 0.28 mL/min (9/03/04 Run 4)

Sample C

3 cm; Air: 351 CCM; Water: 0.28 mL/min (3/28/05 Run 7)

**Figure 7.15. Air/Water flow patterns near channel entrance.**

Similar air/water flow patterns are observed for all three GDM sample images in Figure 7.15. Isolated water droplets are observed emerging from the GDM.
Figure 7.16. Air/Water flow patterns near channel entrance.

Figure 7.16 shows a comparison of GDM Sample B and C. The Sample B image shows a wave formation that has formed from a water slug that has grown to nearly block the channel. This wave flows through the channel and knocks off the water drop seen in the Sample B image. The Sample C image shows water lumps on the GDM surface. There are no water droplets seen in the Sample C image, and there appears to be an air-core type flow starting to form – water on the channel walls with air flowing through the center.
Sample B

4 cm; Air: 175 CCM; Water: 0.56 mL/min (8/31/04 Run 7)

Sample C

4 cm; Air: 175 CCM; Water: 0.56 mL/min (3/31/05 Run 8)

**Figure 7.17.** Air/Water flow patterns near channel entrance.

The Figure 7.17 images also show droplets formed for the GDM Sample B and no droplets for the GDM Sample C. There does not seem to be an air-core type flow in this section of the channel under the given flow conditions for GDM Sample C, but there is water present on the channel bottom, sidewalls and top channel corners.

Figure 7.18 shows a clear difference in GDM performance behavior for the GDM Samples B and C. Under the given flow conditions isolated droplets form on the surface of GDM Sample B, but no droplets are seen on GDM Sample C. A clear air-core type flow is seen in the GDM Sample C image of Figure 7.18. This flow pattern could lead to an under performing cathode gas channel as the reactant gas would not be able to reach as many reaction sites due to the layer of water flowing on the GDM surface.
Sample B

6 cm; Air: 88 CCM; Water: 1.12 mL/min (8/30/04 Run 7)

Sample C

4 cm; Air: 88 CCM; Water: 1.12 mL/min (4/11/05 Run 5)

Figure 7.18. Air/Water flow patterns near channel entrance.

Sample B

5 cm; Air: 88 CCM; Water: 0.56 mL/min (8/30/04 Run 17)

Sample C

3 cm; Air: 88 CCM; Water: 0.56 mL/min (4/11/05 Run 1)

Figure 7.19. Air/Water flow patterns near channel entrance.
Figure 7.19 shows the same general patterns as seen in Figure 7.18, for the same air flow rate and half the water flow rate. A layer of water is present on the Sample C GDM surface.

Sample B

[Image of Sample B]

4 cm; Air: 48 CCM; Water: 1.12 mL/min (8/26/04 Run 3)

Sample C

[Image of Sample C]

4 cm; Air: 48 CCM; Water: 1.12 mL/min (4/12/05 Run 1)

Figure 7.20. Air/Water flow patterns near channel entrance.

For the lowest air flow rate, water was observed flowing as a lump on the GDM surface as seen in the Sample C image of Figure 7.20. This flow pattern could lead to an under performing cathode gas channel as the reactant gas would not be able to reach as many reaction sites due to the layer of water flowing on the GDM surface. The GDM sample B still produced water droplets for these flow conditions. Similar patterns are seen in the images of Figure 7.21 for the GDM Samples B and C.
Sample B

4 cm; Air: 48 CCM; Water: 0.56 mL/min (8/27/04 Run 5)

Sample C

4 cm; Air: 48 CCM; Water: 0.56 mL/min (4/12/05 Run 6)

Figure 7.21. Air/Water flow patterns near channel entrance.
Sample A

15.5 cm; Air: 714 CCM; Water: 1.12 mL/min (7/27/04 Run 7)

Sample B

10 cm; Air: 714 CCM; Water: 1.12 mL/min (9/03/04 Run 8)

Sample C

10 cm; Air: 714 CCM; Water: 1.12 mL/min (3/24/05 Run 1)

Figure 7.22. Air/Water flow patterns near channel middle.

Figure 7.22 shows flow patterns near the channel middle. Like the images of Figure 7.13, water droplets were observed for all three GDM samples at the given air and water flow rates, but the Sample C GDM produced a much larger departure droplet diameter than did Sample A or B.
Sample A

15.5 cm; Air: 714 CCM; Water: 0.56 mL/min (7/27/04 Run 6)

Sample B

9 cm; Air: 714 CCM; Water: 0.56 mL/min (9/06/04 Run 5)

Sample C

10 cm; Air: 714 CCM; Water: 0.56 mL/min (3/25/05 Run 5)

Figure 7.23. Air/Water flow patterns near channel middle.

There doesn’t appear to be much distinction between the GDM samples in the images of Figure 7.23. However, there appears to be more water near the GDM surface of Sample C than the other two samples.
Sample A

20.5 cm; Air: 351 CCM; Water: 0.28 mL/min (7/26/04 Run 4)

Sample B

10 cm; Air: 351 CCM; Water: 0.28 mL/min (9/02/04 Run 6)

Sample C

11 cm; Air: 351 CCM; Water: 0.28 mL/min (3/29/05 Run 1)

Figure 7.24. Air/Water flow patterns near channel middle.

Water droplets are seen in the images of Figure 7.24 for GDM Sample A and B but not for Sample C. A large water lump is present on the GDM Sample C surface and water is seen in the top channel corner and draining down the channel sidewall.
In Figure 7.25, water droplets are seen on the GDM surface of Samples A and B but not Sample C. GDM Sample C formed no droplets under these flow conditions, and instead showed signs of a classic two-phase flow pattern seen in solid-walled microchannels and minichannels. The type of flow seen in the GDM Sample C image of Figure 7.25 is referred to as "slug-annular flow" or "liquid ring flow" by Kawaji and Chung (2003). This flow pattern could lead to an under performing cathode gas channel as the reactant gas would not be able to reach as many reaction sites due to the layer of water flowing on the GDM surface.
Sample A

16.5 cm; Air: 175 CCM; Water: 0.56 mL/min (8/09/04 Run 6)

Sample B

10 cm; Air: 175 CCM; Water: 0.56 mL/min (8/31/04 Run 10)

Sample C

16 cm; Air: 175 CCM; Water: 0.56 mL/min (3/31/05 Run 11)

Figure 7.26. Air/Water flow patterns near channel middle.

As in Figure 7.25, water droplets are seen in the images of Figure 7.26 on the GDM surface of Samples A and B but not Sample C. GDM Sample C formed no droplets under these flow conditions, and also showed signs of a classic two-phase flow pattern seen in solid-walled microchannels and minichannels. The type of flow seen in the GDM Sample C image of Figure 7.26 is referred to as “liquid lump flow” by Kawaji and Chung (2003). This flow pattern could lead to an under performing cathode gas channel as the reactant gas would not be able to reach as many reaction sites due to the layer of water flowing on the GDM surface.
Sample A

16.5 cm; Air: 175 CCM; Water: 0.28 mL/min (8/10/04 Run 1)

Sample B

9.5 cm; Air: 175 CCM; Water: 0.28 mL/min (8/31/04 Run 6)

Sample C

12 cm; Air: 175 CCM; Water: 0.28 mL/min (3/31/05 Run 14)

Figure 7.27. Air/Water flow patterns near channel middle.

Water droplets are seen in the images of Figure 7.27 on the GDM surface of Samples A and B but not Sample C. GDM Sample C formed no droplets under these flow conditions, but water was observed flowing in the channel corners and down the channel sidewall.
Sample B

11 cm; Air: 88 CCM; Water: 1.12 mL/min (8/30/04 Run 5)

Sample C

11 cm; Air: 88 CCM; Water: 1.12 mL/min (4/11/05 Run 6)

Figure 7.28. Air/Water flow patterns near channel middle.

Water droplets are seen in the images of Figure 7.28 on the GDM surface of Sample B but not Sample C. GDM Sample C formed no droplets under these flow conditions. Sample C showed signs of a classic two-phase flow pattern seen in solid-walled microchannels and minichannels referred to as “plug/slug flow” by Kawaji and Chung (2003). As in some of the previous cases, this flow pattern could lead to an under performing cathode gas channel as the reactant gas would not be able to reach as many reaction sites due to the layer of water flowing on the GDM surface. Similar flow patterns are seen in the images of Figures 7.29 and 7.30.
Sample B

10 cm; Air: 88 CCM; Water: 0.56 mL/min (8/31/04 Run 1)

Sample C

10 cm; Air: 88 CCM; Water: 0.56 mL/min (4/11/05 Run 2)

Figure 7.29. Air/Water flow patterns near channel middle.

Sample B

9.5 cm; Air: 88 CCM; Water: 0.28 mL/min (8/31/04 Run 4)

Sample C

10 cm; Air: 88 CCM; Water: 0.28 mL/min (4/01/05 Run 1)

Figure 7.30. Air/Water flow patterns near channel middle.
In Figure 7.31, water droplets are seen on the surface of GDM Sample B but not on GDM Sample C. The section of GDM Sample C that is visible in the images of Figure 7.31 is covered by a thick layer of flowing water. This flow pattern could lead to an underperforming cathode gas channel as the reactant gas would not be able to reach as many reaction sites due to the layer of water flowing on the GDM surface. Similar flow patterns are seen in the images of Figures 7.32 and 7.33.
Sample B
12 cm; Air: 48 CCM; Water: 0.56 mL/min (8/27/04 Run 4)

Sample C
11 cm; Air: 48 CCM; Water: 0.56 mL/min (4/12/05 Run 7)

Figure 7.32. Air/Water flow patterns near channel middle.

Sample B
15 cm; Air: 48 CCM; Water: 0.28 mL/min (8/27/04 Run 8)

Sample C
11 cm; Air: 48 CCM; Water: 0.28 mL/min (4/12/05 Run 11)

Figure 7.33. Air/Water flow patterns near channel middle.
In Figure 7.34, water droplets are seen on the surface of GDM Sample A but not on GDM Sample C. The section of GDM Sample C that is visible in the images of Figure 7.34 is almost completely covered by a layer of flowing water. This flow pattern could lead to an under performing cathode gas channel as the reactant gas would not be able to reach as many reaction sites due to the layer of water flowing on the GDM surface.
Sample A

23 cm; Air: 714 CCM; Water: 0.56 mL/min (7/27/04 Run 3)

Sample C

24 cm; Air: 714 CCM; Water: 0.56 mL/min (3/25/05 Run 10)

Figure 7.35. Air/Water flow patterns near channel exit.

Figure 7.35 shows droplet activity on the GDM surface for Sample A but not for Sample C. The GDM Sample C image of Figure 7.35 shows water flowing in the channel corners and draining down the channel sidewall.
Sample B

20 cm; Air: 351 CCM; Water: 1.12 mL/min (9/01/04 Run 6)

Sample C

25 cm; Air: 351 CCM; Water: 1.12 mL/min (3/30/05 Run 11)

Figure 7.36. Air/Water flow patterns near channel exit.

Figure 7.36 shows droplet activity on the GDM surface for Sample B but not for Sample C. A lump of water can be seen flowing on the surface of the GDM Sample C, and it looks as if an air-core type flow is starting. This flow pattern could lead to an under performing cathode gas channel as the reactant gas would not be able to reach as many reaction sites due to the layer of water flowing on the GDM surface.
Sample A

25 cm; Air: 351 CCM; Water: 0.56 mL/min (7/26/04 Run 2)

Sample C

26 cm; Air: 351 CCM; Water: 0.56 mL/min (3/30/05 Run 2)

Figure 7.37. Air/Water flow patterns near channel exit.

In Figure 7.37, water droplets are seen on the surface of GDM Sample A but not on GDM Sample C. The section of GDM Sample C that is visible in the images of Figure 7.37 is almost completely covered by a layer of water of varying thickness. This flow pattern could lead to an under performing cathode gas channel as the reactant gas would not be able to reach as many reaction sites due to the layer of water flowing on the GDM surface. Similar patterns are seen in Figures 7.38 and 7.39.
Sample A

23 cm; Air: 351 CCM; Water: 0.28 mL/min (7/26/04 Run 6)

Sample C

25 cm; Air: 351 CCM; Water: 0.28 mL/min (3/29/05 Run 4)

Figure 7.38. Air/Water flow patterns near channel exit.

Sample B

23 cm; Air: 88 CCM; Water: 1.12 mL/min (8/30/04 Run 1)

Sample C

25 cm; Air: 88 CCM; Water: 1.12 mL/min (4/11/05 Run 8)

Figure 7.39. Air/Water flow patterns near channel exit.
In Figure 7.40, water droplets are seen on the surface of GDM Sample B but not on GDM Sample C. The flow pattern seen in the image of GDM Sample C of Figure 7.40 is of the “plug/slug flow” type described by Kawaji and Chung (2003). This flow pattern could lead to an under performing cathode gas channel as the reactant gas would not be able to reach as many reaction sites due to the layer of water flowing on the GDM surface. Similar patterns are seen in Figure 7.41.
Sample B

25 cm; Air: 48 CCM; Water: 1.12 mL/min (8/26/04 Run 10)

Sample C

25 cm; Air: 48 CCM; Water: 1.12 mL/min (4/12/05 Run 5)

Figure 7.41. Air/Water flow patterns near channel exit.

Sample B

25 cm; Air: 48 CCM; Water: 0.56 mL/min (8/27/04 Run 2)

Sample C

25 cm; Air: 48 CCM; Water: 0.56 mL/min (4/12/05 Run 9)

Figure 7.42. Air/Water flow patterns near channel exit.
In Figure 7.42, water droplets are seen on the surface of GDM Sample B but not on GDM Sample C. The flow pattern seen in the image of GDM Sample C of Figure 7.42 is of the “liquid lump flow” type described by Kawaji and Chung (2003). This flow pattern could lead to an under performing cathode gas channel as the reactant gas would not be able to reach as many reaction sites due to the layer of water flowing on the GDM surface.

7.5 Experimental Two-Phase Pressure Drop Measurements

Pressure measurements were obtained across the minichannel. Figure 7.43 shows a plot of pressure drop across the test section at the different air flow rates for the GDM Samples B and C. Note that the effect of water in the channel on pressure drop can be seen as the pressure drop increases not only with increasing air flow rate, but also with increasing water flow rate. It appears that the flow patterns seen in the GDM Sample C data lead to a lower pressure drop across the test section than the flow patterns observed in the GDM Sample B experiments.

![Figure 7.43](image)

Figure 7.43. Experimental pressure drop as a function of actual air flow rate with water flow rate indicated. GDM Sample B and C comparison.
The two-phase pressure drop correlations defined in Section 2 are used to obtain the theoretical two-phase pressure drop values for the air and water flows studied in the present work. Since the two phases are not mixed before entering the test section minichannel, half of the water flow rate is used to calculate the average vapor mass fraction \( x \) in the test section for the frictional pressure drop calculations. However, Chisholm (1983) specifies the exit vapor mass fraction for use in Equation (2.14), so the full water flow rate is used in calculating the vapor mass fraction for the pressure drop due to momentum flux.

The experimental two-phase frictional pressure drop data from the GDM Sample B and C experiments are shown on the theoretical frictional pressure drop vs. superficial gas velocity plots given by Figures 7.44 – 7.46.

![Figure 7.44. Pressure drop as a function of superficial gas velocity. 0.28 mL/min water flow rate. Experimental and theoretical comparison, GDM Sample B and C.](image-url)
Figure 7.45. Pressure drop as a function of superficial gas velocity. 0.56 mL/min water flow rate. Experimental and theoretical comparison, GDM Sample B and C.
Figure 7.46. Pressure drop as a function of superficial gas velocity. 1.12 mL/min water flow rate. Experimental and theoretical comparison, GDM Sample B and C.

The Chisholm (1973) correlation fits the experimental frictional pressure drop data best for the GDM Sample B for the case of the 0.28 mL/min water flow rate. At this same water flow rate, the experimental frictional pressure drop data for the GDM Sample C agrees well with the Chisholm (1967) correlation derived from the work of Lockhart and Martinelli (1949) with $C = 5$ and also with Mishima and Hibiki (1996) modification with $C = 6.12$. In fact, many of the correlations agree within experimental uncertainty with the GDM Sample C data for superficial gas velocities of 5 m/s and below.

At the 0.56 mL/min water flow rate, several of the correlations still agree with the experimental pressure drop data for GDM Sample C for superficial gas velocities of 2.5 m/s and below, but above that velocity the experimental pressure drop data for GDM Sample C is bounded by the Chisholm (1967) correlation with $C = 5$ and the Chen et al. (2001) correlation. The experimental pressure drop data for the GDM Sample B is bounded by the
Chisholm (1973) correlation with \( n = 1 \) and Mishima and Hibiki (1996) with \( C = 6.12 \) for superficial gas velocities at or below 5 m/s, however, at the 10 m/s superficial gas velocity the GDM Sample B experimental pressure drop is bounded on the low side by the Chisholm (1967) correlation with \( C = 12 \). The parameter \( C = 12 \) is suggested for two-phase flows where the liquid phase is laminar and the gas phase is turbulent, which could point to a possible early transition to turbulent flow for the gas phase at the higher superficial gas velocity.

For the highest water flow rate, 1.12 mL/min, the GDM Sample C experimental pressure drop data is well represented by both the Chen et al. (2001) correlation and the Lee and Lee (2001) correlation. The GDM Sample B experimental data is represented fairly well by the Mishima and Hibiki (1996) correlation with \( C = 6.12 \) for gas superficial velocities of 2.5 m/s and below and then by the Chisolm (1967) correlation with \( C = 12 \) for the higher superficial velocities, although the experimental data points are under predicted with increasing superficial gas velocity.

The comparison of the experimental pressure drop data for the different flow types observed for the GDM Sample B and C shows that the existing theoretical two-phase frictional pressure drop correlations are useful for predicting two-phase pressure drop for these flows. For all the water flow rates (Figures 7.44 – 7.46), the correlations presented in Section 2 provide an upper and lower bound for the experimental pressure drop data.
8. CONCLUSIONS

An experimental investigation has been performed in order to better understand the mechanisms of water transport in a PEMFC cathode minichannel. A rectangular minichannel was constructed with an optically transparent sidewall so that high-speed images could be obtained of water emerging through a given GDM sample and into a channel of flowing air. The following conclusions have been drawn from the present work:

1. The mechanism of water droplet departure from a hydrophobic diffusion media surface has been identified for an isolated droplet growing from a discrete location. It can be described as a droplet that grows to a critical size until it is sheared from the GDM surface due to the force of the air. Droplets undergo different degrees of deformation depending on air flow rate, GDM surface wetability, and local GDM surface geometry, but generally take the form of Figure 6.1 at the onset of departure. The range of departure droplet diameters observed in the present work is summarized in Table 7.1 for the three GDM samples tested.

2. Droplets were seen emerging from the same location on the GDM over time indicating the presence of preferential water pore locations. This behavior was observed in an operating fuel cell as reported in the work of Yang et al. (2004).

3. Water droplets sticking to certain regions of the GDM have been observed. Droplets were seen emerging from one location and then sliding to another location and stopping. These droplets continued to grow at their new locations by being fed from water droplets at the original location. This behavior was typically observed when the growing drop and the feeder drop were in fairly close proximity, but there was at least one instance observed of this activity over a longer distance with GDM Sample C.

4. Differences were observed between the three GDM samples. Samples A and B behaved generally the same with respect to discrete droplet formation, although the Sample B departure droplet diameter data show more spread. Sample C showed very
little droplet formation, and instead showed two-phase flow patterns that are
indicative of GDM flooding. Often, much of the surface of the GDM Sample C was
completely covered with a thick layer of flowing water, which would render an in-situ
fuel cell cathode channel inoperable.

