# Measuring Hydrodynamic Drag of Swimsuits Using Acoustic Doppler Velocimetry

Anita X. Sumali <sup>a)</sup>\* Smriti Chaulagain <sup>b)</sup> Mario F. Sumali <sup>c)</sup> Mark C. Stone <sup>b)</sup> <sup>a)</sup> Texas A&M University, College Station, TX <sup>b)</sup> University of New Mexico, Albuquerque, NM <sup>c)</sup> La Cueva High School, Albuquerque, NM

# ABSTRACT

Some scientific publications (e.g., Luo et al., 2015) mention that expensive Fastskin swimsuits have a special texture to lower hydrodynamic drag and give an advantage in swimming competitions. Our research attempted to investigate that claim. In particular, we measured the skin drag (part of the total passive drag) of different swimsuits using an experimental flume and an Acoustic Doppler Velocimeter (ADV). In the boundary layer, downstream velocity was measured at several distances from the swimsuit surface. The resulting plot of velocity versus distance was curve-fit with an exponential function that decays towards the free-flow velocity as distance increases. From the decay exponent, a metric of drag (proportional to the shear stress on the swimsuit surface) was derived to characterize the skin drag of the swimsuit. Finally, the metric was plotted against the prices of the swimsuits. The result indicates that a more expensive swimsuit does not necessarily give less skin drag than a less expensive swimsuit. We discovered that velocity readings from the ADV near the boundary is biased, and explain that the bias applies consistently to all the swimsuits we tested. Therefore, our conclusion is not affected by the bias.

KEYWORDS: Aquatic Sport, Swimwear, Friction, Flume, Signal Convolution

## **INTRODUCTION**

Morrison (2012) reports that a racing swimsuit reduces drag by 16.6% and therefore increases swimming speed. The racing swimsuit is several times more expensive than average swimsuits. Moreover, that racing swimsuit is excessively tight, uncomfortable, and takes a lot of effort to put on or take off (an average of 30 - 45 minutes with the help of one or more assistants (Mountjoy et al., 2009)). Although many swimmers claim to feel faster racing in an expensive swimsuit than in a regular practice swimsuit (Mooney, 2012), to our knowledge there has not been any scientific proof that indicates a relationship between the cost of swimsuits and the suits' speed through the water. Our research was designed to test the belief that more expensive swimsuits have lower drag.

#### **BACKGROUND LITERATURE**

Prior to the 2004 Athens Olympic Games, Krieger (2004) investigated the performance of the then-new "Fastskin" swimsuit which were becoming extremely popular among competitive swimmers. Bixler (2007) modelled the fluid dynamics for the swimsuit manufacturer and reported that the design reduced the passive drag force, thereby enabling the wearer to swim faster. Krieger mentions a statistical model of Olympic swimming time average improvement over time. The model was able to tell if an unexpected improvement was drastic enough to be an outlier such as a new doping method. The model was used to analyze the swimming times of swimmers wearing a new Fastskin swimsuit in competitions and did not show that the new swimsuit actually resulted in a revolutionary performance improvement. Krieger's report might be evidence that the new competition swimsuits were not likely to cause a radical improvement in swimming time. In fact, preliminary data from the 2000 Sydney Olympics showed that a small group that wore the Fastskin showed slightly poorer time than another small group that wore conventional suits.

Luo et al. (2015) mentions that special swimsuit surface textures emulate shark skin and reduce drag. Zhang et al. (2011) shows that the shark skin surface effectively inhibits turbulence in the water, and as a result reduces the wall friction. Their article discusses experiments and computer simulations to understand the mechanism of drag reduction. It shows a method to simulate the turbulent flow on grooved-scale surfaces. The numerical simulation is based on the real biological shark skin, through an accurate scanning of the surface using a scanning electron microscope. The simulation result explains the drag reduction mechanism. To validate the model of the drag-reducing effect of the shark skin surface, Zhang et al. performed measurements of drag forces on their textured versus non-textured surfaces in a water tunnel. The experimental results are fairly consistent with the numerical simulation. Bixler and Bhushan (2013) measured drag forces on surfaces with various "riblets" designed to emulate the pattern of the scales on the skin of the shark. Bixler and Bhushan conclude that scalloped riblets with a staggered configuration are similar to the shark skin. Compared to smooth surfaces, riblets of certain geometry and spacing are able to reduce water drag forces by up to 5%. This result shows that it is possible that the texture of the shark skin results in lower drag forces compared to smooth surfaces.

