Wall shear stress measurements in water by molecular tagging velocimetry at high spatio-temporal resolution

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Wall shear stress measurements in water by molecular tagging velocimetry at high spatio-temporal resolution

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Abstract
Wall shear stress is one of the most important (if not the most important) quantities to resolve for many applied fields of fluid mechanics, including naval hydrodynamics and aerodynamics. In high-Reynolds number flows, it cannot be simulated directly and one is forced to use models. The latter typically rely on experimental datasets for their development and subsequent validation. However, measuring wall shear stress at high Reynolds numbers is very challenging, especially in water. Historically, molecular tagging velocimetry (MTV) has been demonstrated to measure instantaneous wall shear stress, but it suffers from limited temporal and spatial resolutions. By generating fine and prompt patterns (thanks to Talbot-effect structured illumination and photobleaching rhodamine 6G, respectively), we demonstrate MTV with unprecedented spatio-temporal resolution. Here, the measurement of instantaneous wall shear stress is reported in a transitional boundary layer and in a turbulent channel flow at $\text{Re}_\tau \approx 800$ and 1,200.

Keywords: MTV, wall shear stress, wall-bounded turbulence, structured illumination

1 Introduction
In turbulent flows, velocity gradients are very strong near walls. At high Reynolds numbers, computing power is not adequate to directly simulate such flows and the wall shear stress needs to be modeled. Standard computational fluid dynamics (CFD) turbulence models rely on wall functions. In such models, the wall shear stress is the most important quantity and the main validation target for experiments. Experimentally, the mean wall shear stress can be measured either directly or indirectly. In direct measurement, the instantaneous wall shear can be resolved from the velocity gradient in the viscous sublayer.

Essentially nonintrusive particle image velocimetry (PIV) has become the most commonly used optical diagnostic for measuring velocity fields. This technique is well documented and has reached a high level of maturity with a broad community of users. Optically, it is comparatively simple to deploy; it requires a single laser system. However, because of its volumetric averaging nature and need for high particle density, PIV has limitations in resolving the smallest scales of turbulence needed for computational fluid dynamics development and validation. It should be noted that the single-pixel resolution ensemble correlation for micro-PIV (Westerweel et al, 2004; Kähler et al, 2006) and single line...
correlation (Willert, 2015; Willert et al., 2018) has enabled to obtain moments of velocity at the wall as well as the probability density function (PDF) of wall shear stress.

Molecular tagging velocimetry (MTV) is another nonintrusive optical diagnostic in which PIV macroscopic particles are replaced by molecular tracers. It is well-suited to measure velocity gradients as it provides velocity profiles on continuous regular patterns (typically lines or grids). However, in liquids, the technique has suffered from limited temporal and spatial resolutions and the need for specialized lasers (Koochesfahani and Nocera, 2007). To date, three MTV approaches have been classified: MTV by direct phosphorescence (using a phosphorescent dye), absorbance (using a photochromic dye), and photoproduct fluorescence (typically using a caged dye). The main drawbacks of those variants are respectively the weak phosphorescence signal (requiring intensified cameras and long integration times above 500 µs), the lack of photochromic dyes that are soluble in water, and the 30 ms fluorescence rise time after uncaging (preventing high-speed interrogation).

Another neglected option is photobleaching-based MTV, which can be characterized as MTV based on reverse photoproduct fluorescence. In the write pulse, intense illumination irreversibly photo-degrades a fluorescent dye uniformly dissolved in the fluid. In other words, the fluorescent dye molecules are photobleached, or permanently destroyed, and unable to fluoresce. During the read pulse, the pattern of tracers appears dark against a bright background from laser-induced fluorescence (LIF). This is typically harder to resolve than a bright pattern in a dark background since it is more easily contaminated by experimental noise. Yet, this approach is attractive as the pattern generation is prompt (it is on the order of the write pulse length) and it is possible to select widely available and inexpensive (as well as potentially safe) dyes, allowing its deployment in large facilities.