5. There is relatively little spread in the advancing contact angle data with
increasing departure droplet diameter, but the receding contact angle is influenced by
air flow rate for a given departure droplet diameter. Receding contact angles are
difficult to quantify in a meaningful way due to the strong influence air flow rate has
on this droplet feature. The range of contact angles observed in the present work are
summarized in Tables 7.2 and 7.3 for the three GDM samples.

6. Flow patterns typically ascribed to horizontal two-phase, air-water flows were
observed for many of the flow conditions with GDM Sample C. However, GDM
Samples A and B displayed different patterns, with the main difference being the
water droplets emerging through the GDM and interacting with water slugs in the gas
channel.

7. Experimental pressure drop measurements for the type of flow seen in the GDM
Sample B experiment were observed to be much higher than the GDM Sample C
measurements. For the GDM Sample B, the Chisholm (1973) correlation fits the
experimental data best at the 0.28 mL/min water flow rate, but for the same water
flow rate, the Chisholm (1967) correlation with $C = 5$ is a better fit for the GDM
Sample C experimental pressure drop data.

8. At the 0.56 mL/min water flow rate, the GDM Sample B experimental pressure
drop data fall nearly in the middle of two correlations with Chisholm (1973)
providing the upper bound and a combination of Mishima and Hibiki (1996) with $C =
6.12$ and Chisholm (1967) with $C = 12$ forming the lower bound. The GDM Sample
C experimental pressure drop data is bounded by Chisholm (1967) with $C = 5$ and
Lee and Lee (2001) for the 0.56 mL/min water flow rate.
9. At the highest water flow rate, nearly all of the GDM Sample C experimental pressure drop data can be described by either the Lee and Lee (2001) correlation or the Chen (2001) correlation within experimental uncertainties. The GDM Sample B experimental pressure drop data closely follow a combination of the Mishima and Hibiki (1996) correlation with $C = 6.12$ and the Chisholm (1967) correlation with $C = 12$ which could indicate a transition to turbulent gas flow at the higher superficial gas velocities.
REFERENCES


ADDITIONAL REFERENCES


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APPENDIX A: Pressure Transducer Calibration

Figures 4.6 and 4.7 are combined below and the pressure sensors used in the present work are indicated.

![Diagram of pressure transducer calibration setup]

### Location vs. Δp DP01

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### Pressure (psi) vs. Voltage (mV)

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#### 0-5 psi, Channel Pressure Drop DP01

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\[ R^2 = 0.99999 \]
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P02
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0-15 psi, System Line Pressure P02

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<th>Location:</th>
<th>Rotameter Inlet P01</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range:</td>
<td>0 - 30 psi</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Pressure (psi)</th>
<th>Voltage (mV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>0.09996</td>
</tr>
<tr>
<td>28</td>
<td>0.09401</td>
</tr>
<tr>
<td>26</td>
<td>0.08741</td>
</tr>
<tr>
<td>24</td>
<td>0.08077</td>
</tr>
<tr>
<td>22</td>
<td>0.07413</td>
</tr>
<tr>
<td>20</td>
<td>0.06749</td>
</tr>
<tr>
<td>18</td>
<td>0.0609</td>
</tr>
<tr>
<td>16</td>
<td>0.05421</td>
</tr>
<tr>
<td>14</td>
<td>0.04761</td>
</tr>
<tr>
<td>12</td>
<td>0.04097</td>
</tr>
<tr>
<td>10</td>
<td>0.03433</td>
</tr>
<tr>
<td>8</td>
<td>0.02769</td>
</tr>
<tr>
<td>6</td>
<td>0.0211</td>
</tr>
<tr>
<td>4</td>
<td>0.01441</td>
</tr>
<tr>
<td>2</td>
<td>0.00781</td>
</tr>
<tr>
<td>0</td>
<td>0.00117</td>
</tr>
</tbody>
</table>

For the range 0-30 psi, Rotameter Inlet P01, the data can be fitted to a linear equation:

\[ y = 302.23118x - 0.37544 \]

where \( y \) is the voltage in mV and \( x \) is the pressure in psi. The coefficient of determination, \( R^2 \), is 0.99997, indicating a very strong linear relationship between pressure and voltage.
<table>
<thead>
<tr>
<th>Pressure (psi)</th>
<th>Voltage (mV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>0.05132</td>
</tr>
<tr>
<td>4.5</td>
<td>0.04634</td>
</tr>
<tr>
<td>4</td>
<td>0.04141</td>
</tr>
<tr>
<td>3.5</td>
<td>0.03638</td>
</tr>
<tr>
<td>3</td>
<td>0.03143</td>
</tr>
<tr>
<td>2.5</td>
<td>0.02642</td>
</tr>
<tr>
<td>2</td>
<td>0.02139</td>
</tr>
<tr>
<td>1.5</td>
<td>0.01636</td>
</tr>
<tr>
<td>1</td>
<td>0.01133</td>
</tr>
<tr>
<td>0.5</td>
<td>0.0063</td>
</tr>
<tr>
<td>0</td>
<td>0.00127</td>
</tr>
</tbody>
</table>

\[ y = 99.86665x - 0.13239 \]

\[ R^2 = 0.99999 \]
APPENDIX B: Syringe Pump Calibration

Minitab Output for Syringe Pump Calibration

**Descriptive Statistics: 0.28 Pump Setting**

<table>
<thead>
<tr>
<th>Variable</th>
<th>N</th>
<th>N*</th>
<th>Mean</th>
<th>SE Mean</th>
<th>StDev</th>
<th>Minimum</th>
<th>Q1</th>
<th>Median</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.28</td>
<td>14</td>
<td>0</td>
<td>0.28112</td>
<td>0.000225</td>
<td>0.000840</td>
<td>0.28010</td>
<td>0.28049</td>
<td>0.28092</td>
</tr>
</tbody>
</table>

**Variable Q3 Maximum**

| 0.28     | 0.28204 | 0.28270 |

**Descriptive Statistics: 0.56 Pump Setting**

<table>
<thead>
<tr>
<th>Variable</th>
<th>N</th>
<th>N*</th>
<th>Mean</th>
<th>SE Mean</th>
<th>StDev</th>
<th>Minimum</th>
<th>Q1</th>
<th>Median</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.56</td>
<td>14</td>
<td>0</td>
<td>0.56333</td>
<td>0.000539</td>
<td>0.00202</td>
<td>0.56048</td>
<td>0.56149</td>
<td>0.56365</td>
</tr>
</tbody>
</table>

**Variable Q3 Maximum**

| 0.56     | 0.56452 | 0.56792 |

**Descriptive Statistics: 1.12 Pump Setting**

<table>
<thead>
<tr>
<th>Variable</th>
<th>N</th>
<th>N*</th>
<th>Mean</th>
<th>SE Mean</th>
<th>StDev</th>
<th>Minimum</th>
<th>Q1</th>
<th>Median</th>
<th>Q3</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.12</td>
<td>14</td>
<td>0</td>
<td>1.1279</td>
<td>0.000760</td>
<td>0.00285</td>
<td>1.1216</td>
<td>1.1270</td>
<td>1.1278</td>
<td>1.1287</td>
</tr>
</tbody>
</table>

**Variable Maximum**

| 1.12     | 1.1341 |
APPENDIX C: Data Acquisition System

Pressure data was acquired with a National Instruments Data Acquisition System (DAQ). Raw millivolt signals were recorded from each pressure transducer in the test facility at 5 samples per second, and the data was stored in Excel spreadsheets. The calibration equations from Appendix A were embedded into the LabVIEW graphical user interface for display and monitoring purposes.

The system uses a SCXI-1000 chassis with a SCXI-1303 terminal block, and the LabVIEW software is version 6i.
APPENDIX D: Sample A Datasheets

A typical datasheet entry is shown below and a description is given for the parameters.

Run number for a specific day

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run</td>
<td>14</td>
</tr>
<tr>
<td>Air flow</td>
<td>175 ACCM</td>
</tr>
<tr>
<td>Water flow</td>
<td>1.12 ml/min</td>
</tr>
<tr>
<td>Rec. Rate</td>
<td>1000 fps</td>
</tr>
<tr>
<td>Shutter</td>
<td>1/6000</td>
</tr>
<tr>
<td>Resolution</td>
<td>1024 x 256</td>
</tr>
<tr>
<td>Location</td>
<td>3.5 cm</td>
</tr>
<tr>
<td>Saved</td>
<td>8.19 sec</td>
</tr>
<tr>
<td>Frames</td>
<td>8190 frames</td>
</tr>
<tr>
<td>Lens</td>
<td>Std Nikkon w/2X teleplus</td>
</tr>
<tr>
<td>Name</td>
<td>Run_14_1point12_mL_175CCM</td>
</tr>
<tr>
<td>File Size</td>
<td>1.99 GB</td>
</tr>
<tr>
<td>View</td>
<td>side</td>
</tr>
<tr>
<td>Notes</td>
<td>drop departure fr759; fr1769; fr2716; fr3605; continues until wave at fr4952 after wave, sidewall drop or drop hits sidewall</td>
</tr>
</tbody>
</table>

System time for the pressure data acquisition system computer
Rate at which the high-speed video was recorded (fps)
Location from the compression fixture outer edge to the center of the camera lens
Number of seconds saved
Total number of frames saved
High-speed images taken through channel sidewall
Run: 1
Air flow: 351 ACCM
Water flow: 0.56 mL/min
Rec. Rate: 1000 fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 15 cm
Saved: 8.19 sec
Frames: 8190 frames
Lens: Std Nikkon
Name: Run_1point56_mL_351CCM
File Size: 1.99 GB
View: Bottom
Notes: single drop through film on bottom

Run: 2
Air flow: 351 ACCM
Water flow: 0.56 mL/min
Rec. Rate: 500 fps
Shutter: 1/5000
Resolution: 1024 x 256
Location: 14 cm
Saved: 16.38 sec
Frames: 8190 frames
Lens: Std Nikkon
Name: Run_2point56_mL_351CCM
File Size: 1.99 GB
View: Bottom
Notes: same as in run2 but it looks like one through and one from side

Run: 3
Air flow: 351 ACCM
Water flow: 0.56 mL/min
Rec. Rate: 500 fps
Shutter: 1/5000
Resolution: 1024 x 256
Location: 14 cm
Saved: 16.38 sec
Frames: 8190 frames
Lens: Std Nikkon
Name: Run_3point56_mL_351CCM
File Size: 1.99 GB
View: Bottom
Notes: two drops very close together possibly one drop through and one drop trapped

Run: 4
Air flow: 351 ACCM
Water flow: 0.56 mL/min
Rec. Rate: 500 fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 13 cm
Saved: 16.38 sec
Frames: 8190 frames
Lens: Std Nikkon w/2X teleplus
Name: Run_4point56_mL_351CCM
File Size: 1.99 GB
View: Bottom
Notes: no droplet activity

Run: 5
Air flow: 351 ACCM
Water flow: 1.12 mL/min
Rec. Rate: 500 fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 16 cm
Saved: 16.38 sec
Frames: 8190 frames
Lens: Std Nikkon w/2X teleplus
Name: Run_5_1point12_mL_351CCM
File Size: 1.99 GB
View: Bottom
Notes: Single drop just outside of film patch

Run: 6
Air flow: 351 ACCM
Water flow: 1.12 mL/min
Rec. Rate: 500 fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 16 cm
Saved: 16.38 sec
Frames: 8190 frames
Lens: Std Nikkon w/2X teleplus
Name: Run_6_1point12_mL_351CCM
File Size: 1.99 GB
View: Bottom
Notes: Single drop through a bottom film patch
<table>
<thead>
<tr>
<th>Run:</th>
<th>7</th>
<th>Run:</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air flow:</td>
<td>351 ACCM</td>
<td>Air flow:</td>
<td>351 ACCM</td>
</tr>
<tr>
<td>Water flow:</td>
<td>1.12 mL/min</td>
<td>Water flow:</td>
<td>2 mL/min</td>
</tr>
<tr>
<td>Rec. Rate:</td>
<td>500 fps</td>
<td>Rec. Rate:</td>
<td>500 fps</td>
</tr>
<tr>
<td>Shutter:</td>
<td>1/6000</td>
<td>Shutter:</td>
<td>1/6000</td>
</tr>
<tr>
<td>Resolution:</td>
<td>1024 x 256</td>
<td>Resolution:</td>
<td>1024 x 256</td>
</tr>
<tr>
<td>Location:</td>
<td>16 cm</td>
<td>Location:</td>
<td>15.5 cm</td>
</tr>
<tr>
<td>Saved:</td>
<td>16.38 sec</td>
<td>Saved:</td>
<td>16.38 sec</td>
</tr>
<tr>
<td>Frames:</td>
<td>8190 frames</td>
<td>Frames:</td>
<td>8190 frames</td>
</tr>
<tr>
<td>Name:</td>
<td>Run_7_1point12_ml_351CCM</td>
<td>Name:</td>
<td>Run_10_2_ml_351CCM</td>
</tr>
<tr>
<td>Notes:</td>
<td>single drop initial break through partial bottom film</td>
<td>Notes:</td>
<td>Single drop with film on channel bottom</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Run:</th>
<th>8</th>
<th>Run:</th>
<th>11</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air flow:</td>
<td>351 ACCM</td>
<td>Air flow:</td>
<td>351 ACCM</td>
</tr>
<tr>
<td>Water flow:</td>
<td>2 mL/min</td>
<td>Water flow:</td>
<td>2 mL/min</td>
</tr>
<tr>
<td>Rec. Rate:</td>
<td>500 fps</td>
<td>Rec. Rate:</td>
<td>500 fps</td>
</tr>
<tr>
<td>Shutter:</td>
<td>1/6000</td>
<td>Shutter:</td>
<td>1/6000</td>
</tr>
<tr>
<td>Resolution:</td>
<td>1024 x 256</td>
<td>Resolution:</td>
<td>1024 x 256</td>
</tr>
<tr>
<td>Location:</td>
<td>16 cm</td>
<td>Location:</td>
<td>17 cm</td>
</tr>
<tr>
<td>Saved:</td>
<td>16.38 sec</td>
<td>Saved:</td>
<td>16.38 sec</td>
</tr>
<tr>
<td>Frames:</td>
<td>8190 frames</td>
<td>Frames:</td>
<td>8190 frames</td>
</tr>
<tr>
<td>Lens:</td>
<td>Std Nikkon w/2X teleplus</td>
<td>Lens:</td>
<td>Std Nikkon w/2X teleplus</td>
</tr>
<tr>
<td>Name:</td>
<td>Run_8_2_ml_351CCM</td>
<td>Name:</td>
<td>Run_10_2_ml_351CCM</td>
</tr>
<tr>
<td>File Size:</td>
<td>1.99 GB</td>
<td>File Size:</td>
<td>1.99 GB</td>
</tr>
<tr>
<td>View:</td>
<td>Bottom</td>
<td>View:</td>
<td>Side</td>
</tr>
<tr>
<td>Notes:</td>
<td>Single drop with continuous film on bottom</td>
<td>Notes:</td>
<td>Single drop interacting with side-wall drop</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Run:</th>
<th>9</th>
<th>Run:</th>
<th>12</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air flow:</td>
<td>351 ACCM</td>
<td>Air flow:</td>
<td>351 ACCM</td>
</tr>
<tr>
<td>Water flow:</td>
<td>2 mL/min</td>
<td>Water flow:</td>
<td>2 mL/min</td>
</tr>
<tr>
<td>Rec. Rate:</td>
<td>500 fps</td>
<td>Rec. Rate:</td>
<td>1000 fps</td>
</tr>
<tr>
<td>Shutter:</td>
<td>1/6000</td>
<td>Shutter:</td>
<td>1/6000</td>
</tr>
<tr>
<td>Resolution:</td>
<td>1024 x 256</td>
<td>Resolution:</td>
<td>1024 x 256</td>
</tr>
<tr>
<td>Location:</td>
<td>14 cm</td>
<td>Location:</td>
<td>16 cm</td>
</tr>
<tr>
<td>Saved:</td>
<td>16.38 sec</td>
<td>Saved:</td>
<td>8.19 sec</td>
</tr>
<tr>
<td>Frames:</td>
<td>8190 frames</td>
<td>Frames:</td>
<td>8190 frames</td>
</tr>
<tr>
<td>Lens:</td>
<td>Std Nikkon w/2X teleplus</td>
<td>Lens:</td>
<td>Std Nikkon w/2X teleplus</td>
</tr>
<tr>
<td>Name:</td>
<td>Run_9_2_ml_351CCM</td>
<td>Name:</td>
<td>Run_10_2_ml_351CCM</td>
</tr>
<tr>
<td>File Size:</td>
<td>1.99 GB</td>
<td>File Size:</td>
<td>1.99 GB</td>
</tr>
<tr>
<td>View:</td>
<td>Bottom</td>
<td>View:</td>
<td>Side</td>
</tr>
<tr>
<td>Notes:</td>
<td>tear drop interacting with side-wall drop</td>
<td>Notes:</td>
<td>Single drop interacting with sidewall draining</td>
</tr>
</tbody>
</table>
### GDM Sample A Datasheet

**7/26/2004**

**Sample A w/Kynar**

<table>
<thead>
<tr>
<th>Run</th>
<th>Airflow</th>
<th>Waterflow</th>
<th>Rec. Rate</th>
<th>Shutter</th>
<th>Resolution</th>
<th>Location</th>
<th>Saved</th>
<th>Frames</th>
<th>Lens</th>
<th>Name</th>
<th>File Size</th>
<th>View</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>351 ACCM</td>
<td>0.56 mL/min</td>
<td>1000 fps</td>
<td>1/6000</td>
<td>1024 x 256</td>
<td>25 cm</td>
<td>8.19 sec</td>
<td>8190 frames</td>
<td>Std Nikkon w/2X teleplus</td>
<td>Run_1_point56_mL_351CCM</td>
<td>1.99 GB</td>
<td>side</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>single drop side wall drops</td>
</tr>
<tr>
<td>2</td>
<td>351 ACCM</td>
<td>0.56 mL/min</td>
<td>1000 fps</td>
<td>1/6000</td>
<td>1024 x 256</td>
<td>25 cm</td>
<td>8.19 sec</td>
<td>8190 frames</td>
<td>Std Nikkon w/2X teleplus</td>
<td>Run_2_point56_mL_351CCM</td>
<td>1.99 GB</td>
<td>side</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>single drop side wall drops</td>
</tr>
<tr>
<td>3</td>
<td>351 ACCM</td>
<td>0.56 mL/min</td>
<td>1000 fps</td>
<td>1/6000</td>
<td>1024 x 256</td>
<td>6 cm</td>
<td>8.19 sec</td>
<td>8190 frames</td>
<td>Std Nikkon w/2X teleplus</td>
<td>Run_3_point56_mL_351CCM</td>
<td>1.99 GB</td>
<td>side</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>single drop growing, then touching side wall</td>
</tr>
<tr>
<td>4</td>
<td>351 ACCM</td>
<td>0.28 mL/min</td>
<td>1000 fps</td>
<td>1/6000</td>
<td>1024 x 256</td>
<td>20.5 cm</td>
<td>8.19 sec</td>
<td>8190 frames</td>
<td>Std Nikkon w/2X teleplus</td>
<td>Run_4_point28_mL_351CCM</td>
<td>1.99 GB</td>
<td>side</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>single drop break off &amp; sticking growing behind sidewall drop</td>
</tr>
<tr>
<td>5</td>
<td>351 ACCM</td>
<td>0.28 mL/min</td>
<td>1000 fps</td>
<td>1/6000</td>
<td>1024 x 256</td>
<td>20.5 cm</td>
<td>8.19 sec</td>
<td>8190 frames</td>
<td>Std Nikkon w/2X teleplus</td>
<td>Run_5_point28_mL_351CCM</td>
<td>1.99 GB</td>
<td>side</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>drop growing, sticking to GDM small drop feeding large drop</td>
</tr>
<tr>
<td>6</td>
<td>351 ACCM</td>
<td>0.28 mL/min</td>
<td>1000 fps</td>
<td>1/6000</td>
<td>1024 x 256</td>
<td>23 cm</td>
<td>8.19 sec</td>
<td>8190 frames</td>
<td>Std Nikkon w/2X teleplus</td>
<td>Run_6_point28_mL_351CCM</td>
<td>1.99 GB</td>
<td>side</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>drop growing, interacts w/side drain and other drop</td>
</tr>
</tbody>
</table>