Benjanuvatra et al. (2002) examined the drag forces of full-length Fastskin swimsuits and compared them with those of standard swimsuits using a cross-sectional comparison completed with nine Australian national-level (elite) swimmers. The data suggested that the full-length Fastskin swimsuits created less total hydrodynamic resistance than normal swimsuits. The study focuses on drag during surface towing, which is much more complex than drag on fully-immersed body. A moving body on the water surface introduces complex surface wave drags (Mollendorf et al., 2004). More importantly, the use of human swimmers would introduce unwanted variability in the results, which may well overwhelm the difference in drags between Fastskin and regular swimsuits. Toussaint et al. (2002) presented a thorough analysis of drag forces on swimmers including measurements on several swimmers under numerous motions and conditions. They developed sophisticated methods to measure drags, including the system to "measure active drag" (MAD-system) and velocity perturbation method (VPM), among other techniques that will advance drag measurement technology for swimmers. An important point learned from their article is that active drag (the drag on moving swimmers) is far more complex than we will be able to measure and analyze. In our research, we measure the drag contribution from the swimsuit only, not the overall drag during swimming. Thus, we measure only passive drag caused by the swimsuit.

Vennell et al. (2006) performed measurements of passive drag using a pool with a flow generator, and a towed mannequin. The measurements spanned common human swimming speeds. This test setup focused on the measurement of passive drag, especially the drag caused by the swimsuit. The use of a mannequin eliminated the variability caused by human swimmers. Mollendorf et al. (2004) measured passive drag forces on towed swimmers at varying speeds. Using regression analysis, they decomposed the drag forces into: 1) Pressure drag assumed to be proportional to velocity squared; 2) Wave drag assumed to be proportional to velocity squared; 2) Wave drag assumed to be proportional to velocity squared; 2) Wave drag assumed to be proportional to velocity squared; 2) Wave drag assumed to be proportional to velocity squared; 2) Wave drag assumed to be proportional to velocity squared; 2) Wave drag assumed to be proportional to velocity squared; 2) Wave drag assumed to be proportional to velocity squared; 2) Wave drag assumed to be proportional to velocity squared; 2) Wave drag assumed to be proportional to velocity squared; 2) Wave drag assumed to be proportional to velocity squared; 2) Wave drag assumed to be proportional to velocity to the fourth power. Wave drag is the smallest component of drag; and 3) Skin friction drag which is the total drag minus the other two drags. Their data showed that skin friction drag is the largest component of total drag when the swimsuit covered the whole torso. Mollendorf et al. also showed that skin friction drag was the drag most affected by swimsuits. The difference in drag forces caused by different swimsuits is small. However, that difference is what the expensive swimsuit manufacturers claim to be the advantage of their expensive swimsuit. Our method is designed to measure this small difference among swimsuits.

Based on Mollendorf et al. (2004), our experiments will measure only the skin friction drag. Unlike the methods discussed above, our method of measuring skin friction drag does not require measurement of forces. Instead, we use the boundary layer theory (e.g., Kreith, 2000) to directly measure how the surface or the swimsuit slows down water flow.

#### **EXPERIMENT**

In our experiment, the swimsuit was held stationary, and water flowed over the swimsuit. We measured the velocity of the water at different distances from the swimsuit and used the different velocities to estimate a skin drag coefficient. To measure the flow velocity, we used an Acoustic Doppler Velocimeter (MicroADV<sup>®</sup>, three-probe, SonTek Technical Notes, 2016). This ADV generates 16 MHz ultrasonic vibration at the end of a rod. The vibration excites particulate matter in the flow. The resulting particle vibration frequency is Doppler-shifted by the velocity of the water flow. Frequency shifts in three directions are sensed by three probes beyond the end of the rod. These frequency shifts are transformed into flow velocity components (u, v, and w) in three cartesian directions (x, y and z). The ADV also measures the distance from the swimsuit surface by measuring the time of flight of ultrasonic pulses from and back to the generator. The sampling rate was 50 Hz.