Photobleaching-based velocimetry was initially developed with fluorescein (Rička, 1987; Sollows et al., 1991), but other dyes have been used - see Fort and Bardet (Fort and Bardet, 2021) for a review. Alternative candidates may be found in extensive studies conducted on dye photobleaching (Imamura and Koizumi, 1955; Eggeling et al., 1998) including multiple variants of eosin, rhodamine, and coumarin dyes. Here we employ rhodamine 6G (R6G) dye which is very commonly used in experimental fluid dynamics and tunable dye lasers.

Probing high-velocity flows requires a velocimeter with a short integration time to appropriately “freeze” the flow. In aqueous solutions, the typical maximum velocity probed with MTV by phosphorescence has been on the order of a few centimeters per second. With photobleaching-based velocimetry, the shortest reported photobleaching - or write - time had been limited to 30 µs (Hosokawa et al., 2014). This integration time is still too long for high-Reynolds-number flows of interest in applications ranging from naval hydrodynamics to industrial flows and aerodynamics. Over the last several years, we have significantly improved the spatio-temporal resolution of molecular tagging velocimetry in water (more than four orders of magnitude temporally, and two orders of magnitude spatially) and are now in a position of measuring directly the instantaneous wall shear stress with quantifiable and traceable uncertainties. This manuscript presents these developments.

2 TESI-MTV by photobleaching of R6G

2.1 Operating principles and optical apparatus of MTV by photobleaching of R6G

For this study, widely available rhodamine 6G dye is the molecular tracer. It is important to emphasize that the fluorescent dye is highly soluble in water, unlike typical caged dyes. Moreover, unlike MTV by phosphorescence, the proposed method does not require additional alcohol which evaporates quickly in an open channel and makes keeping the mixture fraction in equilibrium very challenging. The dye is also robust to shear degradation as its molecules are not ripped apart by the pump, even at high power. We initially relied on an expensive spectroscopic-grade (99% purity) dye (Sec. 3) before using a lower quality R6G (MilliporeSigma, CAS Number: 989-38-8, ≈95% purity) without noticeable degradation of the MTV signal. For reference, MilliporeSigma sells
Wall shear stress measurements in water by molecular tagging velocimetry at high
355 nm, 10 ns
~10-100 μJ/line/pulse
550 nm, τ ~ 4 ns
20-1000 ns
527 nm, 10
~ 100-1000 μJ/pulse
Reconstructed velocity
Write pulse
Read pulse 1
Read pulse 2
Fig. 1: Operating principles of MTV by photobleaching of rhodamine 6G.

99% purity R6G for $134/g and 95% for $0.7/g. Reaching a 100 μg/L concentration in a 1.4 million gallon facility such as the NAVSEA’s William B. Morgan large cavitation channel (LCC) would then cost less than $400 using the second option.

Figure 1 shows the operating principles of the MTV technique in the two-laser write/read configuration. A 355 nm frequency-tripled, pulsed, high-speed Nd:YAG laser photobleaches the dye efficiently. Sec. 3 relies on a first laser that can provide 100 mJ per pulse at 10 Hz (Spectra-Physics, INDI-40-10-HG), and the one used in Sec. 4 (Pho-tonics DX-355-28) provides 0.7 mJ per pulse at up to 40 kHz. The write process is prompt (7 ns FWHM for the first laser and 14 ns FWHM for the second) enabling very short read times; it is also permanent. The read signal is a planar laser-induced fluorescence (PLIF) of the untagged dye by a 527 nm, frequency-doubled, high-speed, pulsed (180 ns) Nd:YLF laser (Photonics DM-527-25). It operates between a single pulse and 10 kHz, with a maximal energy per pulse of 25 mJ at 1 kHz, which decreases to 2.5 mJ at 10 kHz. A +250 mm cylindrical lens generates the thin laser sheet and the read is typically accomplished with very small fluences. A digital delay/pulse generator (Berkeley Nucleonics 577) serves as a master clock to synchronize the lasers and camera. TTL pulses are monitored with an oscilloscope, while the outputs of the lasers are controlled with photodiodes and powermeters.