---

**File Size:** 1.99 GB

**View:** side

**Notes:**
- Run 1: Single drop side wall drops
- Run 2: Single drop side wall drops
- Run 3: Single drop side wall drops
- Run 4: Single drop break off & sticking growing behind sidewall drop
- Run 5: Drop growing, sticking to GDM small drop feeding large drop
- Run 6: Drop growing, interacts with side drain and other drop

---

*D3*
### Sample A w/Kynar

<table>
<thead>
<tr>
<th>Run:</th>
<th>7</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air flow:</td>
<td>351 ACCM</td>
<td>351 ACCM</td>
</tr>
<tr>
<td>Water flow:</td>
<td>0.28 mL/min</td>
<td>0.28 mL/min</td>
</tr>
<tr>
<td>Rec. Rate:</td>
<td>1000 fps</td>
<td>1000 fps</td>
</tr>
<tr>
<td>Shutter:</td>
<td>1/6000</td>
<td>1/6000</td>
</tr>
<tr>
<td>Resolution:</td>
<td>1024 x 256</td>
<td>1024 x 256</td>
</tr>
<tr>
<td>Location:</td>
<td>23 cm</td>
<td>23 cm</td>
</tr>
<tr>
<td>Saved:</td>
<td>8.19 sec</td>
<td>8.19 sec</td>
</tr>
<tr>
<td>Frames:</td>
<td>8190 frames</td>
<td>8190 frames</td>
</tr>
<tr>
<td>Lens:</td>
<td>Std Nikkon w/2X teleplus</td>
<td>Std Nikkon w/2X teleplus</td>
</tr>
<tr>
<td>Name:</td>
<td>Run_7_point28_mL_351CCM</td>
<td>Run_10_point28_mL_351CCM</td>
</tr>
<tr>
<td>File Size:</td>
<td>1.99 GB</td>
<td>1.99 GB</td>
</tr>
<tr>
<td>View:</td>
<td>bottom</td>
<td>bottom</td>
</tr>
<tr>
<td>Notes:</td>
<td>bottom view of Run 6 drop growing, interacts w/side drain and other drop</td>
<td>single drop growing at same location as in Run 9</td>
</tr>
</tbody>
</table>

#### Run 7 Details
- **Water flow:** 0.28 mL/min
- **Rec. Rate:** 1000 fps
- **Location:** 23 cm
- **Saved:** 8.19 sec
- **Frames:** 8190 frames
- **Lens:** Std Nikkon w/2X teleplus
- **Name:** Run_7_point28_mL_351CCM
- **File Size:** 1.99 GB
- **View:** bottom
- **Notes:** bottom view of Run 6 drop growing, interacts w/side drain and other drop

#### Run 10 Details
- **Water flow:** 0.28 mL/min
- **Rec. Rate:** 1000 fps
- **Location:** 23 cm
- **Saved:** 8.19 sec
- **Frames:** 8190 frames
- **Lens:** Std Nikkon w/2X teleplus
- **Name:** Run_10_point28_mL_351CCM
- **File Size:** 1.99 GB
- **View:** bottom
- **Notes:** single drop growing at same location as in Run 9

### Run 8

<table>
<thead>
<tr>
<th>Run:</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air flow:</td>
<td>351 ACCM</td>
</tr>
<tr>
<td>Water flow:</td>
<td>0.28 mL/min</td>
</tr>
<tr>
<td>Rec. Rate:</td>
<td>1000 fps</td>
</tr>
<tr>
<td>Shutter:</td>
<td>1/6000</td>
</tr>
<tr>
<td>Resolution:</td>
<td>1024 x 256</td>
</tr>
<tr>
<td>Location:</td>
<td>23 cm</td>
</tr>
<tr>
<td>Saved:</td>
<td>8.19 sec</td>
</tr>
<tr>
<td>Frames:</td>
<td>8190 frames</td>
</tr>
<tr>
<td>Lens:</td>
<td>Std Nikkon w/2X teleplus</td>
</tr>
<tr>
<td>Name:</td>
<td>Run_8_point28_mL_351CCM</td>
</tr>
<tr>
<td>File Size:</td>
<td>1.99 GB</td>
</tr>
<tr>
<td>View:</td>
<td>bottom</td>
</tr>
<tr>
<td>Notes:</td>
<td>single drop growing seen through water film</td>
</tr>
</tbody>
</table>

#### Run 8 Details
- **Water flow:** 0.28 mL/min
- **Rec. Rate:** 1000 fps
- **Location:** 23 cm
- **Saved:** 8.19 sec
- **Frames:** 8190 frames
- **Lens:** Std Nikkon w/2X teleplus
- **Name:** Run_8_point28_mL_351CCM
- **File Size:** 1.99 GB
- **View:** bottom
- **Notes:** single drop growing seen through water film

### Run 9

<table>
<thead>
<tr>
<th>Run:</th>
<th>9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air flow:</td>
<td>351 ACCM</td>
</tr>
<tr>
<td>Water flow:</td>
<td>0.28 mL/min</td>
</tr>
<tr>
<td>Rec. Rate:</td>
<td>1000 fps</td>
</tr>
<tr>
<td>Shutter:</td>
<td>1/6000</td>
</tr>
<tr>
<td>Resolution:</td>
<td>1024 x 256</td>
</tr>
<tr>
<td>Location:</td>
<td>23 cm</td>
</tr>
<tr>
<td>Saved:</td>
<td>8.19 sec</td>
</tr>
<tr>
<td>Frames:</td>
<td>8190 frames</td>
</tr>
<tr>
<td>Lens:</td>
<td>Std Nikkon w/2X teleplus</td>
</tr>
<tr>
<td>Name:</td>
<td>Run_9_point28_mL_351CCM</td>
</tr>
<tr>
<td>File Size:</td>
<td>1.99 GB</td>
</tr>
<tr>
<td>View:</td>
<td>bottom</td>
</tr>
<tr>
<td>Notes:</td>
<td>single drop growing another single drop pops out @ frame 3246 and frame 6434 and beyond</td>
</tr>
</tbody>
</table>

#### Run 9 Details
- **Water flow:** 0.28 mL/min
- **Rec. Rate:** 1000 fps
- **Location:** 23 cm
- **Saved:** 8.19 sec
- **Frames:** 8190 frames
- **Lens:** Std Nikkon w/2X teleplus
- **Name:** Run_9_point28_mL_351CCM
- **File Size:** 1.99 GB
- **View:** bottom
- **Notes:** another single drop pops out at frame 3246 and frame 6434 and beyond

### Run 11

<table>
<thead>
<tr>
<th>Run:</th>
<th>11</th>
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</thead>
<tbody>
<tr>
<td>Air flow:</td>
<td>351 ACCM</td>
</tr>
<tr>
<td>Water flow:</td>
<td>0.28 mL/min</td>
</tr>
<tr>
<td>Rec. Rate:</td>
<td>1000 fps</td>
</tr>
<tr>
<td>Shutter:</td>
<td>1/6000</td>
</tr>
<tr>
<td>Resolution:</td>
<td>1024 x 256</td>
</tr>
<tr>
<td>Location:</td>
<td>23 cm</td>
</tr>
<tr>
<td>Saved:</td>
<td>8.19 sec</td>
</tr>
<tr>
<td>Frames:</td>
<td>8190 frames</td>
</tr>
<tr>
<td>Lens:</td>
<td>Std Nikkon w/2X teleplus</td>
</tr>
<tr>
<td>Name:</td>
<td>Run_11_point28_mL_351CCM</td>
</tr>
<tr>
<td>File Size:</td>
<td>1.99 GB</td>
</tr>
<tr>
<td>View:</td>
<td>side</td>
</tr>
<tr>
<td>Notes:</td>
<td>single drop growing at same location as in Run 10</td>
</tr>
</tbody>
</table>

#### Run 11 Details
- **Water flow:** 0.28 mL/min
- **Rec. Rate:** 1000 fps
- **Location:** 23 cm
- **Saved:** 8.19 sec
- **Frames:** 8190 frames
- **Lens:** Std Nikkon w/2X teleplus
- **Name:** Run_11_point28_mL_351CCM
- **File Size:** 1.99 GB
- **View:** side
- **Notes:** single drop growing at same location as in Run 10

### Run 12

<table>
<thead>
<tr>
<th>Run:</th>
<th>12</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air flow:</td>
<td>351 ACCM</td>
</tr>
<tr>
<td>Water flow:</td>
<td>0.28 mL/min</td>
</tr>
<tr>
<td>Rec. Rate:</td>
<td>1000 fps</td>
</tr>
<tr>
<td>Shutter:</td>
<td>1/6000</td>
</tr>
<tr>
<td>Resolution:</td>
<td>1024 x 256</td>
</tr>
<tr>
<td>Location:</td>
<td>23 cm</td>
</tr>
<tr>
<td>Saved:</td>
<td>8.19 sec</td>
</tr>
<tr>
<td>Frames:</td>
<td>8190 frames</td>
</tr>
<tr>
<td>Lens:</td>
<td>Std Nikkon w/2X teleplus</td>
</tr>
<tr>
<td>Name:</td>
<td>Run_12_point28_mL_351CCM</td>
</tr>
<tr>
<td>File Size:</td>
<td>1.99 GB</td>
</tr>
<tr>
<td>View:</td>
<td>side</td>
</tr>
<tr>
<td>Notes:</td>
<td>single drop growing in front of back sidewall drop</td>
</tr>
</tbody>
</table>

#### Run 12 Details
- **Water flow:** 0.28 mL/min
- **Rec. Rate:** 1000 fps
- **Location:** 6 cm
- **Saved:** 8.19 sec
- **Frames:** 8190 frames
- **Lens:** Std Nikkon w/2X teleplus
- **Name:** Run_12_point28_mL_351CCM
- **File Size:** 1.99 GB
- **View:** side
- **Notes:** single drop growing in front of back sidewall drop
### Sample A w/Kynar

<table>
<thead>
<tr>
<th>Run</th>
<th>Airflow</th>
<th>Waterflow</th>
<th>Rec. Rate</th>
<th>Shutter</th>
<th>Resolution</th>
<th>Location</th>
<th>Saved</th>
<th>Frames</th>
<th>Lens</th>
<th>Name</th>
<th>File Size</th>
<th>View</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>714 ACCM</td>
<td>0.56 mL/min</td>
<td>1000 fps</td>
<td>1/6000</td>
<td>1024 x 256</td>
<td>23 cm</td>
<td>8.19 sec</td>
<td>8190 frames</td>
<td>Std Nikon w/2X teleplus</td>
<td>Run_1_point56_mL_714CCM</td>
<td>1.99 GB</td>
<td>side</td>
<td>two drops near same location</td>
</tr>
<tr>
<td>2</td>
<td>714 ACCM</td>
<td>0.56 mL/min</td>
<td>1000 fps</td>
<td>1/6000</td>
<td>1024 x 256</td>
<td>22.5 cm</td>
<td>8.19 sec</td>
<td>8190 frames</td>
<td>Std Nikon w/2X teleplus</td>
<td>Run_2_point56_mL_714CCM</td>
<td>1.99 GB</td>
<td>side</td>
<td>single drop sidewall drops present</td>
</tr>
<tr>
<td>3</td>
<td>714 ACCM</td>
<td>0.56 mL/min</td>
<td>1000 fps</td>
<td>1/6000</td>
<td>1024 x 256</td>
<td>23 cm</td>
<td>8.19 sec</td>
<td>8190 frames</td>
<td>Std Nikon w/2X teleplus</td>
<td>Run_3_point56_mL_714CCM</td>
<td>1.99 GB</td>
<td>side</td>
<td>two single drops far apart sidewall drops present location moved just slightly right of Run 2</td>
</tr>
<tr>
<td>4</td>
<td>714 ACCM</td>
<td>0.56 mL/min</td>
<td>1000 fps</td>
<td>1/6000</td>
<td>1024 x 256</td>
<td>16 cm</td>
<td>8.19 sec</td>
<td>8190 frames</td>
<td>Std Nikon w/2X teleplus</td>
<td>Run_4_point56_mL_714CCM</td>
<td>1.99 GB</td>
<td>bottom</td>
<td>one single drop growing and breaking off, water in corner</td>
</tr>
<tr>
<td>5</td>
<td>714 ACCM</td>
<td>0.56 mL/min</td>
<td>1000 fps</td>
<td>1/6000</td>
<td>1024 x 256</td>
<td>16 cm</td>
<td>8.19 sec</td>
<td>8190 frames</td>
<td>Std Nikon w/2X teleplus</td>
<td>Run_5_point56_mL_714CCM</td>
<td>1.99 GB</td>
<td>side</td>
<td>one single drop growing and same location as Run 4</td>
</tr>
<tr>
<td>6</td>
<td>714 ACCM</td>
<td>0.56 mL/min</td>
<td>1000 fps</td>
<td>1/6000</td>
<td>1024 x 256</td>
<td>15.5 cm</td>
<td>8.19 sec</td>
<td>8190 frames</td>
<td>Std Nikon w/2X teleplus</td>
<td>Run_6_point56_mL_714CCM</td>
<td>1.99 GB</td>
<td>side</td>
<td>one single drop growing</td>
</tr>
</tbody>
</table>

**D5**
7/27/2004

Sample A w/Kynar

Run: 7
Air flow: 714 ACCM
Water flow: 1.12 mL/min
Rec. Rate: 1000 fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 15.5 cm
Saved: 8.19 sec
Frames: 8190 frames
Lens: Std Nikkon w/2X teleplus
Name: Run_7_1point12_mL_714CCM
File Size: 1.99 GB
View: side
Notes: one single drop growing

Run: 8
Air flow: 714 ACCM
Water flow: 1.12 mL/min
Rec. Rate: 1000 fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 4.5 cm
Saved: 8.19 sec
Frames: 8190 frames
Lens: Std Nikkon w/2X teleplus
Name: Run_8_1point12_mL_714CCM
File Size: 1.99 GB
View: side
Notes: one single drop growing and shearing off side wall drops

Run: 9
Air flow: 714 ACCM
Water flow: 1.12 mL/min
Rec. Rate: 1000 fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 4.5 cm
Saved: 8.19 sec
Frames: 8190 frames
Lens: Std Nikkon w/2X teleplus
Name: Run_9_1point12_mL_714CCM
File Size: 1.99 GB
View: side
Notes: one single drop growing and sticking to GDM fed by other drops same location as Run 8
Run: 1  
Air flow: 714 ACCM  
Water flow: 1.12 mL/min  
Rec. Rate: 1000 fps  
Shutter: 1/6000  
Resolution: 1024 x 256  
Location: 5 cm  
Saved: 8.19 sec  
Frames: 8190 frames  
Lens: Std Nikon w/2X teleplus  
Name: Run_1_1point12_mL_714CCM  
File Size: 1.99 GB  
View: side  
Notes: one single drop growing and sticking to GDM, fed by drop same location as prev. Run 9

Run: 2  
Air flow: 714 ACCM  
Water flow: 1.12 mL/min  
Rec. Rate: 1000 fps  
Shutter: 1/6000  
Resolution: 1024 x 256  
Location: 5 cm  
Saved: 8.19 sec  
Frames: 8190 frames  
Lens: Std Nikon w/2X teleplus  
Name: Run_2_1point12_mL_714CCM  
File Size: 1.99 GB  
View: side  
Notes: one single drop growing same as in Run 1

Run: 3  
Air flow: 714 ACCM  
Water flow: 1.12 mL/min  
Rec. Rate: 1000 fps  
Shutter: 1/6000  
Resolution: 1024 x 256  
Location: 5 cm  
Saved: 8.19 sec  
Frames: 8190 frames  
Lens: Std Nikon w/2X teleplus  
Name: Run_3_1point12_mL_714CCM  
File Size: 1.99 GB  
View: side  
Notes: one single drop growing same as in Run 2

Run: 4  
Air flow: 714 ACCM  
Water flow: 1.12 mL/min  
Rec. Rate: 1000 fps  
Shutter: 1/6000  
Resolution: 1024 x 256  
Location: 5 cm  
Saved: 8.19 sec  
Frames: 8190 frames  
Lens: Std Nikon w/2X teleplus  
Name: Run_4_1point12_mL_714CCM  
File Size: 1.99 GB  
View: bottom  
Notes: one single drop growing and same as in Run 1-3

Run: 5  
Air flow: 714 ACCM  
Water flow: 1.12 mL/min  
Rec. Rate: 1000 fps  
Shutter: 1/6000  
Resolution: 1024 x 256  
Location: 5 cm  
Saved: 8.19 sec  
Frames: 8190 frames  
Lens: Std Nikon w/2X teleplus  
Name: Run_5_1point12_mL_714CCM  
File Size: 1.99 GB  
View: bottom  
Notes: one single drop growing and same as in Run 4

Run: 6  
Air flow: 714 ACCM  
Water flow: 1.12 mL/min  
Rec. Rate: 1000 fps  
Shutter: 1/6000  
Resolution: 1024 x 256  
Location: 6.5 cm  
Saved: 8.19 sec  
Frames: 8190 frames  
Lens: Std Nikon w/2X teleplus  
Name: Run_6_1point12_mL_714CCM  
File Size: 1.99 GB  
View: bottom  
Notes: one single drop growing and shearing from single pore lighting not great
Sample A w/Kynar

Run: 7
Air flow: 714 ACCM
Water flow: 1.12 mL/min
Rec. Rate: 1000 fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 6.5 cm
Saved: 8.19 sec
Frames: 8190 frames
Lens: Std Nikkon w/2X teleplus
Name: Run_7_1point12_mL_714CCM
File Size: 1.99 GB
View: side
Notes: one single drop growing and shearing from single pore
same as Run 6

Run: 8
Air flow: 714 ACCM
Water flow: 1.12 mL/min
Rec. Rate: 1000 fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 6.5 cm
Saved: 8.19 sec
Frames: 8190 frames
Lens: Std Nikkon w/2X teleplus
Name: Run_8_1point12_mL_714CCM
File Size: 1.99 GB
View: side
Notes: one single drop growing and shearing from single pore
same as Run 7

Run: 9
Air flow: 714 ACCM
Water flow: 1.12 mL/min
Rec. Rate: 1000 fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 16.5 cm
Saved: 8.19 sec
Frames: 8190 frames
Lens: Std Nikkon w/2X teleplus
Name: Run_9_1point12_mL_714CCM
File Size: 1.99 GB
View: side
Notes: one single drop growing and running down sidewall
Run: 1
Air flow: 714 ACCM
Water flow: 1.12 mL/min
Rec. Rate: 1000 fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 22 cm
Saved: 8.19 sec
Frames: 8190 frames
Lens: Std Nikkon w/2X teleplus
Name: Run_1_1point12_mL_714CCM
File Size: 1.99 GB
View: side
Notes: one single drop growing and sticking to GDM
alot of sidwall drops and activity frame 4591 upstream drop

Run: 2
Air flow: 714 ACCM
Water flow: 1.12 mL/min
Rec. Rate: 1000 fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 22 cm
Saved: 8.19 sec
Frames: 8190 frames
Lens: Std Nikkon w/2X teleplus
Name: Run_2_1point12_mL_714CCM
File Size: 1.99 GB
View: side
Notes: one single drop growing and same as Run 1