Our tests were done in a laboratory hydraulic flume (Figure 1), which created laminar water flow (e.g., Neufeld, 2008). Figure 2 shows our experimental setup. The swimsuit was fixed on a flat board on the bottom of the flume. The temporary angle profile bar showing on the left was removed before the test. A test point was chosen at 200 mm from the leading edge of the swimsuit, on the mid-line between the side walls. Above the test point on the swimsuit, the ADV was fixed in the downstream and sideways positions. The stem appears offset in Figure 2 because of light refraction in the water. A slider enabled the ADV to be positioned arbitrarily in the vertical (y) direction. Water in the flume was made to flow over the swimsuit at

a constant, controlled flow rate. High above the swimsuit surface, the free-stream velocity  $u_0$  was measured using the velocimeter. The depth of the flowing water in the flume was a few hundred millimeters. For each test, the free stream velocity  $u_0$  was measured at three depths near the water surface. The  $u_0$  that was chosen was the one that resulted in the highest coefficient of correlation in the regression analysis below. For "Swimsuit 1", the free stream velocity used was  $u_0 = 0.280$  m/s. As the ADV was brought down closer to the swimsuit surface, the measured velocity u(y) decreased. The velocities in the boundary layer are listed with the corresponding distances from the swimsuit surface in Table 1.



Figure 1. Flume used in the skin friction measurement.



Figure 2. Acoustic Doppler Velocimeter (ADV) over a swimsuit.

y, mm	3.041	3.041	3.569	3.813	3.813	4.416	5.762
<i>u</i> , mm/s	236.7	239.9	241.0	247.0	248.7	243.7	256.4
<i>y</i> , mm	6.863	6.904	8.276	9.633	10.089	12.545	19.856
<i>u</i> , mm/s	257.9	262.5	262.4	263.4	266.2	274.3	276.2

Table 1. Velocity versus distance from Swimsuit 1.

For Swimsuit 2, the velocities in the boundary layer, along with the distances from the swimsuit surface, are listed in Table 2. The free flow velocity was also 280 mm/s.

<i>y</i> , mm	3.405	3.765	5.825	6.403	7.058
<i>u</i> , mm/s	234.02	242.29	252.95	257.05	260.09
<i>y</i> , mm	8.026	8.891	10.199	14.026	15.453
<i>u</i> , mm/s	262.53	265.52	270.15	275.74	276.61

Table 2. Velocity versus distance from Swimsuit 2.

#### HYDRODYNAMICS OF THE EXPERIMENTAL METHOD

Figure 3 illustrates how a solid surface like a swimsuit affects water flow. On the surface of the swimsuit, the water velocity is zero because of the no-slip boundary condition. Within a fraction of millimeter from the surface, the velocity increases with distance from the surface. In this layer, the increase is rapid but linear. This layer is called the laminar sublayer or viscous sublayer. The ADV is not capable of measuring velocity in this layer (for a reason that will be explained near the end of this paper). As the velocimeter is moved farther from the viscous sublayer (vertical distance *y* is increased), the downstream velocity *u* grows higher with distance *y* from the surface, approaching the free velocity  $u_0$ , which is the unimpeded velocity and the highest velocity for any distance *y*). However, the rate of the velocity growth decays with distance. Thus, we assume that  $u(y) = u_0 - u_0 \exp(-ay)$ , and define

$$u_{loss} = u_0 - u(y) \tag{1}$$

which can be assumed to decay exponentially with y, i.e.,

$$u_{loss} = u_0 \exp(-ay) \tag{2}$$

where *a* is a constant that is a property of the swimsuit surface. Water flows slower near the swimsuit surface because that surface 'drags' the water with a shear stress  $\tau_0$ . In the flow, the shear stress is the gradient of the velocity times the density of water. Right on the swimsuit surface, this shear stress is  $\tau_0$  where

$$\tau_0/\varrho = du/dy|_{y=0} \tag{3}$$

(where  $\varphi$  = density of water). Equations (2) and (3) show that a higher shear stress on the surface of a swimsuit (i.e. higher drag) will result in a steeper gradient of velocity in the boundary layer.