In the first demonstration (Sec. 3), a 16-bit sCMOS camera (Andor Zyla 5.5) captures the emitted fluorescence signal of R6G. We switched to a 10-bit, 1920 x 1080 pixel, CMOS camera
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(IDT Y7-S3) for the second high-speed deployment (Sec. 4). The signal displays a bright background and dark MTV lines where the dye has been photobleached.

2.2 Optimization of UV fluence and dye concentration

R6G dye is commonly used in experimental fluid dynamics and tunable dye lasers as it resists well to photobleaching; a priori, it is a poor candidate for photobleaching-based velocimetry. Nevertheless, the R6G peaks of absorption - a main peak at 524 nm and a secondary peak at 347 nm (Eggeling et al., 2005) - are conveniently matched to the wavelengths of frequency-doubled and tripled lasers based on neodymium-doped crystals (Nd:YAG, Nd:YLF, or Nd:YVO₄). Its 550 nm peak of emissivity matches well the spectral response of digital cameras, and many spectral filters and dichroic mirrors are commercially available at these wavelengths.

While R6G is very stable at its primary (green) peak of absorption, Fort and Bardet (2021) showed that it takes nearly five orders of magnitude less fluence to permanently photobleach the dye with a 10 ns pulse at its secondary (UV) peak (Fig. 2). In fact, the curves diverge for a different pulse length as photobleaching kinetics are limited by the time constant $1/k_{Sn1}$ equal to 15 fs in the UV and 4 ns in the green. Remarkably, at 350 nm the photobleaching fluence is nearly constant for a pulse length of 200 ps to 20 ns. In fact, over this range, the fluence needed to photobleach 99% of the dye was derived analytically:

$$F = 4.7k_{Sn1}/(k_{bSn}\sigma_{1n}\gamma) \approx 0.8 \text{ J/cm}^2$$  \(1\)

where $k_{bSn}$ is a rate constant, $\sigma_{1n}$ is a cross-section, and $\gamma = \lambda/(hc)$ is the reciprocal photon energy.

As a reference, $F$ for photobleaching in the UV is only one to two orders of magnitude above the fluorescence saturation fluence of R6G at 532 nm, $F_{sat}$; the saturation irradiance is $5 \times 10^5$ W/cm² (Shan et al., 2004).

Unlike fluorescent dye uncaging and dye phosphorescence, the irreversible photobleaching process is prompt and the depleted tracers can be immediately interrogated. In fact, the illuminated dye can be completely photobleached before the write pulse ends. Thus, the pattern can be read as closely as the laser jitter and synchronization allows, i.e. typically less than 1 ns. The write image integration time is only equal to the laser pulse duration (a few nanoseconds to hundreds of nanoseconds depending on the laser type) plus the fluorescence lifetime of R6G ($\approx 4$ ns).

The contrast is defined as the intensity difference between the maximum (fluorescence) and minimum (photobleaching) brightness normalized by the maximum brightness. Since the photobleaching process is nonlinear (Fort and Bardet, 2021), the apparent width of the photobleached signal depends on both the write laser beamlet width and its fluence. At lower fluence, the apparent MTV line width is smaller than the UV laser beamlet and increases with increasing fluence. However, the contrast follows the same trend and is unsuitably weak when the apparent MTV line width is too narrow. Pouya et al (2019) find that a 20% contrast is sufficient for MTV, and experimentally, we obtain a good contrast for a write beamlet with a mean fluence of $F_b = 8$ J/cm². This is only 10 times the theoretical value of Eq. (1) which relies on empirical rate constants at 350 nm (at the 355 nm wavelength of our laser, the absorption cross-section is already 35% smaller), and does not model a full Gaussian beam in space imaged within a green laser sheet. At this fluence, the apparent photobleached line width and the UV beamlet width are nearly equal. The mean energy

![Fig. 2: Fluence needed to reach 99% of R6G photobleaching in the UV and green for various pulse lengths $\tau_p$. The solid curves are numerically solved from a five-level model of fluorescence (Fort and Bardet, 2021) and the dashed values are from Eq. (1). The dotted blue line is the saturation fluence of R6G, $F_{sat}$, at 532 nm.](image-url)
per beamlet, $E_b$, is below 20 $\mu$J for the fine MTV patterns demonstrated here.