Run: 3
Air flow: 714 ACCM
Water flow: 1.12 mL/min
Rec. Rate: 2000 fps
Shutter: 1/10000
Resolution: 1024 x 256
Location: 23 cm
Saved: 4.095 sec
Frames: 8190 frames
Lens: Std Nikkon w/2X teleplus
Name: Run_3_1point12_mL_714CCM
File Size: 1.99 GB
View: side
Notes: one single drop growing and draining down side wall drop formation

Run: 4
Air flow: 714 ACCM
Water flow: 1.12 mL/min
Rec. Rate: 1000 fps
Shutter: 1/10000
Resolution: 1024 x 256
Location: 5 cm
Saved: 8.19 sec
Frames: 8190 frames
Lens: Microscope w/2X teleplus
Name: Run_4_1point12_mL_714CCM
File Size: 1.99 GB
View: bottom
Notes: one single drop growing and shearing off

Run: 5
Air flow: 714 ACCM
Water flow: 1.12 mL/min
Rec. Rate: 1000 fps
Shutter: 1/10000
Resolution: 1024 x 256
Location: 5 cm
Saved: 8.19 sec
Frames: 8190 frames
Lens: Microscope w/2X teleplus
Name: Run_5_1point12_mL_714CCM
File Size: 1.99 GB
View: bottom
Notes: one single drop growing and shearing off, same as 4

Run: 6
Air flow: 714 ACCM
Water flow: 1.12 mL/min
Rec. Rate: 1000 fps
Shutter: 1/10000
Resolution: 1024 x 256
Location: 5 cm
Saved: 8.19 sec
Frames: 8190 frames
Lens: Microscope w/2X teleplus
Name: Run_6_1point12_mL_714CCM
File Size: 1.99 GB
View: bottom
Notes: one single drop growing and shearing off, same as 4 and 5
### Sample A w/Kynar

<table>
<thead>
<tr>
<th>Run</th>
<th>Airflow</th>
<th>Waterflow</th>
<th>Rec. Rate</th>
<th>Shutter</th>
<th>Resolution</th>
<th>Location</th>
<th>Saved</th>
<th>Frames</th>
<th>Lens</th>
<th>Name</th>
<th>File Size</th>
<th>View</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>175 ACCM</td>
<td>1.12 mL/min</td>
<td>1000 fps</td>
<td>1/6000</td>
<td>1024 x 256</td>
<td>16.5 cm</td>
<td>8.19 sec</td>
<td>8190 frames</td>
<td>Std Nikkon w/2X teleplus</td>
<td>Run_1_1point12_mL_175CCM</td>
<td>1.99 GB</td>
<td>side</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>175 ACCM</td>
<td>1.12 mL/min</td>
<td>1000 fps</td>
<td>1/6000</td>
<td>1024 x 256</td>
<td>16.5 cm</td>
<td>8.19 sec</td>
<td>8190 frames</td>
<td>Std Nikkon w/2X teleplus</td>
<td>Run_4_1point12_mL_175CCM</td>
<td>1.99 GB</td>
<td>side</td>
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<tr>
<td>2</td>
<td>175 ACCM</td>
<td>1.12 mL/min</td>
<td>1000 fps</td>
<td>1/6000</td>
<td>1024 x 256</td>
<td>16.5 cm</td>
<td>8.19 sec</td>
<td>8190 frames</td>
<td>Std Nikkon w/2X teleplus</td>
<td>Run_2_1point12_mL_175CCM</td>
<td>1.99 GB</td>
<td>side</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>175 ACCM</td>
<td>1.12 mL/min</td>
<td>1000 fps</td>
<td>1/6000</td>
<td>1024 x 256</td>
<td>16.5 cm</td>
<td>8.19 sec</td>
<td>8190 frames</td>
<td>Std Nikkon w/2X teleplus</td>
<td>Run_5_1point12_mL_175CCM</td>
<td>1.99 GB</td>
<td>side</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>175 ACCM</td>
<td>1.12 mL/min</td>
<td>1000 fps</td>
<td>1/6000</td>
<td>1024 x 256</td>
<td>16.5 cm</td>
<td>8.19 sec</td>
<td>8190 frames</td>
<td>Std Nikkon w/2X teleplus</td>
<td>Run_3_1point12_mL_175CCM</td>
<td>1.99 GB</td>
<td>side</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>175 ACCM</td>
<td>0.56 mL/min</td>
<td>1000 fps</td>
<td>1/6000</td>
<td>1024 x 256</td>
<td>16.5 cm</td>
<td>1.538 sec</td>
<td>1538 frames</td>
<td>Std Nikkon w/2X teleplus</td>
<td>Run_6_point56_mL_175CCM</td>
<td>384 MB</td>
<td>side</td>
<td></td>
</tr>
</tbody>
</table>

**Notes:**
- Drop grows and touches bottom film
### GDM Sample A Datasheet

**Baseline Assumptions:**
- **Run:** 7
- Air flow: 175 ACCM
- Water flow: 0.56 mL/min
- Rec. Rate: 1000 fps
- Shutter: 1/6000
- Resolution: 1024 x 256
- Location: 16.5 cm
- Frames: 8190 frames
- Lens: Std Nikkon w/2X teleplus
- Name: Run_7_point56_mL_175CCM
- File Size: 1.99 GB
- View: side
- Notes: drop grows and touches bottom film

**Run:** 8
- Air flow: 175 ACCM
- Water flow: 0.56 mL/min
- Rec. Rate: 1000 fps
- Shutter: 1/6000
- Resolution: 1024 x 256
- Location: 16.5 cm
- Frames: 1222 frames
- Lens: Std Nikkon w/2X teleplus
- Name: Run_8_point56_mL_175CCM
- File Size: 305 MB
- View: side

**Run:** 9
- Air flow: 175 ACCM
- Water flow: 0.56 mL/min
- Rec. Rate: 1000 fps
- Shutter: 1/6000
- Resolution: 1024 x 256
- Location: 16.5 cm
- Frames: 4525 frames
- Lens: Std Nikkon w/2X teleplus
- Name: Run_9_point56_mL_175CCM
- File Size: 1.1 GB
- View: side

**Run** 10
- Air flow: 175 ACCM
- Water flow: 3.28 mL/min
- Rec. Rate: 1000 fps
- Shutter: 1/6000
- Resolution: 1024 x 256
- Location: 16.5 cm
- Frames: 819 frames
- Lens: Std Nikkon w/2X teleplus
- Name: Run_10_3point28_mL_175CCM
- File Size: 1.99 GB
- View: side
- Notes: location slightly different

**Run** 11
- Air flow: 175 ACCM
- Water flow: 3.28 mL/min
- Rec. Rate: 1000 fps
- Shutter: 1/6000
- Resolution: 1024 x 256
- Location: 16.5 cm
- Frames: 8190 frames
- Lens: Std Nikkon w/2X teleplus
- Name: Run_11_3point28_mL_175CCM
- File Size: 1.99 GB
- View: side
- Notes: location same as run 11

**Run** 12
- Air flow: 175 ACCM
- Water flow: 3.28 mL/min
- Rec. Rate: 1000 fps
- Shutter: 1/6000
- Resolution: 1024 x 256
- Location: 16.5 cm
- Frames: 819 frames
- Lens: Std Nikkon w/2X teleplus
- Name: Run_12_3point28_mL_175CCM
- File Size: 1.99 GB
- View: side
- Notes: location same as run 11
8/9/2004

Sample A w/Kynar

Run: 13
Air flow: 175 ACCM
Water flow: 3.28 mL/min
Rec. Rate: 1000 fps
Shutter: 1/20000
Resolution: 1024 x 256
Location: 16.5 cm
Saved: 8.19 sec
Frames: 8190 frames
Lens: Std Nikkon w/2X teleplus
Name: Run_13_3point28_mL_175CCM
File Size: 1.99 GB
View: side
Notes: location same as run 12

Run: 14
Air flow: 175 ACCM
Water flow: 2.28 mL/min
Rec. Rate: 1000 fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 16.5 cm
Saved: 2.625 sec
Frames: 2625 frames
Lens: Std Nikkon w/2X teleplus
Name: Run_14_2point28_mL_175CCM
File Size: 656 MB
View: side
Notes:
8/10/2004  
Sample A w/Kynar

Run: 1
Air flow: 175  ACCM
Water flow: 0.28  mL/min
Rec. Rate: 1000  fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 16.5  cm
Saved: 3.53  sec
Frames: 3530  frames
Lens: Std Nikkon w/2X teleplus
Name: Run_1_point28_mL_175CCM
FileSize: 882  MB
View: side
Notes:

Run: 2
Air flow: 175  ACCM
Water flow: 0.28  mL/min
Rec. Rate: 1000  fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 16.5  cm
Saved: 3.937  sec
Frames: 3937  frames
Lens: Std Nikkon w/2X teleplus
Name: Run_2_point28_mL_175CCM
FileSize: 984  MB
View: side
Notes:

Run: 3
Air flow: 175  ACCM
Water flow: 0.28  mL/min
Rec. Rate: 1000  fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 16.5  cm
Saved: 2.806  sec
Frames: 2806  frames
Lens: Std Nikkon w/2X teleplus
Name: Run_3_point28_mL_175CCM
FileSize: 701  MB
View: side
Notes:
### Run 1
- **Airflow:** 48 ACCM
- **Waterflow:** 1.12 mL/min
- **Rec. Rate:** 1000 fps
- **Shutter:** 1/6000
- **Resolution:** 1024 x 256
- **Location:** 3 cm
- **Saved:** 8.19 sec
- **Frames:** 8190
- **Lens:** Std Nikkon w/2X teleplus
- **Name:** Run_1_1point12_mL_48CCM
- **File Size:** 1.99 GB
- **View:** side
- **Notes:** Stratified flow, several small drops hanging on GDM

### Run 2
- **Airflow:** 48 ACCM
- **Waterflow:** 1.12 mL/min
- **Rec. Rate:** 1000 fps
- **Shutter:** 1/6000
- **Resolution:** 1024 x 256
- **Location:** 2.5 cm
- **Saved:** 2.127 sec
- **Frames:** 2127
- **Lens:** Std Nikkon w/2X teleplus
- **Name:** Run_2_1point12_mL_48CCM
- **File Size:** 531 MB
- **View:** side
- **Notes:** Drop growing on or near side wall pulled into water film on channel bottom

### Run 3
- **Airflow:** 48 ACCM
- **Waterflow:** 1.12 mL/min
- **Rec. Rate:** 1000 fps
- **Shutter:** 1/6000
- **Resolution:** 1024 x 256
- **Location:** 4 cm
- **Saved:** 8.19 sec
- **Frames:** 8190
- **Lens:** Std Nikkon w/2X teleplus
- **Name:** Run_3_1point12_mL_48CCM
- **File Size:** 1.99 GB
- **View:** side
- **Notes:** Single Drop frame 2455 hits wall frame 4845 drop shear frame 6197

### Run 4
- **Airflow:** 48 ACCM
- **Waterflow:** 1.12 mL/min
- **Rec. Rate:** 1000 fps
- **Shutter:** 1/6000
- **Resolution:** 1024 x 256
- **Location:** 12 cm
- **Saved:** 8.19 sec
- **Frames:** 8190
- **Lens:** Std Nikkon w/2X teleplus
- **Name:** Run_4_1point12_mL_48CCM
- **File Size:** 1.99 GB
- **View:** side
- **Notes:** droplet activity interacting with water in channel

### Run 5
- **Airflow:** 48 ACCM
- **Waterflow:** 1.12 mL/min
- **Rec. Rate:** 1000 fps
- **Shutter:** 1/6000
- **Resolution:** 1024 x 256
- **Location:** 12 cm
- **Saved:** 8.19 sec
- **Frames:** 8190
- **Lens:** Std Nikkon w/2X teleplus
- **Name:** Run_5_1point12_mL_48CCM
- **File Size:** 1.99 GB
- **View:** side
- **Notes:** same location as run 4 alot of water in channel frame 469 air bubble formed

### Run 6
- **Airflow:** 48 ACCM
- **Waterflow:** 1.12 mL/min
- **Rec. Rate:** 1000 fps
- **Shutter:** 1/6000
- **Resolution:** 1024 x 256
- **Location:** 17 cm
- **Saved:** 8.19 sec
- **Frames:** 8190
- **Lens:** Std Nikkon w/2X teleplus
- **Name:** Run_6_1point12_mL_48CCM
- **File Size:** 1.99 GB
- **View:** side
- **Notes:** departure fr 1767 departure fr 5670
Sample B w/MPL and tape

<table>
<thead>
<tr>
<th>Run</th>
<th>t</th>
<th>Air flow</th>
<th>Water flow</th>
<th>Rec. Rate</th>
<th>Shutter</th>
<th>Resolution</th>
<th>Location</th>
<th>Saved</th>
<th>Frames</th>
<th>Lens</th>
<th>Name</th>
<th>File Size</th>
<th>View</th>
<th>Notes</th>
</tr>
</thead>
</table>
| 7   | 7:00| 48 AC CM | 1.12 mL/min| 1000 fps  | 1/6000  | 1024 x 256 | 17 cm    | 8.19  | 8190   |      | Run_7_1point12_minutes_48C CM | 1.99 GB   | side | same location as run 6
      |     |          |            |           |         |             |          |       |        |      | fr 4565 drop hit bottom water
      |     |          |            |           |         |             |          |       |        |      | fr 7535 drop hits corner water
| 8   | 7:28| 48 AC CM | 1.12 mL/min| 1000 fps  | 1/6000  | 1024 x 256 | 19.5 cm  | 8.19  | 8190   |      | Run_8_1point12_minutes_48C CM | 1.99 GB   | side | drops shearing, sliding over slug
      |     |          |            |           |         |             |          |       |        |      | slug gone at fr 2056 and shear stops
      |     |          |            |           |         |             |          |       |        |      | shear at fr 3511; 4130; 4836; 5462;
      |     |          |            |           |         |             |          |       |        |      | drop/slug fr 6538; 6773; 6996; 7205; 7392; 7544
| 9   | 8:02| 48 AC CM | 1.12 mL/min| 1000 fps  | 1/6000  | 1024 x 256 | 20 cm    | 8.19  | 8190   |      | Run_9_1point12_minutes_48C CM | 1.99 GB   | side | near same location as run 8
      |     |          |            |           |         |             |          |       |        |      | large drop fr 932
      |     |          |            |           |         |             |          |       |        |      | shear fr 2451; fr 3932-4384; bounce 5374; 6112; 7474
### GDM Sample B Datasheet

**Sample B w/MPL and tape**

**Run:** 1  \( t = 12:44p \)
- **Air flow:** 48 ACCM
- **Water flow:** 0.56 mL/min
- **Rec. Rate:** 1000 fps
- **Shutter:** 1/6000
- **Resolution:** 1024 x 256
- **Location:** 2 cm
- **Saved:** 8.19 sec
- **Frames:** 8190 frames
  - **Lens:** Std Nikkon w/2X teleplus
  - **Name:** Run_1_point56_mL_48CCM
- **File Size:** 1.99 GB
- **View:** side
- **Notes:** sidewall drops

**Run:** 2  \( t = 2:25 \)
- **Air flow:** 48 ACCM
- **Water flow:** 0.56 mL/min
- **Rec. Rate:** 1000 fps
- **Shutter:** 1/6000
- **Resolution:** 1024 x 256
- **Location:** 25 cm
- **Saved:** 8.19 sec
- **Frames:** 8190 frames
  - **Lens:** Std Nikkon w/2X teleplus
  - **Name:** Run_2_point56_mL_48CCM
- **File Size:** 1.99 GB
- **View:** side
- **Notes:** single drop pulled by wet GDM

**Run:** 3  \( t = 2:49 \)
- **Air flow:** 48 ACCM
- **Water flow:** 0.56 mL/min
- **Rec. Rate:** 1000 fps
- **Shutter:** 1/6000
- **Resolution:** 1024 x 256
- **Location:** 22 cm
- **Saved:** 8.19 sec
- **Frames:** 8190 frames
  - **Lens:** Std Nikkon w/2X teleplus
  - **Name:** Run_3_point56_mL_48CCM
- **File Size:** 1.99 GB
- **View:** side
- **Notes:** single drop hitting water formation

**Run:** 4  \( t = 3:27 \)
- **Air flow:** 48 ACCM
- **Water flow:** 0.56 mL/min
- **Rec. Rate:** 1000 fps
- **Shutter:** 1/6000
- **Resolution:** 1024 x 256
- **Location:** 12 cm
- **Saved:** 4.299 sec
- **Frames:** 4299 frames
  - **Lens:** Std Nikkon w/2X teleplus
  - **Name:** Run_4_point56_mL_48CCM
- **File Size:** 1.04 GB
- **View:** side
- **Notes:** drop grows into side wall shows no deformation from airflow

**Run:** 5  \( t = 3:53 \)
- **Air flow:** 48 ACCM
- **Water flow:** 0.56 mL/min
- **Rec. Rate:** 1000 fps
- **Shutter:** 1/6000
- **Resolution:** 1024 x 256
- **Location:** 4 cm
- **Saved:** 8.19 sec
- **Frames:** 8190 frames
  - **Lens:** Std Nikkon w/2X teleplus
  - **Name:** Run_5_point56_mL_48CCM
- **File Size:** 1.99 GB
- **View:** side
- **Notes:** large drop no deformation gets washed away by slug fr 3240

**Run:** 6  \( t = 4:55 \)
- **Air flow:** 48 ACCM
- **Water flow:** 0.28 mL/min
- **Rec. Rate:** 1000 fps
- **Shutter:** 1/6000
- **Resolution:** 1024 x 256
- **Location:** 18 cm
- **Saved:** 8.19 sec
- **Frames:** 8190 frames
  - **Lens:** Std Nikkon w/2X teleplus
  - **Name:** Run_6_point28_mL_48CCM
- **File Size:** 1.99 GB
- **View:** side
- **Notes:** single drop hits sidewall fr 1625 fr3440, fr5255, fr7211
### Run 8

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run</td>
<td>8</td>
</tr>
<tr>
<td>t</td>
<td>6:11</td>
</tr>
<tr>
<td>Air flow</td>
<td>48 ACCM</td>
</tr>
<tr>
<td>Water flow</td>
<td>0.28 mL/min</td>
</tr>
<tr>
<td>Rec. Rate</td>
<td>1000 fps</td>
</tr>
<tr>
<td>Shutter</td>
<td>1/6000</td>
</tr>
<tr>
<td>Resolution</td>
<td>1024 x 256</td>
</tr>
<tr>
<td>Location</td>
<td>15 cm</td>
</tr>
<tr>
<td>Saved</td>
<td>8.19 sec</td>
</tr>
<tr>
<td>Frames</td>
<td>8190 frames</td>
</tr>
<tr>
<td>Lens</td>
<td>Std Nikkon w/2X teleplus</td>
</tr>
<tr>
<td>Name</td>
<td>Run_8_point28_mL_48CCM</td>
</tr>
<tr>
<td>File Size</td>
<td>1.99 GB</td>
</tr>
<tr>
<td>View</td>
<td>side</td>
</tr>
<tr>
<td>Notes</td>
<td>small drop pulled into wet location of GDM</td>
</tr>
</tbody>
</table>
Sample B w/MPL and tape

8/30/2004

Run: 1  \( t = 11:56a \)
Air flow: 88 ACCM
Water flow: 1.12 mL/min
Rec. Rate: 1000 fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 23 cm
Saved: 8.19 sec
Frames: 8190 frames
Lens: Std Nikkon w/2X teleplus
Name: Run_1_1point12_mL_88CCM
File Size: 1.99 GB
View: side
Notes: three large hanging drops
drop shear fr3732
stratified flow

Run: 2  \( t = 12:32p \)
Air flow: 88 ACCM
Water flow: 1.12 mL/min
Rec. Rate: 1000 fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 24.5 cm
Saved: 8.19 sec
Frames: 8190 frames
Lens: Std Nikkon w/2X teleplus
Name: Run_2_1point12_mL_88CCM
File Size: 1.99 GB
View: side
Notes: drop hanging, sidewall draining