Figure 3. Speed loss decays exponentially with distance from swimsuit surface.

Now, because  $u_{loss}$  has the opposite sign of u (Eq. (1)), the shear stress on the swimsuit surface is

$$\tau_0 = -\varrho \ du_{loss}/dy|_{y=0} \tag{4}$$

Inserting Eq. (2) into Eq. (4), we obtain the skin drag, which is the shear stress on the surface of the swimsuit:

$$\tau_0 = a \ \varrho \ u_0 \tag{5}$$

Thus, a swimsuit with a greater value of *a* gives a higher skin drag. This skin drag coefficient *a* can be obtained by performing a linear regression analysis on  $\ln(u_{loss})$  as a function of *y*.

We could take advantage of the knowledge that on the swimsuit surface,

$$u_{loss}|_{y=0} = u_0 \tag{6}$$

by fixing the intercept of the regression line to  $u_0$ . However, letting the linear regression analysis determine the intercept gives a higher goodness of fit (smaller error) in the curve-fitting. Also, results below will indicate that the ADV measurement had a bias that grew large as it was brought closer to the swimsuit surface. It is important to note that the best region for measuring skin drag is the very thin viscous sublayer right on the swimsuit surface, where du/dy is nearly constant. An ADV does not have the required accuracy to be used in that viscous layer. Therefore, the method in this paper is a stretch from the "gold-standard" method of measuring skin drag by measuring velocities only in the thin viscous layer. Near the end of this paper, we will discuss a bias caused by using an ADV in the boundary layer region that is two orders of magnitude thicker than the viscous sublayer. Fortunately, the biased measurements were still able to be curve-fit and be used for relative comparison among different swimsuits, as the results below will suggest.

#### RESULTS

The ADV recorded velocities in three directions at several heights above the swimsuit surface. We use only the velocity u in the downstream direction x. The much lower velocities in the two other directions (v and w, Fig. B1 in Appendix B) are not used.

The "loss velocity" as a function of distance y from the surface,

$$u_{loss}(\mathbf{y}) = u_0 - u(\mathbf{y}) \tag{7}$$

was used to calculate the drag coefficient in the analysis below.

Linear regression analysis was performed, with *y* as the independent variable, and  $\ln(u_{loss})$  as the dependent variable. The linear regression gives the slope of the line  $\ln(u_{loss})$  vs *y*. This slope has a negative value because the loss velocity  $u_{loss}$  decreases as the distance *y* from the surface increases. Equation (2) defined the coefficient that indicates drag as the negative of the slope. Each swimsuit gives a different slope *a*. A swimsuit with a larger value of *a* gives a higher skin friction, and therefore a higher drag. The captions in Figure 4 and Figure 5 for each swimsuit shows the negative of the slope (= *a*) and the price of Swimsuit 1 and Swimsuit 2. A steeper slope means a higher skin drag, which is manifested in the measurement by a more rapid loss of velocity as the probe gets closer to the swimsuit.



Figure 4. Regression analysis of Swimsuit 1. Price = 32, a = 149.

The measurement of velocity versus distance from the surface, and the calculation of drag *a* as above, were performed on three other swimsuits of various prices. Appendix A shows the linear regression graphs, the skin drags *a*, and the prices of Swimsuits 3, 4, and 5. Figure 6 plots skin drag versus price for all the swimsuits. The results suggest that the more expensive swimsuits do not necessarily have lower skin drag. In fact, linear regression analysis would show a positive correlation between skin drag and price. That is, a more expen-

sive swimsuit tends to have a higher skin drag. This result is contrary to the belief that more expensive swimsuits have lower skin drag. Swimsuit skin drag should not be correlated with price. (Unlike, for example, the square footage of a house in a neighborhood is correlated with price.) However, the motivation for this research from the beginning was to fact-check the publications that associate expensive swimsuits with lower drag. The natural scatter of the data points and the small number of swimsuits tested do not allow us to make a strong conclusion beyond that "Our experiment does not support the belief that more expensive swimsuits have lower skin drag".



Figure 5. Regression analysis of Swimsuit 2. Price = 350, a = 215.