Fort and Bardet (2021) show that for a dye concentration from 4 $\mu$g/L to 740 $\mu$g/L the contrast increases rapidly with the dye concentration before reaching a plateau near 100 $\mu$g/L. We find that this concentration is adequate for a good contrast in a multiline MTV experiment. The apparent increase of the contrast with dye concentration may be similar to the decrease of fluorescence half-life decay time (and signal-to-noise ratio increase) observed under continuous photobleaching of fluorescein (Wang and Fiedler, 2000) and coumarin-102 (Kuang et al, 2013). For a fixed fluence at a high concentration, the contrast may start being limited by attenuation of the beam through the liquid before the region of interest.

2.3 TESI: Structured illumination based on the Talbot effect

Fine laser patterns are generated with Talbot-effect structured illumination. The main operating principles are briefly reviewed here, see Fort et al (2020) for an extensive discussion.

When a laser beam travels through a microlens array, it is divided into individual beamlets that are focused at the focal plane of the microlenses with the array periodicity $p_0$. The Talbot effect is an interference phenomenon; the initial periodicity is reproduced in the so-called Talbot planes after the Talbot distance $z_T$. For a laser wavelength $\lambda$, $z_T$ is expressed in classical paraxial approximation ($\lambda << p_0$) as:

$$z_T = \frac{p_0^2}{\lambda} \tag{2}$$

The initial periodicity is also multiplied at rational multiples of the Talbot distance in the fractional Talbot planes. For $M$ and $N$ coprime positive integers and $K \leq 1$ a third positive integer, the periodicity $p$ of the beamlets at a distance $z_n$ after the focal plane of the microlens array is:

$$p\left[z_n = (M/N + K) z_T\right] = \frac{p_0}{N} \tag{3}$$

The number of beamlets generated in the focal plane of the microlenses is equal to the number of illuminated microlenses. Assuming that the structured beam overall width is constant in the near field, the number of beamlets $n$ is predicted at the fractional Talbot planes $M/N$ as $n \approx Nn_0$.

The deployment presented here relies on the fractional Talbot planes of a 300-$\mu$m-spaced cylindrical microlens array (Edmund Optics, 86-840) under 355 nm light ($z_T = 254$ mm). A +150 mm cylindrical lens focuses the structured light into a raw of fine lines at the measurement station. In Eq. (2), the origin ($z_n = 0$) is located 8 mm after the microlens array (this is the value of its focal length).

3 Initial deployment in an open channel down to 17 $\mu$m spatial resolution

The data presented in this section are obtained in a water open channel made out of 9.5 mm thick UV-grade fused quartz. The flume is filled with 40 mm (83 L in total) of filtered water and 100 $\mu$g/L of dissolved R6G. The lower range of a 1.5 HP pump delivers a 150 mm/s flow. The TESI

![Fig. 3: Setup for TESI-MTV in the open channel](image)

Table 1: Parameters of the patterns in Fig. 4 from left to right. $z$ is the distance from the microlens array to the measurement station

<table>
<thead>
<tr>
<th>$M/N$</th>
<th>1/2</th>
<th>2/3</th>
<th>3/4</th>
<th>4/7</th>
<th>5/8</th>
</tr>
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<tr>
<td>$z$ (mm)</td>
<td>135</td>
<td>177</td>
<td>198</td>
<td>153</td>
<td>166</td>
</tr>
<tr>
<td>$p$ (µm)</td>
<td>154</td>
<td>103</td>
<td>77</td>
<td>44</td>
<td>38</td>
</tr>
<tr>
<td>$w$ (µm)</td>
<td>22</td>
<td>21</td>
<td>23</td>
<td>18</td>
<td>17</td>
</tr>
<tr>
<td>$E_b$ (µJ)</td>
<td>65</td>
<td>44</td>
<td>33</td>
<td>19</td>
<td>16</td>
</tr>
<tr>
<td>$F_b$ (J/cm²)</td>
<td>18</td>
<td>12</td>
<td>8</td>
<td>8</td>
<td>7</td>
</tr>
</tbody>
</table>