Run: 3  \( t = 1:28 \)
Air flow: 88 ACCM
Water flow: 1.12 mL/min
Rec. Rate: 1000 fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 19 cm
Saved: 8.19 sec
Frames: 8190 frames
Lens: Std Nikkon w/2X teleplus
Name: Run_3_1point12_mL_88CCM
File Size: 1.99 GB
View: side
Notes: single drop growing into
side/bottom water
stratified flow

Run: 4  \( t = 1:52 \)
Air flow: 88 ACCM
Water flow: 1.12 mL/min
Rec. Rate: 1000 fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 19 cm
Saved: 8.19 sec
Frames: 8190 frames
Lens: Std Nikkon w/2X teleplus
Name: Run_4_1point12_mL_88CCM
File Size: 1.99 GB
View: side
Notes: same location as run 3
single drop into side/bottom water
stratified flow

Run: 5  \( t = 2:17 \)
Air flow: 88 ACCM
Water flow: 1.12 mL/min
Rec. Rate: 1000 fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 11 cm
Saved: 8.19 sec
Frames: 8190 frames
Lens: Std Nikkon w/2X teleplus
Name: Run_5_1point12_mL_88CCM
File Size: 1.99 GB
View: side
Notes: single drop hitting sidewall

Run: 6  \( t = 2:44 \)
Air flow: 88 ACCM
Water flow: 1.12 mL/min
Rec. Rate: 1000 fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 16 cm
Saved: 8.19 sec
Frames: 8190 frames
Lens: Std Nikkon w/2X teleplus
Name: Run_6_1point12_mL_88CCM
File Size: 1.99 GB
View: side
Notes: drop pulled backwards into
sidewall water fr2547
Run: 7  t = 3:22
Air flow: 88  ACCM
Water flow: 1.12  mL/min
Rec. Rate: 1000  fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 6  cm
Saved: 8.19  sec
Frames: 8190  frames
Lens: Std Nikkon w/2X teleplus
Name: Run_7_1point12_mL_88CCM
File Size: 1.99  GB
View: side
Notes: single drop growing into sidewall

Run: 8  t = 3:47
Air flow: 88  ACCM
Water flow: 1.12  mL/min
Rec. Rate: 1000  fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 6  cm
Saved: 8.19  sec
Frames: 8190  frames
Lens: Std Nikkon w/2X teleplus
Name: Run_8_1point12_mL_88CCM
File Size: 1.99  GB
View: side
Notes: single drop hits sidewall
water slug on channel bottom

Run: 9  t = 4:15
Air flow: 88  ACCM
Water flow: 1.12  mL/min
Rec. Rate: 1000  fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 10  cm
Saved: 8.19  sec
Frames: 8190  frames
Lens: Std Nikkon w/2X teleplus
Name: Run_9_1point12_mL_88CCM
File Size: 1.99  GB
View: side
Notes: single drop hit with wave fr1475
single drop hits wall/water fr 3724

Run: 10  t = 4:43
Air flow: 88  ACCM
Water flow: 1.12  mL/min
Rec. Rate: 1000  fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 9  cm
Saved: 8.19  sec
Frames: 8190  frames
Lens: Std Nikkon w/2X teleplus
Name: Run_10_1point12_mL_88CCM
File Size: 1.99  GB
View: side
Notes: departure fr4730
stratified flow

Run: 11  t = 5:08
Air flow: 88  ACCM
Water flow: 1.12  mL/min
Rec. Rate: 1000  fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 9  cm
Saved: 8.19  sec
Frames: 8190  frames
Lens: Std Nikkon w/2X teleplus
Name: Run_11_1point12_mL_88CCM
File Size: 1.99  GB
View: side
Notes: same location as run 10
departure fr7690

Run: 12  t = 5:33
Air flow: 88  ACCM
Water flow: 0.56  mL/min
Rec. Rate: 1000  fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 9  cm
Saved: 8.19  sec
Frames: 8190  frames
Lens: Std Nikkon w/2X teleplus
Name: Run_12_point56_mL_88CCM
File Size: 1.99  GB
View: side
Notes: departure fr2559
water slug on bottom
Run: 13  
t = 6:05
Air flow: 88  
ACCM
Water flow: 0.56  
mL/min
Rec. Rate: 1000  
fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 19  
cm
Saved: 8.19  
sec
Frames: 8190  
frames
Lens: Std Nikkon w/2X teleplus
Name: Run_13_point56_mL_88CCM
File Size: 1.99  
GB
View: side
Notes: single drop growing into
sidewall water

Run: 14  
t = 7:04
Air flow: 88  
ACCM
Water flow: 0.56  
mL/min
Rec. Rate: 1000  
fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 19  
cm
Saved: 8.19  
sec
Frames: 8190  
frames
Lens: Std Nikkon w/2X teleplus
Name: Run_14_point56_mL_88CCM
File Size: 1.99  
GB
View: side
Notes: two drops close together
large drop hits sidewall fr1246

Run: 15  
t = 8:26
Air flow: 88  
ACCM
Water flow: 0.56  
mL/min
Rec. Rate: 1000  
fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 19  
cm
Saved: 8.19  
sec
Frames: 8190  
frames
Lens: Std Nikkon w/2X teleplus
Name: Run_15_point56_mL_88CCM
File Size: 1.99  
GB
View: side
Notes: same as run 14

Run: 16  
t = 9:02
Air flow: 88  
ACCM
Water flow: 0.56  
mL/min
Rec. Rate: 1000  
fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 4  
cm
Saved: 8.19  
sec
Frames: 8190  
frames
Lens: Std Nikkon w/2X teleplus
Name: Run_16_point56_mL_88CCM
File Size: 1.99  
GB
View: side
Notes: sidewall drop

Run: 17  
t = 9:28
Air flow: 88  
ACCM
Water flow: 0.56  
mL/min
Rec. Rate: 1000  
fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 5  
cm
Saved: 8.19  
sec
Frames: 8190  
frames
Lens: Std Nikkon w/2X teleplus
Name: Run_17_point56_mL_88CCM
File Size: 1.99  
GB
View: side
Notes: Hanging droplets
very little deformation

Notes:

- Run 13: Single drop growing into the sidewall water.
- Run 14: Two drops close together; large drop hits the sidewall.
- Run 15: Same setup as Run 14.
- Run 16: Sidewall drop.
- Run 17: Hanging droplets with very little deformation.
### GDM Sample B Datasheet

8/31/2004 Sample B w/MPL and tape

<table>
<thead>
<tr>
<th>Run</th>
<th>1</th>
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<tbody>
<tr>
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<td>88 ACCM</td>
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</tr>
<tr>
<td>Water flow</td>
<td>0.56 mL/min</td>
<td></td>
</tr>
<tr>
<td>Rec. Rate</td>
<td>1000 fps</td>
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<tr>
<td>Shutter</td>
<td>1/6000</td>
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<tr>
<td>Resolution</td>
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<td>Location</td>
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<td>8.19 sec</td>
<td></td>
</tr>
<tr>
<td>Frames</td>
<td>8190 frames</td>
<td></td>
</tr>
<tr>
<td>Lens</td>
<td>Std Nikkon w/2X teleplus</td>
<td></td>
</tr>
<tr>
<td>Name</td>
<td>Run_1_point56_mL_88CCM</td>
<td></td>
</tr>
<tr>
<td>File Size</td>
<td>1.99 GB</td>
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<tr>
<td>View</td>
<td>side</td>
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</tr>
<tr>
<td>Notes</td>
<td>departure fr1829 (water ramp), drop from same location hits wall at fr7253</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Run</th>
<th>4</th>
<th>t = 12:20</th>
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</thead>
<tbody>
<tr>
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<td>88 ACCM</td>
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</tr>
<tr>
<td>Water flow</td>
<td>0.28 mL/min</td>
<td></td>
</tr>
<tr>
<td>Rec. Rate</td>
<td>1000 fps</td>
<td></td>
</tr>
<tr>
<td>Shutter</td>
<td>1/6000</td>
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</tr>
<tr>
<td>Resolution</td>
<td>1024 x 256</td>
<td></td>
</tr>
<tr>
<td>Location</td>
<td>9.5 cm</td>
<td></td>
</tr>
<tr>
<td>Saved</td>
<td>8.19 sec</td>
<td></td>
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<tr>
<td>Frames</td>
<td>8190 frames</td>
<td></td>
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<tr>
<td>Lens</td>
<td>Std Nikkon w/2X teleplus</td>
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<tr>
<td>Name</td>
<td>Run_4_point28_mL_88CCM</td>
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<tr>
<td>File Size</td>
<td>1.99 GB</td>
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</tr>
<tr>
<td>View</td>
<td>side</td>
<td></td>
</tr>
<tr>
<td>Notes</td>
<td>same location as run 3, single drop hitting sidewall</td>
<td></td>
</tr>
</tbody>
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<table>
<thead>
<tr>
<th>Run</th>
<th>2</th>
<th>t = 11:22</th>
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<tr>
<td>Air flow</td>
<td>88 ACCM</td>
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<tr>
<td>Water flow</td>
<td>0.56 mL/min</td>
<td></td>
</tr>
<tr>
<td>Rec. Rate</td>
<td>1000 fps</td>
<td></td>
</tr>
<tr>
<td>Shutter</td>
<td>1/6000</td>
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<tr>
<td>Resolution</td>
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<td></td>
</tr>
<tr>
<td>Location</td>
<td>10 cm</td>
<td></td>
</tr>
<tr>
<td>Saved</td>
<td>8.19 sec</td>
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</tr>
<tr>
<td>Frames</td>
<td>8190 frames</td>
<td></td>
</tr>
<tr>
<td>Lens</td>
<td>Std Nikkon w/2X teleplus</td>
<td></td>
</tr>
<tr>
<td>Name</td>
<td>Run_2_point56_mL_88CCM</td>
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<td>File Size</td>
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</tr>
<tr>
<td>View</td>
<td>side</td>
<td></td>
</tr>
<tr>
<td>Notes</td>
<td>same location as run 1, drop hits wall, no departure</td>
<td></td>
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<table>
<thead>
<tr>
<th>Run</th>
<th>5</th>
<th>t = 2:38</th>
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<td>Air flow</td>
<td>175 ACCM</td>
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<td>Water flow</td>
<td>0.28 mL/min</td>
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<td>Rec. Rate</td>
<td>1000 fps</td>
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<tr>
<td>Shutter</td>
<td>1/6000</td>
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<td>1024 x 256</td>
<td></td>
</tr>
<tr>
<td>Location</td>
<td>9.5 cm</td>
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<td>Saved</td>
<td>8.19 sec</td>
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</tr>
<tr>
<td>Frames</td>
<td>8190 frames</td>
<td></td>
</tr>
<tr>
<td>Lens</td>
<td>Std Nikkon w/2X teleplus</td>
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</tr>
<tr>
<td>Name</td>
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<tr>
<td>View</td>
<td>side</td>
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<tr>
<td>Notes</td>
<td>large drop hitting bottom/side water</td>
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<th>Run</th>
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<td>Water flow</td>
<td>0.28 mL/min</td>
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<td>Rec. Rate</td>
<td>1000 fps</td>
<td></td>
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<tr>
<td>Shutter</td>
<td>1/6000</td>
<td></td>
</tr>
<tr>
<td>Resolution</td>
<td>1024 x 256</td>
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</tr>
<tr>
<td>Location</td>
<td>9.5 cm</td>
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</tr>
<tr>
<td>Saved</td>
<td>8.19 sec</td>
<td></td>
</tr>
<tr>
<td>Frames</td>
<td>8190 frames</td>
<td></td>
</tr>
<tr>
<td>Lens</td>
<td>Std Nikkon w/2X teleplus</td>
<td></td>
</tr>
<tr>
<td>Name</td>
<td>Run_6_point28_mL_175CCM</td>
<td></td>
</tr>
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<td>File Size</td>
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<tr>
<td>View</td>
<td>side</td>
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</tr>
<tr>
<td>Notes</td>
<td>departure fr2802, compare contact angle with Phase I</td>
<td></td>
</tr>
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View: side
### Sample B w/MPL and tape

<table>
<thead>
<tr>
<th>Run</th>
<th>t</th>
<th>Air flow</th>
<th>Water flow</th>
<th>Rec. Rate</th>
<th>Shutter</th>
<th>Resolution</th>
<th>Location</th>
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<th>Frames</th>
<th>Lens</th>
<th>Name</th>
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<th>View</th>
<th>Notes</th>
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<tbody>
<tr>
<td>7</td>
<td>4:32</td>
<td>175 ACCM</td>
<td>0.56 mL/min</td>
<td>1000 fps</td>
<td>1/6000</td>
<td>1024 x 256</td>
<td>4 cm</td>
<td>8.19 sec</td>
<td>8190 frames</td>
<td>Std Nikkon w/2X teleplus</td>
<td>Run_7_point56_mL_175CCM</td>
<td>1.99 GB</td>
<td>side</td>
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<td></td>
<td>large drop impacts on sidewalk fr8022</td>
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<tr>
<td>8</td>
<td>5:11</td>
<td>175 ACCM</td>
<td>0.56 mL/min</td>
<td>1000 fps</td>
<td>1/6000</td>
<td>1024 x 256</td>
<td>6 cm</td>
<td>8.19 sec</td>
<td>8190 frames</td>
<td>Std Nikkon w/2X teleplus</td>
<td>Run_8_point56_mL_175CCM</td>
<td>1.99 GB</td>
<td>side</td>
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<td>drop impacts on wall fr2335</td>
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<tr>
<td>9</td>
<td>5:53</td>
<td>175 ACCM</td>
<td>0.56 mL/min</td>
<td>1000 fps</td>
<td>1/6000</td>
<td>1024 x 256</td>
<td>9 cm</td>
<td>8.19 sec</td>
<td>8190 frames</td>
<td>Std Nikkon w/2X teleplus</td>
<td>Run_9_point56_mL_175CCM</td>
<td>1.99 GB</td>
<td>side</td>
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<td></td>
<td>single drop growing into sidewall</td>
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<tr>
<td>10</td>
<td>6:17</td>
<td>175 ACCM</td>
<td>0.56 mL/min</td>
<td>1000 fps</td>
<td>1/6000</td>
<td>1024 x 256</td>
<td>10 cm</td>
<td>8.19 sec</td>
<td>8190 frames</td>
<td>Std Nikkon w/2X teleplus</td>
<td>Run_10_point56_mL_175CCM</td>
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<td>departure by water ramp fr5671</td>
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<tr>
<td>11</td>
<td>8:46</td>
<td>175 ACCM</td>
<td>0.56 mL/min</td>
<td>1000 fps</td>
<td>1/6000</td>
<td>1024 x 256</td>
<td>10 cm</td>
<td>8.19 sec</td>
<td>8190 frames</td>
<td>Std Nikkon w/2X teleplus</td>
<td>Run_11_point56_mL_175CCM</td>
<td>1.99 GB</td>
<td>side</td>
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<td>single drop knocked off by wave at fr4420</td>
</tr>
<tr>
<td>12</td>
<td>9:17</td>
<td>175 ACCM</td>
<td>1.12 mL/min</td>
<td>1000 fps</td>
<td>1/6000</td>
<td>1024 x 256</td>
<td>10 cm</td>
<td>8.19 sec</td>
<td>8190 frames</td>
<td>Std Nikkon w/2X teleplus</td>
<td>Run_12_point12_mL_175CCM</td>
<td>1.99 GB</td>
<td>side</td>
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<td></td>
<td>drops pulled into top water formation</td>
</tr>
</tbody>
</table>
Run: 13  t = 9:43
Air flow: 175  ACCM
Water flow: 1.12  mL/min
Rec. Rate: 1000  fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 10  cm
Saved: 8.19  sec
Frames: 8190  frames
Lens: Std Nikkon w/2X teleplus
Name: Run_13_1point12_mL_175CCM
File Size: 1.99  GB
View: side
Notes: same as run 12

Run: 14  t = 10:18
Air flow: 175  ACCM
Water flow: 1.12  mL/min
Rec. Rate: 1000  fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 3.5  cm
Saved: 8.19  sec
Frames: 8190  frames
Lens: Std Nikkon w/2X teleplus
Name: Run_14_1point12_mL_175CCM
File Size: 1.99  GB
View: side
Notes: drop departure fr759; fr1769; fr2716
fr3605; continues until wave at fr4952
after wave, sidewall drop or drop hits sidewall

Run: 15  t = 10:40
Air flow: 175  ACCM
Water flow: 1.12  mL/min
Rec. Rate: 1000  fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 3.5  cm
Saved: 8.19  sec
Frames: 8190  frames
Lens: Std Nikkon w/2X teleplus
Name: Run_15_1point12_mL_175CCM
File Size: 1.99  GB
View: side
Notes: Thin film flow seen at fr86
several droplet departures and interactions
GDM Sample B Datasheet

Sample B w/MPL and tape

Run:  1  t = 12:54p
Air flow: 175 ACCM
Water flow: 1.12 mL/min
Rec. Rate: 1000 fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 5 cm
Saved: 8.19 sec
Frames: 8190 frames
Lens: Std Nikkon w/2X teleplus
Name: Run_1_1point12_mL_175CCM
File Size: 1.99 GB
View: side
Notes: wave knocking off drop
fr1746

Run:  2  t = 2:01
Air flow: 175 ACCM
Water flow: 1.12 mL/min
Rec. Rate: 1000 fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 10 cm
Saved: 8.19 sec
Frames: 8190 frames
Lens: Std Nikkon w/2X teleplus
Name: Run_2_1point12_mL_175CCM
File Size: 1.99 GB
View: side
Notes: annular formation starting at
fr4845

Run:  3  t = 2:54
Air flow: 351 ACCM
Water flow: 1.12 mL/min
Rec. Rate: 1000 fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 9 cm
Saved: 8.19 sec
Frames: 8190 frames
Lens: Std Nikkon w/2X teleplus
Name: Run_3_1point12_mL_351CCM
File Size: 1.99 GB
View: side
Notes: departure at fr4053; fr6510;
wave-induced departure fr5088

Run:  4  t = 3:21
Air flow: 351 ACCM
Water flow: 1.12 mL/min
Rec. Rate: 1000 fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 9 cm
Saved: 8.19 sec
Frames: 8190 frames
Lens: Std Nikkon w/2X teleplus
Name: Run_4_1point12_mL_351CCM
File Size: 1.99 GB
View: side
Notes: bubble in film flow fr4540
water flowing on GDM

Run:  5  t = 3:51
Air flow: 351 ACCM
Water flow: 1.12 mL/min
Rec. Rate: 1000 fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 10 cm
Saved: 8.19 sec
Frames: 8190 frames
Lens: Std Nikkon w/2X teleplus
Name: Run_5_1point12_mL_351CCM
File Size: 1.99 GB
View: side
Notes: departure fr71; fr4465; fr7428
wave-induced departure fr5597

Run:  6  t = 4:18
Air flow: 351 ACCM
Water flow: 1.12 mL/min
Rec. Rate: 1000 fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 20 cm
Saved: 8.19 sec
Frames: 8190 frames
Lens: Std Nikkon w/2X teleplus
Name: Run_6_1point12_mL_351CCM
File Size: 1.99 GB
View: side
Notes: drop growing and hitting side-
wall top corner water

E11
Run: 7  \( t = 5:45 \)
Air flow: 351 ACCM
Water flow: 0.56 mL/min
Rec. Rate: 1000 fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 10 cm
Saved: 8.19 sec
Frames: 8190 frames
Lens: Std Nikkon w/2X teleplus
Name: Run_7_point56_mL_351CCM
File Size: 1.99 GB
View: side
Notes: wave-induced departure fr1561; departure fr6550