Figure 6. Skin Drag vs. Price of Five Swimsuits.

#### **ACCURACY LIMITATION**

The curve-fitting for the five swimsuits gives good correlation coefficients (R > 0.9). The goodness of fit indicates good precision of the velocity slopes which we use to differentiate the skin drags of different swim suites. However, the vertical-axis-intercept is far from predicting the loss velocity  $u_{loss}$  on the swim suit surface. From the regression analysis, the vertical-axis-intercept for Swimsuit 2 would correspond to  $u_{loss} = 92 \text{ mm/s}$ . No-slip boundary condition requires that  $u_{loss} = 280 \text{ mm/s}$  on the surface of Swimsuit 2. Measurements on all the swimsuits we tested gave low  $u_{loss}$  on their surfaces. In our experiment,  $u_{loss}$  was never measured, but inferred from Eq. (1) and the measurement of u(y). The fact that  $u_{loss}$  is biased low means that the measurement of u(y) is biased high. The high bias can be explained below.

The ADV that we utilized in this research is not the highest-accuracy instrument for a boundary layer in general. In free flow, the ADV has an accuracy better than 1% (Voulgaris and Trowbridge, 1998). However, as the probe gets close to the swimsuit surface ("the boundary"), the accuracy deteriorates, perhaps rapidly. The monotonous loss of accuracy with proximity to the boundary can be attributed to the fact that the ADV averages particle velocities over a relatively large volume. The type of ADV we used was a three-probe, 16MHz ADV. According to the manufacturer (Xylem Analytics, 1998), the velocity measurement is an average over a "cylindrical" volume with a radius under 2.25 mm and height of 4.5 mm. SonTek Technical Notes (2016) specifies a radius of 2.00 mm. (In reality, the "cylinder wall" is not straight, but a Gaussian curve revolved around the vertical axis.) Those dimensions of the sample volume are not much less than the range over which we varied the distance y from the swimsuit surface. In using the velocities to estimate drag, we rely on the assumption that the averaged velocity over the height of the sample volume adequately represents the velocity at the distance y from the swimsuit surface. This assumption introduces considerable bias in our measurements. Within the 4.5 mm from the boundary, the ADV averages the lower velocity closer to the boundary with the higher velocity farther from the boundary. This averaging causes the measurement to be significantly higher than the true velocity near the swimsuit surface. In fact, the true zero velocity on the boundary can never be read by the ADV, hence the apparent violation of the no-slip boundary condition. (Daroudian et al. (2010) mentions a method that could be used to provide some correction; but this is outside the scope of our research.) As the ADV gets closer to the boundary, the measurement of u(y) is biased higher, and  $u_{loss}$  is biased lower (Eq. (1)). Then all our calculated velocity gradients and drag are biased low. Therefore, our estimate of the drag coefficient is biased low. Fortunately, the low-biasing of the gradient and drag applies consistently to all the swimsuits we tested. Thus, our relative ranking holds true: A swimsuit with higher skin drag still gives a greater velocity gradient measurement in the boundary layer.

For a mathematical explanation of why the velocity-averaging volume results in high bias near the boundary, see Appendix C. We have shown that the ADV is valuable in comparing skin drag of different surfaces under similar flow conditions. However, the ADV cannot be used for measuring the true skin drag of any particular swimsuit alone. For future researchers in this topic who have the resources, we suggest replacing the ADV with a Laser Doppler Velocimetry (LDV) or a modern Particle Image Velocimetry (PIV), which are today's "gold-standard" methods for measuring velocity in the sub-layers of the boundary layer. Due to their high spatial resolution, LDV and PIV can accurately measure velocities in a very thin viscous sublayer region. The viscous sublayer is the ideal region where skin drag should be measured. The thickness of the viscous sublayer is about five times the kinematic viscosity divided by the free velocity (in our case, about 0.02 mm). In the viscous sublayer, du/dy is practically constant. See for example Mazumder et al. (1981), who performed skin drag measurement with an LDV whose averaging volume had a size of around 0.04 mm. Their measurement in a turbulent wind tunnel requires microscopes and very different instruments than what was available to our research here. The much higher resolution would also enable investigation into whether du/dy is constant in the region closest to the swimsuit surface, which would be revealed if u is plotted against y on a normal scale (not semi log like ours). Only the thin viscous sublayer (about 1% of the boundary layer thickness) would exhibit this constant gradient. With the ADV, the bias and coarse spatial resolution of our method does not allow us to probe that close to the swimsuit with any accuracy. Thus, our analysis resorted to the exponential curve fitting of the velocities in the boundary layer outside the viscous sublayer.