The data presented in this section are obtained in a water open channel made out of 9.5 mm thick UV-grade fused quartz. The flume is filled with 40 mm (83 L in total) of filtered water and 100 $\mu$g/L of dissolved R6G. The lower range of a 1.5 HP pump delivers a 150 mm/s flow. The TESI
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Fig. 4: Instantaneous photobleaching-based MTV frames with five patterns at various fractional Talbot planes (parameters in Table 1): undeformed tagged pattern (top), deformed pattern after 12.5 ms (middle), and velocity field computed from the two frames (bottom). Please note that the finest patterns can exceed printer or screen resolution and may appear aliased.

lines are generated using various fractional Talbot planes of the 300-µm-spaced microlens array. The parameters for each pattern are reported in Table 1, with \( z \) the distance between the microlens array and the test section (it includes the 8 mm microlens focal length). Note that patterns at the first Talbot plane (with \( p = 300 \) µm) have also been obtained, but are not reported here for conciseness.

The UV laser operates at 4 mJ/pulse and the energy per beamlet, \( E_b \), varies from 65 to 16 µJ depending on the pattern. The UV lines travel vertically through the bottom of the fused-quartz channel and overlap with the 0.8 mJ/pulse green read laser sheet at the measurement station above the wall.

The camera captures the emitted fluorescence signal of R6G. The UV laser pulses at 5 Hz and the green laser is gated so that the fluorescence signal is imaged at \( 2 \times 5 \) Hz in a frame-straddling mode synchronized with the UV laser. The first frame of the image pair captures a single read pulse sent 1 µs after the write pulse (Fig. 4, top), and the second frame a second read pulse sent 12.5 ms later (Fig. 4, middle). A long pass spectral filter (Schott, OG550) is placed in front of the camera to remove Mie scattering of dust particles potentially present in the flow and direct reflections. It also blocks the UV pulse on the first frame of the image pair, which only displays the undeformed MTV signal (Fig. 4, top). The 12.5 ms interframe delay is sufficient for an adequate displacement of the tracers, but since they are tagged instantaneously and irreversibly, this delay can be easily adapted to capture faster or slower flow motion.

A lens (Nikon micro-Nikkor 105 mm f/2.8) combined with extension tubes gives an 8.1-mm-wide 6.8-mm-high field of view (FOV) with a 2.1 magnification and a 40 µm depth of field. Only a section of the MTV frames is presented here for the sake of clarity.

In Fig. 4, the images contrast is enhanced by using ImageJ to subtract the background with a 50-pixel rolling ball radius. The dark MTV lines
are detected as minima on the intensity profile. The single-pixel periodic peak detection is performed on MATLAB and uses a vertical moving average with a 6-pixel ($\approx 20 \mu m$) tall window. The instantaneous velocity profiles are computed from the displacement of each line between the undeformed and deformed frames (Fig. 4, bottom). The lack of velocity data points in the right panels is due to the smaller wall-normal extent of the smallest regular patterns (still about 1.5 mm). In the current facility, the boundary layer is weakly turbulent, with an estimated friction velocity and viscous unit of $7 \times 10^{-3} \text{ m/s}$ and $1.4 \times 10^{-4} \text{ m}$, respectively. While the middle panel merely displays an accelerated outer layer compared to the mean flow, Fig. 4 proves that the instantaneous MTV frames successfully display instantaneous velocity profiles at the bottom wall of the open channel. Both the line spacing down to 38 $\mu m$ and the line size down to 17 $\mu m$ as reached here are unprecedented for MTV. This validates that MTV can be deployed at very spatial resolution.

4 Deployment in a turbulent channel at 10 kHz

4.1 Turbulent channel facility

The relatively-small-scale open channel offers a convenient preliminary proof of concept for the technique to demonstrate high spatial resolution, but the flow is in a transitional regime and a dedicated turbulent channel facility was built to demonstrate and validate TESI-MTV by photobleaching in a well-developed turbulent flow and for small viscous scales. In the data reported here, the focus is on the wall shear stress measurement.