Run: 8  \( t = 6:09 \)
Air flow: 351 ACCM
Water flow: 0.56 mL/min
Rec. Rate: 1000 fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 10 cm
Saved: 8.19 sec
Frames: 8190 frames
Lens: Std Nikkon w/2X teleplus
Name: Run_8_point56_mL_351CCM
File Size: 1.99 GB
View: side
Notes: departure fr1686; fr7087
GDM Sample B Datasheet

9/2/2004

Sample B w/MPL and tape

Run: 1  t = 1:26p
Air flow: 351 ACCM
Water flow: 0.56 mL/min
Rec. Rate: 1000 fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 4 cm
Saved: 8.19 sec
Frames: 8190 frames
Lens: Std Nikkon w/2X teleplus
Name: Run_1_point56_mL_351CCM
File Size: 1.99 GB
View: side
Notes: small drop going back into GDM

Run: 2  t = 4:40
Air flow: 351 ACCM
Water flow: 0.56 mL/min
Rec. Rate: 1000 fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 10 cm
Saved: 8.19 sec
Frames: 8190 frames
Lens: Std Nikkon w/2X teleplus
Name: Run_2_point56_mL_351CCM
File Size: 1.99 GB
View: side
Notes: drop growing into top water

Run: 3  t = 5:05
Air flow: 351 ACCM
Water flow: 0.56 mL/min
Rec. Rate: 1000 fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 9 cm
Saved: 8.19 sec
Frames: 8190 frames
Lens: Std Nikkon w/2X teleplus
Name: Run_3_point56_mL_351CCM
File Size: 1.99 GB
View: side
Notes: departure fr1037; fr5052; wave-induced departure fr1695

Run: 4  t = 6:24
Air flow: 351 ACCM
Water flow: 0.28 mL/min
Rec. Rate: 1000 fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 4 cm
Saved: 8.19 sec
Frames: 8190 frames
Lens: Std Nikkon w/2X teleplus
Name: Run_4_point28_mL_351CCM
File Size: 1.99 GB
View: side
Notes: departure fr2124; fr5688
note: flat-front drop

Run: 5  t = 6:52
Air flow: 351 ACCM
Water flow: 0.28 mL/min
Rec. Rate: 1000 fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 3 cm
Saved: 8.19 sec
Frames: 8190 frames
Lens: Std Nikkon w/2X teleplus
Name: Run_5_point28_mL_351CCM
File Size: 1.99 GB
View: side
Notes: sidewall drop

Run: 6  t = 7:28
Air flow: 351 ACCM
Water flow: 0.28 mL/min
Rec. Rate: 1000 fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 10 cm
Saved: 8.19 sec
Frames: 8190 frames
Lens: Std Nikkon w/2X teleplus
Name: Run_6_point28_mL_351CCM
File Size: 1.99 GB
View: side
Notes: departure fr91; fr604; drop attracted to hydrophilic location
GDM Sample B Datasheet

9/3/2004

Sample B w/MPL and tape

Run: 1 t = 2:23p
Cflow: 351 ACCM
Water flow: 0.28 mL/min
Rec. Rate: 1000 fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 10 cm
Saved: 8.19 sec
Frames: 8190 frames
Lens: Std Nikkon w/2X teleplus
Name: Run_1_point28_mL_351CCM
File Size: 1.99 GB
View: side
Notes: drop pulled into top water formation

Run: 2 t = 2:54
Cflow: 351 ACCM
Water flow: 0.28 mL/min
Rec. Rate: 1000 fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 10 cm
Saved: 8.19 sec
Frames: 8190 frames
Lens: Std Nikkon w/2X teleplus
Name: Run_2_point28_mL_351CCM
File Size: 1.99 GB
View: side
Notes: drop pulled into top water formation

Run: 4 t = 3:43
Cflow: 351 ACCM
Water flow: 0.28 mL/min
Rec. Rate: 1000 fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 3 cm
Saved: 8.19 sec
Frames: 8190 frames
Lens: Std Nikkon w/2X teleplus
Name: Run_4_point28_mL_351CCM
File Size: 1.99 GB
View: side
Notes: departure fr2858

Run: 5 t = 4:19
Cflow: 714 ACCM
Water flow: 1.12 mL/min
Rec. Rate: 1000 fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 3 cm
Saved: 8.19 sec
Frames: 8190 frames
Lens: Std Nikkon w/2X teleplus
Name: Run_5_point12_mL_714CCM
File Size: 1.99 GB
View: side
Notes: sidewall drop-like behavior

Run: 6 t = 4:43
Cflow: 714 ACCM
Water flow: 1.12 mL/min
Rec. Rate: 1000 fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 5.5 cm
Saved: 8.19 sec
Frames: 8190 frames
Lens: Std Nikkon w/2X teleplus
Name: Run_6_point12_mL_714CCM
File Size: 1.99 GB
View: side
Notes: departure fr4743
9/3/2004
Sample B w/MPL and tape

Run: 7  t = 5:07
Air flow: 714 ACCM
Water flow: 1.12 mL/min
Rec. Rate: 1000 fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 5.5 cm
Saved: 8.19 sec
Frames: 8190 frames
Lens: Std Nikkon w/2X teleplus
Name: Run_7_1point12_ml_714CCM
File Size: 1.99 GB
View: side
Notes: departure fr3512

Run: 8  t = 5:42
Air flow: 714 ACCM
Water flow: 1.12 mL/min
Rec. Rate: 1000 fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 10 cm
Saved: 8.19 sec
Frames: 8190 frames
Lens: Std Nikkon w/2X teleplus
Name: Run_8_1point12_ml_714CCM
File Size: 1.99 GB
View: side
Notes: several departures

Run: 9  t = 6:03
Air flow: 714 ACCM
Water flow: 1.12 mL/min
Rec. Rate: 1000 fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 10 cm
Saved: 8.19 sec
Frames: 8190 frames
Lens: Std Nikkon w/2X teleplus
Name: Run_9_1point12_ml_714CCM
File Size: 1.99 GB
View: side
Notes: same as run 8
9/6/2004

Sample B w/MPL and tape

Run: 1  t = 11:00a
Air flow: 714  ACCM
Water flow: 1.12  mL/min
Rec. Rate: 1000  fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 9.5  cm
Saved: 8.19  sec
Frames: 8190  frames
Lens: Std Nikkon w/2X teleplus
Name: Run_1_1point12_mL_714CCM
FileSize: 1.99  GB
View: side
Notes: departure fr493;
two drops fr1001; fr1538; fr2106

Run: 2  t = 11:23
Air flow: 714  ACCM
Water flow: 1.12  mL/min
Rec. Rate: 1000  fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 9.5  cm
Saved: 8.19  sec
Frames: 8190  frames
Lens: Std Nikkon w/2X teleplus
Name: Run_2_1point12_mL_714CCM
FileSize: 1.99  GB
View: side
Notes: departure fr693; fr1789; fr 2832; fr3798; etc.

Run: 3  t = 11:48
Air flow: 714  ACCM
Water flow: 1.12  mL/min
Rec. Rate: 1000  fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 9.5  cm
Saved: 8.19  sec
Frames: 8190  frames
Lens: Std Nikkon w/2X teleplus
Name: Run_3_1point12_mL_714CCM
FileSize: 1.99  GB
View: side
Notes: several departures

Run: 4  t = 1:55
Air flow: 714  ACCM
Water flow: 0.56  mL/min
Rec. Rate: 1000  fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 9  cm
Saved: 8.19  sec
Frames: 8190  frames
Lens: Std Nikkon w/2X teleplus
Name: Run_4_point56_mL_714CCM
FileSize: 1.99  GB
View: side
Notes: sliding departure fr1582

Run: 5  t = 2:17
Air flow: 714  ACCM
Water flow: 0.56  mL/min
Rec. Rate: 1000  fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 9  cm
Saved: 8.19  sec
Frames: 8190  frames
Lens: Std Nikkon w/2X teleplus
Name: Run_5_point56_mL_714CCM
FileSize: 1.99  GB
View: side
Notes: 2 departure locations

Run: 6  t = 2:50
Air flow: 714  ACCM
Water flow: 0.56  mL/min
Rec. Rate: 1000  fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 9.5  cm
Saved: 8.19  sec
Frames: 8190  frames
Lens: Std Nikkon w/2X teleplus
Name: Run_6_point56_mL_714CCM
FileSize: 1.99  GB
View: side
Notes: departure fr347; etc.
### Sample B w/MPL and tape

<table>
<thead>
<tr>
<th>Run:</th>
<th></th>
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<tbody>
<tr>
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</tr>
<tr>
<td>Water flow:</td>
<td>0.56</td>
<td>mL/min</td>
<td></td>
</tr>
<tr>
<td>Rec. Rate:</td>
<td>1000</td>
<td>fps</td>
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</tr>
<tr>
<td>Shutter:</td>
<td>1/6000</td>
<td></td>
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</tr>
<tr>
<td>Resolution:</td>
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</tr>
<tr>
<td>Lens:</td>
<td>Std Nikkon w/2X teleplus</td>
<td></td>
<td></td>
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<tr>
<td>Name:</td>
<td>Run_7_point56_mL_714CCM</td>
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<td>File Size:</td>
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<tr>
<td>View:</td>
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<tr>
<td>Notes:</td>
<td>drop pulled into top water fr1892</td>
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### Run 8 t = 4:47

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<td>Water flow:</td>
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<td>mL/min</td>
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<td>Rec. Rate:</td>
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<tr>
<td>Shutter:</td>
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<tr>
<td>Resolution:</td>
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<tr>
<td>Location:</td>
<td>3 cm</td>
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<td>Frames:</td>
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<td></td>
</tr>
<tr>
<td>Lens:</td>
<td>Std Nikkon w/2X teleplus</td>
<td></td>
<td></td>
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<tr>
<td>Name:</td>
<td>Run_8_point56_mL_714CCM</td>
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</tr>
<tr>
<td>View:</td>
<td>side</td>
<td></td>
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<tr>
<td>Notes:</td>
<td>departure of sidewall drop or near sidewall drop</td>
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### Run 9 t = 5:21

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<td>Water flow:</td>
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<td>mL/min</td>
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<tr>
<td>Shutter:</td>
<td>1/6000</td>
<td></td>
<td></td>
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<tr>
<td>Resolution:</td>
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<tr>
<td>Location:</td>
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</tr>
<tr>
<td>Saved:</td>
<td>8.19 sec</td>
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<td></td>
</tr>
<tr>
<td>Frames:</td>
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<td></td>
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</tr>
<tr>
<td>Lens:</td>
<td>Std Nikkon w/2X teleplus</td>
<td></td>
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<tr>
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<td>Run_9_point56_mL_714CCM</td>
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<tr>
<td>View:</td>
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<tr>
<td>Notes:</td>
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### Run 10 t = 7:38

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<td>mL/min</td>
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<td>1/6000</td>
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<tr>
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<tr>
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<td>8.19 sec</td>
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<tr>
<td>Frames:</td>
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<tr>
<td>Lens:</td>
<td>Std Nikkon w/2X teleplus</td>
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<tr>
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### Run 11 t = 8:01

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<td>mL/min</td>
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<td>Saved:</td>
<td>8.19 sec</td>
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<tr>
<td>Frames:</td>
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<td>Lens:</td>
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<td>View:</td>
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<tr>
<td>Notes:</td>
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### Run 12 t = 9:36

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<td>Water flow:</td>
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<td>mL/min</td>
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<td>Rec. Rate:</td>
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<td>fps</td>
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<td>Shutter:</td>
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<tr>
<td>Saved:</td>
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<td>Frames:</td>
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<tr>
<td>Lens:</td>
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<td></td>
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<tr>
<td>View:</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Notes:</td>
<td>water flowing along top GDM surface</td>
<td></td>
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</table>
Sample B w/MPL and tape

Run: 1  t = 2:37p
Air flow: 714  ACCM
Water flow: 0.28  mL/min
Rec. Rate: 1000  fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 12  cm
Saved: 8.19  sec
Frames: 8190  frames
Lens: Std Nikkon w/2X teleplus
Name: Run_1_point28_mL_714CCM
File Size: 1.99  GB
View: side
Notes: water flowing along top
GDM surface

Run: 4  t = 5:22
Air flow: 714  ACCM
Water flow: 0.28  mL/min
Rec. Rate: 1000  fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 5  cm
Saved: 8.19  sec
Frames: 8190  frames
Lens: Std Nikkon w/2X teleplus
Name: Run_4_point28_mL_714CCM
File Size: 1.99  GB
View: side
Notes: same as run 2

Run: 2  t = 4:18
Air flow: 714  ACCM
Water flow: 0.28  mL/min
Rec. Rate: 1000  fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 5  cm
Saved: 8.19  sec
Frames: 8190  frames
Lens: Std Nikkon w/2X teleplus
Name: Run_2_point28_mL_714CCM
File Size: 1.99  GB
View: side
Notes: drop pulled into sidewall
water

Run: 3  t = 4:42
Air flow: 714  ACCM
Water flow: 0.28  mL/min
Rec. Rate: 1000  fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 5  cm
Saved: 8.19  sec
Frames: 8190  frames
Lens: Std Nikkon w/2X teleplus
Name: Run_3_point28_mL_714CCM
File Size: 1.99  GB
View: side
Notes: same as run 2
APPENDIX F: Sample C Datasheets
GDM Sample C Datasheet

3/23/2005
Sample C w/ Kynar

Run: 1  t=8:05 pm
Air flow: 714 ACCM
Water flow: 1.12 mL/min
Rec. Rate: 1000 fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 5 cm
Saved: 8.19 sec
Frames: 8190 frames
Lens: Std Nikkon w/2X teleplus
Name: Run_1_1point12_mL_714ACCM
FileSize: 1.99 GB
View: side
Notes: Large drop fr6244 leaves wet tail

Run: 2  t=8:55
Air flow: 714 ACCM
Water flow: 1.12 mL/min
Rec. Rate: 1000 fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 5 cm
Saved: 8.19 sec
Frames: 8190 frames
Lens: Std Nikkon w/2X teleplus
Name: Run_2_1point12_mL_714ACCM
FileSize: 1.99 GB
View: side
Notes: Droplets leaving wet tail

Run: 3  t=9:30
Air flow: 714 ACCM
Water flow: 1.12 mL/min
Rec. Rate: 1000 fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 12 cm
Saved: 8.19 sec
Frames: 8190 frames
Lens: Std Nikkon w/2X teleplus
Name: Run_3_1point12_mL_714ACCM
FileSize: 1.99 GB
View: side
Notes: Droplet fr2984 moves to different location Two droplets interact
### Sample C w/ Kynar

#### Run: 1
- **t=2:39 pm**
- **Air flow:** 714 ACCM
- **Water flow:** 1.12 mL/min
- **Rec. Rate:** 1000 fps
- **Shutter:** 1/6000
- **Resolution:** 1024 x 256
- **Location:** 10 cm
- **Saved:** 8.19 sec
- **Frames:** 8190 frames
- **Lens:** Std Nikkon w/2X teleplus
- **Name:** Run_1_1point12_mL_714ACCM
- **File Size:** 1.99 GB
- **View:** side
- **Notes:** Droplet - leaves water spot

#### Run: 2
- **t=3:10**
- **Air flow:** 714 ACCM
- **Water flow:** 1.12 mL/min
- **Rec. Rate:** 1000 fps
- **Shutter:** 1/6000
- **Resolution:** 1024 x 256
- **Location:** 10 cm
- **Saved:** 8.19 sec
- **Frames:** 8190 frames
- **Lens:** Std Nikkon w/2X teleplus
- **Name:** Run_2_1point12_mL_714ACCM
- **File Size:** 1.99 GB
- **View:** side
- **Notes:** Droplets - leave water behind

#### Run: 3
- **t=4:16**
- **Air flow:** 714 ACCM
- **Water flow:** 1.12 mL/min
- **Rec. Rate:** 1000 fps
- **Shutter:** 1/6000
- **Resolution:** 1024 x 256
- **Location:** 19 cm
- **Saved:** 0.1 sec
- **Frames:** 100 frames
- **Lens:** Std Nikkon w/2X teleplus
- **Name:** Run_3_1point12_mL_714ACCM
- **File Size:** 25 MB
- **View:** side
- **Notes:** Air core, no drops

#### Run: 4
- **t=4:22**
- **Air flow:** 714 ACCM
- **Water flow:** 1.12 mL/min
- **Rec. Rate:** 1000 fps
- **Shutter:** 1/6000
- **Resolution:** 1024 x 256
- **Location:** 19 cm
- **Saved:** 0.1 sec
- **Frames:** 100 frames
- **Lens:** Std Nikkon w/2X teleplus
- **Name:** Run_4_1point12_mL_714ACCM
- **File Size:** 25 MB
- **View:** side
- **Notes:** Air core, no drops

#### Run: 5
- **t=4:53**
- **Air flow:** 714 ACCM
- **Water flow:** 1.12 mL/min
- **Rec. Rate:** 1000 fps
- **Shutter:** 1/6000
- **Resolution:** 1024 x 256
- **Location:** 25 cm
- **Saved:** 0.1 sec
- **Frames:** 100 frames
- **Lens:** Std Nikkon w/2X teleplus
- **Name:** Run_5_1point12_mL_714ACCM
- **File Size:** 25 MB
- **View:** side
- **Notes:** Air core, water on GDM

#### Run: 6
- **t=5:01**
- **Air flow:** 714 ACCM
- **Water flow:** 1.12 mL/min
- **Rec. Rate:** 1000 fps
- **Shutter:** 1/6000
- **Resolution:** 1024 x 256
- **Location:** 25 cm
- **Saved:** 8.19 sec
- **Frames:** 8190 frames
- **Lens:** Std Nikkon w/2X teleplus
- **Name:** Run_6_1point12_mL_714ACCM
- **File Size:** 1.99 GB
- **View:** side
- **Notes:** Air core, growing film, water

---

*GDM Sample C Datasheet*

*File Size: 1.99 GB, View: side, Notes: Air core, growing film, water, lump merges with water on GDM fr5785*
<table>
<thead>
<tr>
<th>Run</th>
<th>Time</th>
<th>Air flow</th>
<th>Water flow</th>
<th>Rec. Rate</th>
<th>Shutter</th>
<th>Resolution</th>
<th>Location</th>
<th>Saved</th>
<th>Frames</th>
<th>Lens</th>
<th>Name</th>
<th>File Size</th>
<th>View</th>
<th>Notes</th>
</tr>
</thead>
</table>
| 1     | 6:32 pm | 714 ACCM | 1.12 mL/min | 1000 fps | 1/6000  | 1024 x 256 | 16 cm   | 8.19 sec | 8190 frames | Std Nikkon w/2X teleplus | Run_1_1point12_mL_714ACCM | 1.99 GB   | side | Sliding drop departure  
Small drop feeding water formation  
Looks like water flows on GDM surface |
| 2     | 7:08 pm | 714 ACCM | 0.56 mL/min | 1000 fps | 1/6000  | 1024 x 256 | 3 cm    | 3 sec    | 3000 frames | Std Nikkon w/2X teleplus | Run_2_point56_mL_714ACCM | 750 MB    | side | Water formation in bottom corner  
no drops |
| 3     | 7:30 pm | 714 ACCM | 0.56 mL/min | 1000 fps | 1/6000  | 1024 x 256 | 5 cm    | 1 sec    | 1000 frames | Std Nikkon w/2X teleplus | Run_3_point56_mL_714ACCM | 250 MB    | side | Sidewall rivulets, sidewall drop merges with sidewall rivulet |
| 4     | 7:37 pm | 714 ACCM | 0.56 mL/min | 1000 fps | 1/6000  | 1024 x 256 | 5 cm    | 8.19 sec | 8190 frames | Std Nikkon w/2X teleplus | Run_4_point56_mL_714ACCM | 1.99 GB   | side | Droplet drains down sidewall rivulet |
| 5     | 8:24 pm | 714 ACCM | 0.56 mL/min | 1000 fps | 1/6000  | 1024 x 256 | 10 cm   | 2 sec    | 2000 frames | Std Nikkon w/2X teleplus | Run_5_point56_mL_714ACCM | 500 MB    | side | Droplet comes in from the left  
crashes into another drop fr1345 |
| 6     | 8:51 pm | 714 ACCM | 0.56 mL/min | 1000 fps | 1/6000  | 1024 x 256 | 10 cm   | 2 sec    | 2000 frames | Std Nikkon w/2X teleplus | Run_6_point56_mL_714ACCM | 500 MB    | side | Drop from left fr189, small drop merges w/larger drop fr1150 and  
slides to another location |
GDM Sample C Datasheet