## **CONCLUDING REMARKS AND FUTURE WORK**

From our experiment using a flume, flow velocity loss in the boundary layer near the swimsuit surface can be modeled with an exponentially decaying function of distance from the swimsuit surface. The decay exponent is proportional to the skin drag on the swimsuit surface. The experiment gives relative estimates of skin drag coefficients of five swimsuits. The result does not support the belief that more expensive swimsuits have lower skin drag. This result is consistent with Toussaint et al. (2002) that measured skin drag using instrumented crawl swimmers, and concluded that swimsuits with special texture designs did not show reduced skin drag outside statistical margins of error.

The scope of our conclusion is limited to skin drag. We measured skin drag because publications mentioned in the Introduction claim that expensive swimsuits have specially engineered surface texture that reduces drag, and because Mollendorf et al. (2004) demonstrate that skin friction drag is the drag most affected by swimsuits. However, skin drag is only one term that contributes to passive drag. Besides skin drag, other factors affect the relationship between swimsuit design and passive drag, such as how the swimsuit shapes the hydrodynamics of the swimmer (Marinho et al., 2012). Moreover, passive drag is only part of active drag which takes into account the movement of the swimmer. It is possible that swimsuits affect speed in other ways than lowering drag. For example, Kainuma et al. (2009) suggested that the extreme tightness of the Speedo LZR swimsuits may constrict blood flow in certain muscles and thereby boost the generation of instantaneous force which help in short-distance sprints. Placebo effects can still boost the performance of swimmers who are wearing expensive swimsuits. A thorough meta-analysis of published results concluded that "the lack of consensus due to the variety of fields of study means that improvements in competitions are still not clarified" (Morales et al., 2019).

This paper shows that our measurement method was effective in measuring skin drag with good precision as Figures 4 and 5 show, subject to the bias discussed above. For future work, a similar method for measuring skin drag is discussed in Appendix D. Additionally, Appendix

D illustrates a different method to measure passive drag beyond skin drag. There we propose the use of a water current generator, a mannequin, and a load cell. This method is similar to Vennell (2006), with the exception that we will examine the velocities in the boundary layer in addition to Venell's correlation of drag force to free-flow velocity. The boundary layer analysis would give deeper insight into how different swimsuits have different passive drags.

# **AUTHOR INFORMATION**

## **Corresponding Author**

\*Anita X. Sumali, dolphinator7@gmail.com

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Figure A1. Regression Analysis for Swimsuit 3. Price = \$150, a = 153.



Figure A2. Regression Analysis for Swimsuit 4: Price = \$250, a = 165.



Figure A3. Regression Analysis for Swimsuit 5: Price \$100, a = 194.

#### **APPENDIX B: TURBULENCE METHOD**

The Speed-Loss method above assumes that the flow is laminar and one-dimensional (that is, all water molecules move only in the downstream direction). In reality, "micro-swirl" turbulence means that each water molecule moves in three dimensions. In the turbulence method, we use the velocities *u* in the flow direction and *w* in the vertical direction. Both are measured against time *t*. Turbulence causes these two velocities to fluctuate. The fluctuation about the mean is calculated as

$$u'(t) = u(t) - mean(u); \tag{B1}$$

$$w'(t) = v(t) - mean(w); \tag{B2}$$

The shear stress at height *y* from the swimsuit surface can be obtained as

$$\tau (t) = \rho u'(t) w'(t)$$
(B3)

Where  $\rho$  = density of the water = 1000 kg/m<sup>3</sup>.