The pump, settling chamber, and contraction section are from Andrée (2014). The contoured nozzle is two-dimensional with an aspect ratio of 9:1. The initial level of turbulence and homogeneity have been well characterized by Andrée (2014). The test section is 146 mm wide ($W$) by 20.3 mm high ($H$), which gives an aspect ratio $W/H = 7.2$ and length $L = 2.97 \text{ m}$ or 146 $H$. These dimensions guaranteed that a fully developed, statistically 2D flow is reached. The maximum bulk velocity delivered by the 50 HP pump is $\approx 20 \text{ m/s}$. It is important to emphasize that while cyclodextrins typically used in MTV by phosphorescence get disturbed at high pump speeds and phosphorescence stops (Prof. Joseph C. Klewicki, personal communication, August 10, 2021), there is no such limitation with R6G. After the test section, the water enters an open return tank and is then recirculated. Finally, a large stainless steel filter housing enables to filter the water. Bags can filter down to less than 2 $\mu m$.

The new test section is divided into three 900-mm-long sections: two made of 5 mm thick acrylic (Clarex) and one of 8 mm thick UV-grade fused quartz (GM Quartz) which starts at 97 $H$ and ends at 146 $H$. The flow is tripped by two rows of 10-mm-wide by 1-mm-deep dimples at the channel inlet, and the measurement station is located 2.45 m (121 $H$) downstream of the trip. A variable-frequency drive controls and extends the pump operating range which enables to reach viscous wall units ($l_{\nu}$) between 17 and 1.4 $\mu m$, and viscous time scales ($t_{\nu}$) between 300 and 2 $\mu s$. This is invaluable to test the ability of MTV to resolve small scales expected in large-Reynolds-number flows of interest to naval hydrodynamics and aerodynamics. Specifically, this will be a powerful tool to estimate spatial filtering due to MTV finite beam diameters and give operating rules to set beam-diameter-to-wall-unit ratio for high-fidelity measurements.

Figure 5 presents the manometer used as a reference to measure the wall shear stress through the pressure gradient. Each tube is connected to one of the 138-mm-spaced (6.8 $H$) pressure taps and then imaged (right) in front of a uniform background. The first two tubes on the left are plugged into the second acrylic channel section and there is a 132.5-mm gap passing the flanges before the other seven pressure taps in the final fused-quartz section. Assuming a negligible effect on the sidewalls, two-dimensionality ensures the mean wall shear stress can be determined from a simple momentum balance with the streamwise pressure gradient: $\tau_w = -(H/2) dP/dx$. A digital camera monitors the manometer. An edge detection scheme is implemented on the digital images to extract the pressure drop. The uncertainty on the pressure gradient is typically 1%.

The 1,500 L loop of the water channel is filled with 200 $\mu g$/L of dissolved R6G. Photobleaching of the dye is performed with the short pulse (7 ns FWHM) of 355 nm UV light and the collimated read laser sheet is parallel to the center...
Fig. 5: Manometer measuring the mean wall shear stress: setup (left) and recorded image (right).

plane of the channel, 40 mm away from it ($\approx 1/4 W$). A razor blade blocks the light of both lasers upstream of the measurement station to avoid altering the incoming flow.

Several write/read repetition rate combinations were tried. In the data reported here, the UV laser pulses at 1 kHz and the green laser gives the read signal at 10 kHz. A macro lens (Laowa 25mm f/2.8 Ultra Macro) gives a 5.4-mm-wide 3.1-mm-high field of view (FOV) with an $M = 2.6$ (2.8 µm/pixel) or 2.8 magnification (2.5 µm/pixel) for the 300-µm-spaced MTV lines. The magnification is increased to $M = 4.0$ (1.8 µm/pixel; 3.5 x 2.0 mm² FOV) for the 100-µm-spaced MTV lines generated at the fractional plane.

4.2 Instantaneous and mean wall shear stresses

Figure 6 shows sample instantaneous MTV data. Here the beamlets are about 25 µm in diameter or two viscous wall units. As seen in Fig. 7, we are able to resolve the instantaneous velocity down to the first wall unit.