3/25/2005 Sample C w/ Kynar

Run: 7   t=9:11 pm
Air flow: 714 ACCM
Water flow: 0.56 mL/min
Rec. Rate: 1000 fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 9 cm
Saved: 8.19 sec
Frames: 8190 frames
Lens: Std Nikkon w/2X teleplus
Name: Run_7_point56_mL_714ACCM
File Size: 1.99 GB
View: side
Notes: Drop from left fr10, fr628

Run: 10   t=10:33
Air flow: 714 ACCM
Water flow: 0.56 mL/min
Rec. Rate: 1000 fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 24 cm
Saved: 1 sec
Frames: 1000 frames
Lens: Std Nikkon w/2X teleplus
Name: Run_10_point56_mL_714ACCM
File Size: 250 MB
View: side
Notes: Air core, no drops, not much water movement

Run: 8   t=9:47
Air flow: 714 ACCM
Water flow: 0.56 mL/min
Rec. Rate: 1000 fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 13 cm
Saved: 8.19 sec
Frames: 8190 frames
Lens: Std Nikkon w/2X teleplus
Name: Run_8_point56_mL_714ACCM
File Size: 1.99 GB
View: side
Notes: Drop departs into water film

Run: 9   t=10:18
Air flow: 714 ACCM
Water flow: 0.56 mL/min
Rec. Rate: 1000 fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 20 cm
Saved: 2.001 sec
Frames: 2001 frames
Lens: Std Nikkon w/2X teleplus
Name: Run_9_point56_mL_714ACCM
File Size: 500 MB
View: side
Notes: No drops, water film in top corner
### Sample C w/ Kynar

**Run:** 1  
**t=4:12 pm**  
**Air flow:** 714 ACCM  
**Water flow:** 0.28 mL/min  
**Rec. Rate:** 1000 fps  
**Shutter:** 1/6000  
**Resolution:** 1024 x 256  
**Location:** 5 cm  
**Saved:** 8.19 sec  
**Frames:** 8190 frames  
**Lens:** Std Nikkon w/2X teleplus  
**Name:** Run_1_point28_mL_714ACCM  
**File Size:** 1.99 GB  
**View:** side  
**Notes:** Water neck, no drops

**Run:** 2  
**t=4:35**  
**Air flow:** 714 ACCM  
**Water flow:** 0.28 mL/min  
**Rec. Rate:** 1000 fps  
**Shutter:** 1/6000  
**Resolution:** 1024 x 256  
**Location:** 5 cm  
**Saved:** 8.19 sec  
**Frames:** 8190 frames  
**Lens:** Std Nikkon w/2X teleplus  
**Name:** Run_2_point28_mL_714ACCM  
**File Size:** 1.99 GB  
**View:** side  
**Notes:** Water draining down sidewall

**Run:** 3  
**t=4:58**  
**Air flow:** 714 ACCM  
**Water flow:** 0.28 mL/min  
**Rec. Rate:** 1000 fps  
**Shutter:** 1/6000  
**Resolution:** 1024 x 256  
**Location:** 3 cm  
**Saved:** 8.19 sec  
**Frames:** 8190 frames  
**Lens:** Std Nikkon w/2X teleplus  
**Name:** Run_3_point28_mL_714ACCM  
**File Size:** 1.99 GB  
**View:** side  
**Notes:** Several drops  
Large drop into smaller drop fr2042

**Run:** 4  
**t=5:37**  
**Air flow:** 714 ACCM  
**Water flow:** 0.28 mL/min  
**Rec. Rate:** 1000 fps  
**Shutter:** 1/6000  
**Resolution:** 1024 x 256  
**Location:** 11 cm  
**Saved:** 8.19 sec  
**Frames:** 8190 frames  
**Lens:** Std Nikkon w/2X teleplus  
**Name:** Run_4_point28_mL_714ACCM  
**File Size:** 1.99 GB  
**View:** side  
**Notes:** Some slug action, no drops

**Run:** 5  
**t=6:19**  
**Air flow:** 714 ACCM  
**Water flow:** 0.28 mL/min  
**Rec. Rate:** 1000 fps  
**Shutter:** 1/6000  
**Resolution:** 1024 x 256  
**Location:** 17 cm  
**Saved:** 8.19 sec  
**Frames:** 8190 frames  
**Lens:** Std Nikkon w/2X teleplus  
**Name:** Run_5_point28_mL_714ACCM  
**File Size:** 1.99 GB  
**View:** side  
**Notes:** No drops  
water on/in top corners

**Run:** 6  
**t=6:54**  
**Air flow:** 714 ACCM  
**Water flow:** 0.28 mL/min  
**Rec. Rate:** 1000 fps  
**Shutter:** 1/6000  
**Resolution:** 1024 x 256  
**Location:** 23 cm  
**Saved:** 2 sec  
**Frames:** 2000 frames  
**Lens:** Std Nikkon w/2X teleplus  
**Name:** Run_6_point28_mL_714ACCM  
**File Size:** 500 MB  
**View:** side  
**Notes:** No drops  
water on/in top corners
GDM Sample C Datasheet

3/28/2005

Sample C w/ Kynar

Run: 7  t=7:40 pm
Air flow: 351 ACCM
Water flow: 0.28 mL/min
Rec. Rate: 1000 fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 3 cm
Saved: 8.19 sec
Frames: 8190 frames
Lens: Std Nikkon w/2X teleplus
Name: Run_7_point28_mL_351ACCM
File Size: 1.99 GB
View: side
Notes: Large water droplets
GDM Sample C Datasheet

3/29/2005 Sample C w/ Kynar

Run:  1  t=3:21 pm
Air flow: 351 ACCM
Water flow: 0.28 mL/min
Rec. Rate: 1000 fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 11 cm
Saved: 1 sec
Frames: 1000 frames
Lens: Std Nikkon w/2X teleplus
Name: Run_1_point28_mL_351ACCM
FileSize: 250 MB
View: side
Notes: No drps, large slug on GDM

Run:  2  t=3:29
Air flow: 351 ACCM
Water flow: 0.28 mL/min
Rec. Rate: 1000 fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 4 cm
Saved: 2 sec
Frames: 2000 frames
Lens: Std Nikkon w/2X teleplus
Name: Run_2_point28_mL_351ACCM
FileSize: 500 MB
View: side
Notes: No drops shearing off
drops on sidewall

Run:  3  t=4:45
Air flow: 351 ACCM
Water flow: 0.28 mL/min
Rec. Rate: 1000 fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 18 cm
Saved: 1 sec
Frames: 1000 frames
Lens: Std Nikkon w/2X teleplus
Name: Run_3_point28_mL_351ACCM
FileSize: 250 MB
View: side
Notes: Slug/film on GDM surface
no drops

Run:  4  t=5:12
Air flow: 351 ACCM
Water flow: 0.28 mL/min
Rec. Rate: 1000 fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 25 cm
Saved: 8.19 sec
Frames: 8190 frames
Lens: Std Nikkon w/2X teleplus
Name: Run_4_point28_mL_351ACCM
FileSize: 1.99 GB
View: side
Notes: Film on GDM surface grows
thicker ~fr2399

Run:  5  t=5:47
Air flow: 351 ACCM
Water flow: 0.28 mL/min
Rec. Rate: 1000 fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 4 cm
Saved: 8.19 sec
Frames: 8190 frames
Lens: Std Nikkon w/2X teleplus
Name: Run_5_point28_mL_351ACCM
FileSize: 1.99 GB
View: side
Notes: No drops shearing off
very small drop shearing off
sidewall

Run:  6  t=6:16
Air flow: 351 ACCM
Water flow: 0.56 mL/min
Rec. Rate: 1000 fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 4 cm
Saved: 8.19 sec
Frames: 8190 frames
Lens: Std Nikkon w/2X teleplus
Name: Run_6_point56_mL_351ACCM
FileSize: 1.99 GB
View: side
Notes: Large drop moves along GDM
and flows into channel corner
water
3/29/2005

Sample C w/ Kynar

Run: 7  t=6:55 pm
Air flow: 351 ACCM
Water flow: 0.56 mL/min
Rec. Rate: 1000 fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 3 cm
Saved: 1.001 sec
Frames: 1001 frames
Lens: Std Nikkon w/2X teleplus
Name: Run_7_point56_mL_351ACCM
FileSize: 250 MB
View: side
Notes: One drop location growing into sidewall
        water slugs on channel bottom

Run: 8  t=7:30
Air flow: 351 ACCM
Water flow: 0.56 mL/min
Rec. Rate: 1000 fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 12 cm
Saved: 8.19 sec
Frames: 8190 frames
Lens: Std Nikkon w/2X teleplus
Name: Run_8_point56_mL_351ACCM
FileSize: 1.99 GB
View: side
Notes: Water slug on GDM merges with water in
        channel corner fr225

Run: 9  t=7:59
Air flow: 351 ACCM
Water flow: 0.56 mL/min
Rec. Rate: 1000 fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 17 cm
Saved: 1 sec
Frames: 1000 frames
Lens: Std Nikkon w/2X teleplus
Name: Run_9_point56_mL_351ACCM
FileSize: 250 MB
View: side
Notes: Air core type flow, two water lumps
        no drops
### Sample C w/ Kynar

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<th>t=7:33 pm</th>
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<td>ACCM</td>
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<tr>
<td>Water flow</td>
<td>0.56</td>
<td>mL/min</td>
</tr>
<tr>
<td>Rec. Rate</td>
<td>1000 fps</td>
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<tr>
<td>Shutter</td>
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<tr>
<td>Resolution</td>
<td>1024 x 256</td>
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<tr>
<td>Location</td>
<td>26 cm</td>
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<td>Saved</td>
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<tr>
<td>Frames</td>
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<td>Lens: Std Nikon w/2X teleplus</td>
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<tr>
<td>Notes: Air core type flow, water on GDM surface, no drops</td>
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<td>Rec. Rate</td>
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<td>Shutter</td>
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<td>Resolution</td>
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<td>Notes: Air core type flow, no drops</td>
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<td>Shutter</td>
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<td>Frames</td>
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<td>Lens: Std Nikon w/2X teleplus</td>
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<td>View: side</td>
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<tr>
<td>Notes: Small drop growing into another drop hitting sidewall</td>
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<td>Water flow</td>
<td>0.56</td>
<td>mL/min</td>
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<tr>
<td>Rec. Rate</td>
<td>1000 fps</td>
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<tr>
<td>Shutter</td>
<td>1/6000</td>
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<tr>
<td>Resolution</td>
<td>1024 x 256</td>
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<tr>
<td>Location</td>
<td>4 cm</td>
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<tr>
<td>Saved</td>
<td>8.19 sec</td>
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<tr>
<td>Frames</td>
<td>8190 frames</td>
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<td>Lens: Std Nikon w/2X teleplus</td>
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<td>File Size</td>
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<td>View: side</td>
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<tr>
<td>Notes: Small drop growing into another drop hitting sidewall</td>
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<table>
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<tr>
<th>Run</th>
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<td>Water flow</td>
<td>0.56</td>
<td>mL/min</td>
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<td>Rec. Rate</td>
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<td>Shutter</td>
<td>1/6000</td>
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<tr>
<td>Resolution</td>
<td>1024 x 256</td>
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<td>Location</td>
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<tr>
<td>Saved</td>
<td>2 sec</td>
<td></td>
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<tr>
<td>Frames</td>
<td>2000 frames</td>
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<td>Lens: Std Nikon w/2X teleplus</td>
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<tr>
<td>View: side</td>
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<tr>
<td>Notes: Small drop growing into another drop - drains down sidewall One drop hangs on GDM</td>
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<th>Run</th>
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<td>ACCM</td>
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<td>Water flow</td>
<td>1.12</td>
<td>mL/min</td>
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<tr>
<td>Rec. Rate</td>
<td>1000 fps</td>
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</tr>
<tr>
<td>Shutter</td>
<td>1/6000</td>
<td></td>
</tr>
<tr>
<td>Resolution</td>
<td>1024 x 256</td>
<td></td>
</tr>
<tr>
<td>Location</td>
<td>4 cm</td>
<td></td>
</tr>
<tr>
<td>Saved</td>
<td>8.19 sec</td>
<td></td>
</tr>
<tr>
<td>Frames</td>
<td>8190 frames</td>
<td></td>
</tr>
<tr>
<td>Lens: Std Nikon w/2X teleplus</td>
<td></td>
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</tr>
<tr>
<td>Name: Run_6_1point12_mL_351ACCM</td>
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<td>File Size</td>
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<tr>
<td>View: side</td>
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<tr>
<td>Notes: Large drop merging with top water, seen through sidewall water</td>
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<td></td>
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### Sample C w/ Kynar

<table>
<thead>
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<th>t</th>
<th>Air flow</th>
<th>Water flow</th>
<th>Rec. Rate</th>
<th>Shutter</th>
<th>Resolution</th>
<th>Location</th>
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<th>Frames</th>
<th>Lens</th>
<th>Name</th>
<th>File Size</th>
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<tbody>
<tr>
<td>7</td>
<td>9:33 pm</td>
<td>351 ACCM</td>
<td>1.12 mL/min</td>
<td>1000 fps</td>
<td>1/6000</td>
<td>1024 x 256</td>
<td>4 cm</td>
<td>8.19 sec</td>
<td>8190 frames</td>
<td>Std Nikkon w/2X teleplus</td>
<td>Run_7_1point12_mL_351ACCM</td>
<td>1.99 GB</td>
<td>side</td>
<td>Large drop shearing off</td>
</tr>
<tr>
<td>8</td>
<td>9:55</td>
<td>351 ACCM</td>
<td>1.12 mL/min</td>
<td>1000 fps</td>
<td>1/6000</td>
<td>1024 x 256</td>
<td>4 cm</td>
<td>8.19 sec</td>
<td>8190 frames</td>
<td>Std Nikkon w/2X teleplus</td>
<td>Run_8_1point12_mL_351ACCM</td>
<td>1.99 GB</td>
<td>side</td>
<td>Large drop shearing off fr1637</td>
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<tr>
<td>9</td>
<td>10:32</td>
<td>351 ACCM</td>
<td>1.12 mL/min</td>
<td>1000 fps</td>
<td>1/6000</td>
<td>1024 x 256</td>
<td>4 cm</td>
<td>8.19 sec</td>
<td>8190 frames</td>
<td>Std Nikkon w/2X teleplus</td>
<td>Run_9_1point12_mL_351ACCM</td>
<td>1.99 GB</td>
<td>side</td>
<td>Several drops shear off, one larger drop does not shear off smaller drop shears w/little deformation</td>
</tr>
<tr>
<td>10</td>
<td>10:53</td>
<td>351 ACCM</td>
<td>1.12 mL/min</td>
<td>1000 fps</td>
<td>1/6000</td>
<td>1024 x 256</td>
<td>4 cm</td>
<td>8.19 sec</td>
<td>8190 frames</td>
<td>Std Nikkon w/2X teleplus</td>
<td>Run_10_1point12_mL_351ACCM</td>
<td>1.99 GB</td>
<td>side</td>
<td>Large drop shearing off</td>
</tr>
<tr>
<td>11</td>
<td>11:29</td>
<td>351 ACCM</td>
<td>1.12 mL/min</td>
<td>1000 fps</td>
<td>1/6000</td>
<td>1024 x 256</td>
<td>25 cm</td>
<td>8.19 sec</td>
<td>8190 frames</td>
<td>Std Nikkon w/2X teleplus</td>
<td>Run_11_1point12_mL_351ACCM</td>
<td>1.99 GB</td>
<td>side</td>
<td>Periodic air core - water lump flowing along top of GDM</td>
</tr>
<tr>
<td>12</td>
<td>12:36 am</td>
<td>351 ACCM</td>
<td>1.12 mL/min</td>
<td>1000 fps</td>
<td>1/6000</td>
<td>1024 x 256</td>
<td>17 cm</td>
<td>1 sec</td>
<td>8190 frames</td>
<td>Std Nikkon w/2X teleplus</td>
<td>Run_12_1point12_mL_351ACCM</td>
<td>250 MB</td>
<td>side</td>
<td>Air core - no visible water movement, no drops</td>
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3/30/2005 Sample C w/ Kynar

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<th>Value</th>
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<tr>
<td>t</td>
<td>12:41 am</td>
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<tr>
<td>Air flow</td>
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<tr>
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<td>1.12 mL/min</td>
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<td>Rec. Rate</td>
<td>1000 fps</td>
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<tr>
<td>Shutter</td>
<td>1/6000</td>
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<td>Resolution</td>
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<tr>
<td>Location</td>
<td>11 cm</td>
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<tr>
<td>Saved</td>
<td>1 sec</td>
</tr>
<tr>
<td>Frames</td>
<td>1000 frames</td>
</tr>
<tr>
<td>Lens</td>
<td>Std Nikkon w/2X teleplus</td>
</tr>
<tr>
<td>Name</td>
<td>Run_13_1point12_mL_351ACCM</td>
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<tr>
<td>File Size</td>
<td>250 MB</td>
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<tr>
<td>View</td>
<td>side</td>
</tr>
<tr>
<td>Notes</td>
<td>Air core - no visible water movement, no drops</td>
</tr>
</tbody>
</table>
Run: 1  t=7:10 pm
Air flow: 175 ACCM
Water flow: 1.12 mL/min
Rec. Rate: 1000 fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 3 cm
Saved: 8.19 sec
Frames: 8190 frames
Lens: Std Nikkon w/2X teleplus
Name: Run_1_1point12_mL_175ACCM
File Size: 1.99 GB
View: side
Notes: Water on sidewall and top channel corner, one drop hits sidewall

Run: 2  t=7:36
Air flow: 175 ACCM
Water flow: 1.12 mL/min
Rec. Rate: 1000 fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 6 cm
Saved: 8.19 sec
Frames: 8190 frames
Lens: Std Nikkon w/2X teleplus
Name: Run_2_1point12_mL_175ACCM
File Size: 1.99 GB
View: side
Notes: Air core type flow, no drops

Run: 3  t=8:19
Air flow: 175 ACCM
Water flow: 1.12 mL/min
Rec. Rate: 1000 fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 6 cm
Saved: 8.19 sec
Frames: 8190 frames
Lens: Std Nikkon w/2X teleplus
Name: Run_3_1point12_mL_175ACCM
File Size: 1.99 GB
View: side
Notes: Water lump moving on top of GDM flowing into other water fr1939

Run: 4  t=8:40
Air flow: 175 ACCM
Water flow: 1.12 mL/min
Rec. Rate: 1000 fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 12 cm
Saved: 8.19 sec
Frames: 8190 frames
Lens: Std Nikkon w/2X teleplus
Name: Run_4_1point12_mL_175ACCM
File Size: 1.99 GB
View: side
Notes: Neck into plug fr1908, Necks fr1251, fr1514, fr2526, fr3838, fr5355, fr7161

Run: 5  t=9:18
Air flow: 175 ACCM
Water flow: 1.12 mL/min
Rec. Rate: 1000 fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 12 cm
Saved: 8.19 sec
Frames: 8190 frames
Lens: Std Nikkon w/2X teleplus
Name: Run_5_1point12_mL_175ACCM
File Size: 1.99 GB
View: side
Notes: No drops, instability fr135, fr350 Neck fr151, fr359, fr427 Good neck fr3694