We used the ADV to measure velocities in three directions at several heights above the swimsuit surface. In the turbulence method, we use the velocities u(t) in the flow direction and w(t) in the vertical direction (Fig. B1). The shear stress at height *y* from the suit surface can be obtained as

$$\tau = \rho \ u' \ w' \tag{B4}$$

Figures B2 show shear stress from measurement on Swimsuit 1 as a function of time, at various distances from the swimsuits. The figures also show the means of the shear stresses at the various distances. Figure B3 shows a linear regression analysis which gives the shear stress right on the swimsuit surface (y = 0) for Swimsuit 1.



Figure B1. Downstream velocity (u) and vertical velocity (w) as functions of time.



Figures B2. Shear stress as functions of time for Swimsuit 1.



Figure B3. Linear regression of shear stress versus distance for Swimsuit 1.

#### **APPENDIX C: CONVOLUTION BY THE ADV**

From Eqs. (1) and (2), the downstream velocity of the water in the flume is

$$u(y) = u_0 [1 - \exp(-ay)] \text{ for } y > 0; \text{ zero otherwise.}$$
(C1)

The ADV measures the velocity not only at the exact position *y* that it measures and gives. Instead, it averages the velocities of particles around *y*, weighting the velocity by some function of *y*. Here, we assume a Gaussian function

$$h(y) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(y-b)^2}{2\sigma^2}}$$
(C2)

where  $\sigma$  is the standard deviation and *b* is the distance between the measured point *y* and the center of the Gaussian function (Xylem Analytics, 1998). Therefore, the averaged velocity that the ADV gives is a convolution of u(y) and h(y) (Dombroski et al, 2007). To simplify the calculation of the convolution, define a reduced velocity from Eq. (C1)

$$u^{*}(y) = 1 - u(y)/u_{0} = \exp(-ay)$$
 (C3)

The convolution of the reduced velocity with the sensor's weighting function is

$$U^{*}(y) = \int_{-\infty}^{\infty} u^{*}(\varphi) h(y - b - \varphi) d\varphi = \int_{0}^{\infty} e^{-a\varphi} e^{-\frac{(y - b - \varphi)^{2}}{2\sigma^{2}}} d\varphi =$$
$$= \frac{1}{2} e^{-a(y - b - a\sigma^{2}/2)} \left[ 1 + erf\left(\frac{y - b - a\sigma^{2}}{\sigma\sqrt{2}}\right) \right]$$
(C4)

Transforming the above convolved reduced velocity similarly to Eq. (C3), we obtain the convolved velocity that the ADV gives:

$$v(y) = u_0 \left[ 1 - U^*(y) \right]$$
(C5)

Figure C1 shows that the convolved velocity reading from the ADV is biased high when the ADV is close to the swimsuit surface. This bias explains the apparent violation of the no-slip boundary condition in our measurements. It also indicates that the drag coefficient calculation (the slope magnitude of log velocity) is biased low. This bias is consistent among all the swimsuits that we tested.



Figure C1. Velocity reading from the ADV is biased high.

#### **APPENDIX D: TETHERED MANNEQUIN WITH A FLOW GENERATOR**

In another setup for measuring drag, the swimsuit will be put on a mannequin suspended horizontally in an endless pool (Figure D1). The endless pool generates flow whose velocity will be varied. The current will impinge the mannequin from the front (head) end, thereby pushing the mannequin in the downstream direction. The mannequin will be tethered with a rope that has a load cell. Therefore, the load cell will measure the force on the mannequin caused by the impinging current. This force is the drag force. We can measure the drag force  $F_D$  as we vary the water speed V which is measured with a velocimeter. If we plot  $F_D$  as a function of  $V^2$ , then a linear regression analysis will determine the drag coefficient  $C_D$ . Each swimsuit will give a slightly different  $C_D$  than other swimsuits. Also, the mannequin without any swimsuit will give the lowest  $C_D$  because the mannequin surface is much smoother than swimsuits. The  $C_D$  of each swimsuit minus the  $C_D$  of the mannequin is the first indicator of the extra drag that each swimsuit introduces. Based on the data of drag forces versus velocity, we will develop a new metric that shows maximum distinction among all the swimsuit that we test.



b)

Figure D1. Experiment Setup, a)3D Model; b) Photograph of Flow Generator Duct with Laminar Honeycomb; c) Load Frame Including Load Cell and Spring Scale.