In Fig. 8, data are reported for a bulk velocity of 1.3 m/s. This corresponds to $u_\tau = 0.08$ m/s, $Re_\tau = 800$, $l_\nu = 13$ µm, and $t_\nu = 166$ µs. On each MTV frame, the wall position is tracked using the intensity gradient, and the horizontal intensity profile is interrogated with a vertical 8-pixel-wide (15 µm) moving average from the wall to the outer layer (top of the frame). An adaptive line fitting helps the detection at each new row and limits outliers. Figure 8 displays the velocity profile unnormalized and normalized in inner units. By averaging the instantaneous velocity gradients (or wall shear stress) over the dataset, one obtains...
the mean wall shear stress, $\tau_x$, which can then be calibrated against the manometer value, $\tau_w$, providing an estimate of the mean bias error in our measurements. Here we find $\tau_x = 5.68$ Pa, which is within 6% of $\tau_w$.

For this flow, the large eddy turnover time is on the order of 4 ms. Here a total of 120,000 frames are acquired and analyzed. However, the data acquired at 1 kHz are time-correlated and the effective sample size for statistical convergence should be reduced from 120,000 to 30,000. In fact, it is further decreased for the specific sample analyzed here, as the autocorrelation function of the measured instantaneous wall shear stress reaches 95% confidence bounds for a lag of 8. At the moment, the analysis is performed on a single MTV line, but five of them are actually recorded on each frame so this will contribute to increase the overall sample size in a future analysis.

Figure 8 shows that the PDF does not display any extreme event at this point, but the skewness toward small values is a good indicator of accuracy on the instantaneous measurements. The tails seem to align with the asymmetric double exponential fit proposed by Guerrero et al (2020). The current processing algorithm suffers from peak-locking due to the noise. Future investigations of the near-wall extremes will be facilitated by using a higher-power laser to increase the signal-to-noise ratio in the viscous sublayer. Dedicated processing schemes should also be developed to extract the largest amount of information present in the unique MTV data.
4.3 Near-wall turbulent structures

Unlike wall-mounted sensors and pointwise diagnostics such as laser Doppler velocimetry (LDV) and nanoscale thermal anemometry probes (NSTAP), MTV also gives access to the full instantaneous velocity profiles from the viscous sublayer to the log-law region. Figures 10 and 11 present the MTV frames obtained at high magnification ($M = 4.0$) using the 2/3 fractional Talbot plane (100 µm spacing). We notice the signature of an inclined coherent vortical structure displaying strong gradients in Fig. 10, and what we believe to be an upward burst in Fig. 11. More MTV images capturing these events can be found in Fort (2021).

At the wall, two effects seem to be responsible for the loss of MTV signal after a few frames. First, the shear stretches the lines which become too thin to be resolved. Another factor is the out-of-plane (spanwise) instantaneous wall shear stress component near the wall (Kline et al., 1967; Brücker, 2015) moving the line out of the read laser sheet. This is the signature of organized structures with a spanwise extent on the order of 100$\tau_w$. The streamwise extent of the structures is even longer; in the present data, this is visualized at the wall where there is an alternation of regions rich in dye, followed by depleted regions.

The effect of excessive photobleaching in low-speed regions is even further highlighted with the write pattern tagged at 4 kHz and read at 1 kHz (Figs. 12 and 13). There is a trade-off between optimum write frequency and flow motion. This ultimately sets limits on how close we can reconstruct the flow at the wall, as discussed after. Naturally, experimentalists should have the processing scheme in mind when acquiring data. The MTV system can be tuned to offer the most suitable raw images for a specific processing approach. Thus, to visually identify the MTV lines, the write/read time interval is often increased to detect substantial deformations, however, a cross-correlation algorithm performs better for smaller displacements. The difference in optimum raw image characteristics is even more accentuated for optical flow methods which prefer only a few pixels
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in displacement. After Schembri et al. (2015), we have confirmed that MTV and PIV/PTV can be performed simultaneously even at the same wavelength, as long as the particles are small compared to the MTV pattern.