Run: 6  t=12:35 am
Air flow: 175 ACCM
Water flow: 1.12 mL/min
Rec. Rate: 1000 fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 19 cm
Saved: 8.19 sec
Frames: 8190 frames
Lens: Std Nikkon w/2X teleplus
Name: Run_6_1point12_mL_175ACCM
File Size: 1.99 GB
View: side
Notes: Slug and Ring flow, slug fr410 fr621, lump fr 4011, ring fr598 fr2138
3/31/2005

Sample C w/ Kynar

Run: 7 t=1:13 am
Air flow: 175 ACCM
Water flow: 1.12 mL/min
Rec. Rate: 1000 fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 24 cm
Saved: 8.19 sec
Frames: 8190 frames
Lens: Std Nikkon w/2X teleplus
Name: Run_7_1point12_mL_175ACCM
File Size: 1.99 GB
View: side
Notes: Slug/ring flow fr516, reforming neck fr1051, reforming ring fr7205

Run: 8 t=2:18
Air flow: 175 ACCM
Water flow: 0.56 mL/min
Rec. Rate: 1000 fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 4 cm
Saved: 1 sec
Frames: 1000 frames
Lens: Std Nikkon w/2X teleplus
Name: Run_8_point56_mL_175ACCM
File Size: 250 MB
View: side
Notes: No drops, water on channel walls, water lump does not move

Run: 9 t=2:28
Air flow: 175 ACCM
Water flow: 0.56 mL/min
Rec. Rate: 1000 fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 11 cm
Saved: 1 sec
Frames: 1000 frames
Lens: Std Nikkon w/2X teleplus
Name: Run_9_point56_mL_175ACCM
File Size: 250 MB
View: side
Notes: Water in corners, no drops

Run: 10 t=2:36
Air flow: 175 ACCM
Water flow: 0.56 mL/min
Rec. Rate: 1000 fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 11 cm
Saved: 1 sec
Frames: 1000 frames
Lens: Std Nikkon w/2X teleplus
Name: Run_10_point56_mL_175ACCM
File Size: 250 MB
View: side
Notes: No drops, water neck draining down sidewall

Run: 11 t=2:41
Air flow: 175 ACCM
Water flow: 0.56 mL/min
Rec. Rate: 1000 fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 16 cm
Saved: 2 sec
Frames: 2000 frames
Lens: Std Nikkon w/2X teleplus
Name: Run_11_point56_mL_175ACCM
File Size: 500 MB
View: side
Notes: No drops, air core - water lump flowing on GDM

Run: 12 t=3:02
Air flow: 175 ACCM
Water flow: 0.56 mL/min
Rec. Rate: 1000 fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 24 cm
Saved: 8.19 sec
Frames: 8190 frames
Lens: Std Nikkon w/2X teleplus
Name: Run_12_point56_mL_175ACCM
File Size: 1.99 GB
View: side
Notes: No drops, large water lump fr1086
Run: 13  t=3:47 am
Air flow: 175  ACCM
Water flow: 0.28  mL/min
Rec. Rate: 1000  fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 4  cm
Saved: 3  sec
Frames: 3000  frames
Lens: Std Nikkon w/2X teleplus
Name: Run_13_point28_mL_175ACCM
File Size: 750  MB
View: side
Notes: Large water lump merges with channel water on walls fr1679

Run: 14  t=4:03
Air flow: 175  ACCM
Water flow: 0.28  mL/min
Rec. Rate: 1000  fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 12  cm
Saved: 2  sec
Frames: 2000  frames
Lens: Std Nikkon w/2X teleplus
Name: Run_14_point28_mL_175ACCM
File Size: 500  MB
View: side
Notes: no drops, water neck draining down sidewalls

Run: 15  t=4:14
Air flow: 175  ACCM
Water flow: 0.28  mL/min
Rec. Rate: 1000  fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 11  cm
Saved: 1  sec
Frames: 1000  frames
Lens: Std Nikkon w/2X teleplus
Name: Run_15_point28_mL_175ACCM
File Size: 250  MB
View: side
Notes: no drops, one large liquid lump

Run: 16  t=4:20
Air flow: 175  ACCM
Water flow: 0.28  mL/min
Rec. Rate: 1000  fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 19  cm
Saved: 1  sec
Frames: 1000  frames
Lens: Std Nikkon w/2X teleplus
Name: Run_16_point28_mL_175ACCM
File Size: 250  MB
View: side
Notes: no drops, air core type flow appears that water is flowing in top corner

Run: 17  t=4:28
Air flow: 175  ACCM
Water flow: 0.28  mL/min
Rec. Rate: 1000  fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 24  cm
Saved: 2  sec
Frames: 2000  frames
Lens: Std Nikkon w/2X teleplus
Name: Run_17_point28_mL_175ACCM
File Size: 500  MB
View: side
Notes: Air core type flow water on GDM

Notes: Large water lump merges with channel water on walls fr1679

Notes: no drops, water neck draining down sidewalls

Notes: no drops, one large liquid lump
4/1/2005

Sample C w/ Kynar

Run: 1
t=2:58 pm
Air flow: 88 ACCM
Water flow: 0.28 mL/min
Rec. Rate: 1000 fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 10 cm
Saved: 8.19 sec
Frames: 8190 frames
Lens: Std Nikkon w/2X teleplus
Name: Run_1_point28_mL_88ACCM
FileSize: 1.99 GB
View: side
Notes: No drops, water formations in channel
merge to form slugs at fr 990, fr2769, fr4302, fr4766, fr6794

Run: 2
t=5:30
Air flow: 88 ACCM
Water flow: 0.28 mL/min
Rec. Rate: 1000 fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 10 cm
Saved: 8.19 sec
Frames: 8190 frames
Lens: Std Nikkon w/2X teleplus
Name: Run_2_point28_mL_88ACCM
FileSize: 1.99 GB
View: side
Notes: No drops, air core type flow with slug formation
fr3679, fr4948, fr5013, fr5254, fr6357, fr7453
Run: 1
t=3:42 pm
Air flow: 88 ACCM
Water flow: 0.28 mL/min
Rec. Rate: 1000 fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 3 cm
Saved: 1 sec
Frames: 1000 frames
Lens: Std Nikkon w/2X teleplus
Name: Run_1_point28_mL_88ACCM
FileSize: 250 MB
View: side
Notes: Large water lump, no drops

Run: 2
t=3:48
Air flow: 88 ACCM
Water flow: 0.28 mL/min
Rec. Rate: 1000 fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 3 cm
Saved: 2 sec
Frames: 2000 frames
Lens: Std Nikkon w/2X teleplus
Name: Run_2_point28_mL_88ACCM
FileSize: 500 MB
View: side
Notes: No drops, water in channel

Run: 3
t=3:59
Air flow: 88 ACCM
Water flow: 0.28 mL/min
Rec. Rate: 1000 fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 17 cm
Saved: 8.19 sec
Frames: 8190 frames
Lens: Std Nikkon w/2X teleplus
Name: Run_3_point28_mL_88ACCM
FileSize: 1.99 GB
View: side
Notes: No drops, several rings and slugs form

Run: 4
t=4:26
Air flow: 88 ACCM
Water flow: 0.28 mL/min
Rec. Rate: 1000 fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 17 cm
Saved: 8.19 sec
Frames: 8190 frames
Lens: Std Nikkon w/2X teleplus
Name: Run_4_point28_mL_88ACCM
FileSize: 1.99 GB
View: side
Notes: No drops, several rings form

Run: 5
t=5:49
Air flow: 88 ACCM
Water flow: 0.28 mL/min
Rec. Rate: 1000 fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 19 cm
Saved: 8.19 sec
Frames: 8190 frames
Lens: Std Nikkon w/2X teleplus
Name: Run_5_point28_mL_88ACCM
FileSize: 1.99 GB
View: side
Notes: No drops, slug flow, ring flow fr2010

Run: 6
t=6:36
Air flow: 88 ACCM
Water flow: 0.28 mL/min
Rec. Rate: 1000 fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 25 cm
Saved: 8.19 sec
Frames: 8190 frames
Lens: Std Nikkon w/2X teleplus
Name: Run_6_point28_mL_88ACCM
FileSize: 1.99 GB
View: side
Notes: No drops, slug flow, very thin ring flow fr1188, fr2174, fr3188, fr3798, fr4345, fr4821, fr7109
4/4/2005

Sample C w/ Kynar

Run: 7  t=7:22 pm
Air flow: 88  ACCM
Water flow: 0.56  mL/min
Rec. Rate: 1000  fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 3  cm
Saved: 1  sec
Frames: 1000  frames
Lens: Std Nikkon w/2X teleplus
Name: Run_7_point56_mL_88ACCM
FileSize: 250  MB
View: side
Notes: No drops, large water lump on GDM, water in channel corners

Run: 8  t=7:28
Air flow: 88  ACCM
Water flow: 0.56  mL/min
Rec. Rate: 1000  fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 6  cm
Saved: 8.19  sec
Frames: 8190  frames
Lens: Std Nikkon w/2X teleplus
Name: Run_8_point56_mL_88ACCM
FileSize: 1.99  GB
View: side
Notes: No drops, water on GDM surface
### GDM Sample C Datasheet

**4/11/2005**

**Sample C w/ Kynar**

<table>
<thead>
<tr>
<th>Run</th>
<th>t (pm)</th>
<th>Air flow</th>
<th>Water flow</th>
<th>Rec. Rate</th>
<th>Shutter</th>
<th>Resolution</th>
<th>Location</th>
<th>Saved</th>
<th>Frames</th>
<th>Lens</th>
<th>Name</th>
<th>File Size</th>
<th>View</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10:18</td>
<td>88 ACCM</td>
<td>0.56 mL/min</td>
<td>1000 fps</td>
<td>1/6000</td>
<td>1024 x 256</td>
<td>3 cm</td>
<td>1.75</td>
<td>1750</td>
<td>Std Nikkon w/2X teleplus</td>
<td>Run_1_point56_mL_88ACCM</td>
<td>437 MB</td>
<td>side</td>
<td>No drops, large water lump merges with channel bottom water</td>
</tr>
<tr>
<td>2</td>
<td>10:36</td>
<td>88 ACCM</td>
<td>0.56 mL/min</td>
<td>1000 fps</td>
<td>1/6000</td>
<td>1024 x 256</td>
<td>10 cm</td>
<td>1 sec</td>
<td>1000</td>
<td>Std Nikkon w/2X teleplus</td>
<td>Run_2_point56_mL_88ACCM</td>
<td>250 MB</td>
<td>side</td>
<td>No drops, large water slug moves through channel</td>
</tr>
<tr>
<td>3</td>
<td>10:47</td>
<td>88 ACCM</td>
<td>0.56 mL/min</td>
<td>1000 fps</td>
<td>1/6000</td>
<td>1024 x 256</td>
<td>18 cm</td>
<td>1.296</td>
<td>1296</td>
<td>Std Nikkon w/2X teleplus</td>
<td>Run_3_point56_mL_88ACCM</td>
<td>324 MB</td>
<td>side</td>
<td>No drops, large water slug sideways necking fr129</td>
</tr>
<tr>
<td>4</td>
<td>11:01</td>
<td>88 ACCM</td>
<td>0.56 mL/min</td>
<td>1000 fps</td>
<td>1/6000</td>
<td>1024 x 256</td>
<td>25 cm</td>
<td>8.19</td>
<td>8190</td>
<td>Std Nikkon w/2X teleplus</td>
<td>Run_4_point56_mL_88ACCM</td>
<td>1.99 GB</td>
<td>side</td>
<td>No drops, several water slugs flow through channel</td>
</tr>
<tr>
<td>5</td>
<td>11:28</td>
<td>88 ACCM</td>
<td>1.12 mL/min</td>
<td>1000 fps</td>
<td>1/6000</td>
<td>1024 x 256</td>
<td>4 cm</td>
<td>8.19</td>
<td>8190</td>
<td>Std Nikkon w/2X teleplus</td>
<td>Run_5_point56_mL_88ACCM</td>
<td>1.99 GB</td>
<td>side</td>
<td>No drops, water film on GDM lump/film grows into slug fr4475 and fr5762</td>
</tr>
<tr>
<td>6</td>
<td>11:53</td>
<td>88 ACCM</td>
<td>1.12 mL/min</td>
<td>1000 fps</td>
<td>1/6000</td>
<td>1024 x 256</td>
<td>11 cm</td>
<td>1</td>
<td>1000</td>
<td>Std Nikkon w/2X teleplus</td>
<td>Run_6_point56_mL_88ACCM</td>
<td>250 MB</td>
<td>side</td>
<td>No drops, water slugs, water in channel corners</td>
</tr>
</tbody>
</table>
4/11/2005

Sample C w/ Kynar

Run: 7  t=12:02 am
Air flow: 88  ACCM
Water flow: 1.12  mL/min
Rec. Rate: 1000  fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 18  cm
Saved: 1  sec
Frames: 1000  frames
Lens: Std Nikkon w/2X teleplus
Name: Run_7_1point12_mL_88ACCM
FileSize: 250  MB
View: side
Notes: No drops, water slugs, water in channel corners

Run: 8  t=12:12
Air flow: 88  ACCM
Water flow: 1.12  mL/min
Rec. Rate: 1000  fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 25  cm
Saved: 8.19  sec
Frames: 8190  frames
Lens: Std Nikkon w/2X teleplus
Name: Run_8_1point12_mL_88ACCM
FileSize: 1.99  GB
View: side
Notes: No drops, large water slug at beginning of video, slug/channel water interactions fr2192
GDM Sample C Datasheet

4/12/2005

Sample C w/ Kynar

Run: 1 t=3:33 pm
Air flow: 48 ACCM
Water flow: 1.12 mL/min
Rec. Rate: 1000 fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 4 cm
Saved: 8.19 sec
Frames: 8190 frames
Lens: Std Nikkon w/2X teleplus
Name: Run_1_1point12_mL_48ACCM
File Size: 1.99 GB
View: side
Notes: No drops, lump moving on top of GDM

Run: 2 t=3:56
Air flow: 48 ACCM
Water flow: 1.12 mL/min
Rec. Rate: 1000 fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 4 cm
Saved: 8.19 sec
Frames: 8190 frames
Lens: Std Nikkon w/2X teleplus
Name: Run_2_1point12_mL_48ACCM
File Size: 1.99 GB
View: side
Notes: No drops, liquid lump forms slug by dropping from GDM fr1521, fr3830

Run: 3 t=6:02
Air flow: 48 ACCM
Water flow: 1.12 mL/min
Rec. Rate: 1000 fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 12 cm
Saved: 2.251 sec
Frames: 2251 frames
Lens: Std Nikkon w/2X teleplus
Name: Run_3_1point12_mL_48ACCM
File Size: 562 MB
View: side
Notes: No drops, lump flow on GDM several lumps ~ periodic

Run: 4 t=6:21
Air flow: 48 ACCM
Water flow: 1.12 mL/min
Rec. Rate: 1000 fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 18 cm
Saved: 8.19 sec
Frames: 8190 frames
Lens: Std Nikkon w/2X teleplus
Name: Run_4_1point12_mL_48ACCM
File Size: 1.99 GB
View: side
Notes: No drops, wavy gas core fr4835

Run: 5 t=6:50
Air flow: 48 ACCM
Water flow: 1.12 mL/min
Rec. Rate: 1000 fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 25 cm
Saved: 8.19 sec
Frames: 8190 frames
Lens: Std Nikkon w/2X teleplus
Name: Run_5_1point12_mL_48ACCM
File Size: 1.99 GB
View: side
Notes: No drops, slug flow

Run: 6 t=7:25
Air flow: 48 ACCM
Water flow: 0.56 mL/min
Rec. Rate: 1000 fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 4 cm
Saved: 8.19 sec
Frames: 8190 frames
Lens: Std Nikkon w/2X teleplus
Name: Run_6_point56_mL_48ACCM
File Size: 1.99 GB
View: side
Notes: No drops, lump flow on GDM
### Sample C w/ Kynar

#### Run 7: 7:29 pm
- **Air flow**: 48 ACCM
- **Water flow**: 0.56 mL/min
- **Rec. Rate**: 1000 fps
- **Shutter**: 1/6000
- **Resolution**: 1024 x 256
- **Location**: 11 cm
- **Saved**: 3.05 sec
- **Frames**: 3050 frames
- **Lens**: Std Nikkon w/2X teleplus
- **Name**: Run_7_point56_mL_48ACCM
- **File Size**: 762 MB
- **View**: side
- **Notes**: No drops, lump flow on GDM nearly periodic

#### Run 8: 8:45 pm
- **Air flow**: 48 ACCM
- **Water flow**: 0.56 mL/min
- **Rec. Rate**: 1000 fps
- **Shutter**: 1/6000
- **Resolution**: 1024 x 256
- **Location**: 19 cm
- **Saved**: 3.5 sec
- **Frames**: 3500 frames
- **Lens**: Std Nikkon w/2X teleplus
- **Name**: Run_8_point56_mL_48ACCM
- **File Size**: 875 MB
- **View**: side
- **Notes**: No drops, water flowing through a lump area

#### Run 9: 9:27 pm
- **Air flow**: 48 ACCM
- **Water flow**: 0.56 mL/min
- **Rec. Rate**: 1000 fps
- **Shutter**: 1/6000
- **Resolution**: 1024 x 256
- **Location**: 25 cm
- **Saved**: 2.001 sec
- **Frames**: 2001 frames
- **Lens**: Std Nikkon w/2X teleplus
- **Name**: Run_9_point56_mL_48ACCM
- **File Size**: 500 MB
- **View**: side
- **Notes**: No drops, water lumps on GDM

#### Run 10: 9:59 pm
- **Air flow**: 48 ACCM
- **Water flow**: 0.28 mL/min
- **Rec. Rate**: 1000 fps
- **Shutter**: 1/6000
- **Resolution**: 1024 x 256
- **Location**: 4 cm
- **Saved**: 4.2 sec
- **Frames**: 4200 frames
- **Lens**: Std Nikkon w/2X teleplus
- **Name**: Run_10_point28_mL_48ACCM
- **File Size**: 1.02 GB
- **View**: side
- **Notes**: No drops, water lump rocks back and forth and then moves down the channel

#### Run 11: 10:17 pm
- **Air flow**: 48 ACCM
- **Water flow**: 0.28 mL/min
- **Rec. Rate**: 1000 fps
- **Shutter**: 1/6000
- **Resolution**: 1024 x 256
- **Location**: 11 cm
- **Saved**: 8.19 sec
- **Frames**: 8190 frames
- **Lens**: Std Nikkon w/2X teleplus
- **Name**: Run_11_point28_mL_48ACCM
- **File Size**: 1.99 GB
- **View**: side
- **Notes**: No drops, backward moving film appears to be lump instability

#### Run 12: 10:42 pm
- **Air flow**: 48 ACCM
- **Water flow**: 0.28 mL/min
- **Rec. Rate**: 1000 fps
- **Shutter**: 1/6000
- **Resolution**: 1024 x 256
- **Location**: 19 cm
- **Saved**: 2 sec
- **Frames**: 2000 frames
- **Lens**: Std Nikkon w/2X teleplus
- **Name**: Run_12_point28_mL_48ACCM
- **File Size**: 500 MB
- **View**: side
- **Notes**: No drops, water lump flowing into a thin film
Run: 13  t=10:56 pm
Air flow: 48  ACCM
Water flow: 0.28  mL/min
Rec. Rate: 1000  fps
Shutter: 1/6000
Resolution: 1024 x 256
Location: 25  cm
Saved: 8.19  sec
Frames: 8190  frames
Lens: Std Nikkon w/2X teleplus
Name: Run_13_point28_mL_48ACCM
FileSize: 1.99  GB
View: side
Notes: No drops, slug flow