Tokumaru and Dimotakis (1995), Deusch et al. (2000), and Cai et al. (2018) proposed dedicated approaches to reconstruct the velocity field from PLIF data, which could be adapted to MTV. Moreover, the PLIF signal contained in the MTV data also encloses additional information of its own. In fact, while the highly contrasted visualizations in Figs. 12 and 13 do not display well-separated lines as for typical MTV, they provide great insights on the flow structures in the boundary layer. In fact, the images are very similar to the historic results obtained with the hydrogen-bubble method.

As of now, it is not fully understood what the best way to combine the MTV, PIV, and PLIF data contained in the raw images would be. A hybrid processing scheme should take advantage of all the existing approaches.

![Fig. 11: Same as Fig. 10, 5 ms (5 write pulses) later.](image)

![Fig. 12: Similar flow structure as Fig. 11 but the lines are 300-µm-spaced (M = 2.6) and the write is at 4 kHz with read tracking at 1 kHz. The flow is still at Reτ = 800 (lν = 13 µm) and imaged up to 3.0 mm (230 lν) above the wall.](image)

5 Conclusions

By combining several developments: improved understanding of rhodamine 6G spectroscopy and
Talbot-effect structured illumination (TESI), we developed a new scheme of molecular tagging velocimetry (MTV). This approach is very versatile and overcomes the three main limitations of MTV in liquids by enabling: the use of broadly available lasers, short integration times, and tunable fine patterns for high spatio-temporal resolution.

R6G is a well-suited dye for MTV by photobleaching. Its UV peak of absorption is nearly tuned to frequency-tripled neodymium-doped lasers (Nd:YAG, Nd:YLF, and Nd:YVO₄), while its main peak in the green matches frequency-doubled Nd-doped lasers. Photobleaching in the UV is very efficient; it can be achieved for modest fluence (≈ 1 J/cm²) and a broad range of pulse length (200 ps to 20 ns). For reference, this is nearly five orders of magnitude less than at the primary peak, where the dye is very stable and can be probed repeatably with very small fluences. Therefore, a wide range of laser combinations is available. The R6G peak of emissivity is also near the peak quantum efficiency of most scientific cameras.

With nanosecond UV laser pulses, the tracers are tagged both promptly (this is more than four orders of magnitude shorter than any MTV scheme in water) and irreversibly. Additionally, the dye is very insensitive to photobleaching under the read (green) pulse. Therefore, the approach allows both short interrogation times that are adapted to high-speed flows - with multiple interrogations of the same tracers, which increases the sensitivity (dynamic range) of the technique - and long probe time for low speed-flows.

The benefit of structured illumination using the Talbot effect has been highlighted, particularly at 10 Hz in a transitional boundary layer. This approach enables for the first time in water the direct measurement of wall shear stress with a nonintrusive and minimally perturbative optical diagnostic. We successfully generate MTV lines with a beamlet spacing between 300 and 38 µm and width down to 17 µm (limited to 200 µm and 100 µm, respectively, in previous MTV studies), while positioning the beamlet-forming optics “far” from the measurement station. This is an unprecedented resolution for velocimetry. The energy needed was very modest below 20 µJ per write UV beamlet.

The technique is also demonstrated in a turbulent channel flow at Reτ ≈ 800 and 1,200 with viscous length scales ℓν = 13 and 8.5 µm. TESI generates 100 to 300 µm-spaced, 25 µm-wide, MTV lines that are tagged at 1 kHz and interrogated at up to 10 kHz. The flow is well-resolved by the optical diagnostic and the mean wall shear stress obtained with MTV is within the uncertainty error of the manometer measurements. We captured the proper trend on the PDF of wall shear stress fluctuations. This indicates that the technique is promising for instantaneous measurements too.

Moreover, the time-resolved high-spatial-resolution data give access to the small-scale turbulent structures near the wall.
Wall shear stress measurements in water by molecular tagging velocimetry at high

Declarations

Ethical Approval. Not applicable.

Competing interests. The authors declare that they have no conflict of interest.

Authors’ contributions. CF conducted the experiments, wrote the main manuscript text and prepared all the figures; PMB supervised the work and contributed via discussions. Both authors reviewed the manuscript.

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Availability of data and materials. Given the exploratory nature of the presented work, the authors conclude that the work contains no data of archival relevance.

References


