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High-Speed Tomographic Measurements of Pulsatile Flows within Compliant Tubes

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Abstract

Pulsatile flow in a compliant tube is the most complex example of a single-phase pipe flow, particularly in cases where a transition to turbulent flow can occur at the peak flow rate. Pulsatile flow is of particular interest to experts in the field of cardiovascular physiology, as the body's network of a beating heart and blood-carrying vessels exhibits this type of flow. This project is directed towards the development of a system, called an Ex-Vivo Heart Perfusion (EVHP) system, which can preserve a human heart in a working, fluid-pumping mode. The primary motive of the presented work is to develop a better understanding of the interactions between compliant tubes and turbulence mechanics in pulsatile flows that could then be used to replicate the downstream conditions of the human body artificially in the EVHP system. To provide a means for comparison, a base case of pulsatile flow in a rigid tube will also be investigated. These investigations are being conducted using a fluid composed of water and potassium thiocyanate, which is refractive index-matched to the tubing within a custom pressure/imaging vessel. This allows distortion-free images to be obtained while controlling the compliance of the tube by pressurizing the chamber. The aim is to develop the experimental system so that time-resolved imaging can be conducted using a multi-camera system. The results will be processed using tomographic particle image velocimetry (TPIV) and Shake-The-Box methods. At present, the system has been constructed and preliminary results have been collected. Advanced results will be presented at the conference.

1 Background and Motivation

Pulsatile and oscillatory flows are a reasonably widely investigated phenomenon. The Womersley solution for fully laminar pulsatile and oscillatory flows in straight, solid tubes has been known for decades (Womersley 1955), and is reasonably consistent as long as its assumptions are met. However, it is not immediately applicable for flows in compliant tubes and the assumptions break down entirely when the flow transitions to turbulence.

Pulsatile turbulent flow investigations in straight tubes have been conducted using dye-based flow visualization (Das and Arakeri 1998), hot-wire anemometry (Hino, Sawamoto, and Takasu-F 1976; Eckmann and Grotberg 1991), laser Doppler velocimetry (LDV) (Lodahl, Sumer, and Fredsøe 1998), and, more recently, 2D PIV (Brindise and Vlachos 2018). Flow visualization methods can define when transition occurs, but cannot further quantify the turbulent properties of the flow. Hot-wire anemometry can quantify local velocity magnitudes, but struggles with quantifying velocity direction and can only build up a database of mean and fluctuating quantities at single points and as such cannot identify coherent structures in the flow. LDV is another 1D technique able to produce velocity direction and with better resolution, but again cannot identify coherent structures. 2D PIV measurements are able to identify coherent structures, but in attempting to quantify turbulent quantities must assume that the out-of-plane component of the velocity behaves similarly to one of the in-plane components, or ignore the out-of-plane components entirely. The majority of these studies have used sinusoidal waveforms, barring a notable exception (Brindise and Vlachos 2018) that investigated the waveform dependence of turbulence generation.

Stereo particle imaging velocimetry is capable of 2D3C measurements (Wieneke 2005), mitigating the assumption about out-of-plane turbulence that 2D PIV is forced to make. Expanding this to a time-resolved measurement would allow for tracking the development of these coherent structures in time. However, even this method has its drawback: out-of-plane motion can sweep coherent structures out of the light sheet. Extending the method to tomographic PIV (TPIV) (Elsinga et al. 2006) can mitigate this issue by allowing volumetric imaging and 3D3C measurements. Another interesting application of these techniques would be to examine the turbulence generation in the boundary layer of the tube, following flat plate studies such as (Schröder et al. 2011). The processing methods used in these investigations will include classical stereo and tomographic PIV processing algorithms (Prasad 2000; Scarano 2013; Schanz, Gesemann, and Schröder 2016), stereo and 3D self-calibration (Wieneke 2005, 2008), PIV uncertainty analysis (Wieneke 2015), and an analysis of the turbulent behavior in the system from the PIV results (Schröder et al. 2011).

Investigations in compliant tubes are frequently directed towards aortic models (Geoghegan et al. 2013). While these studies are useful in trying to understand the flow in a physiological condition, they have geometries that make decomposing the problem into a fundamental case difficult. Vorticity is often generated by the geometry itself, various features can trip the flow, and overall it can be difficult to identify the mechanisms involved in turbulence generation. The straight-tube case has been selected to better investigate the base case of turbulence being generated solely from the classical interaction between the flow's viscosity and its inertia. The primary goal is to develop an understanding of how turbulence generation in pulsatile flow interacts with compliant walls. Understanding this interaction will allow a determination of its importance in the development of an Ex-Vivo Heart Perfusion (EVHP) system that is in development (White et al. 2015).

Another key concern of the study is the ability to image within the glass and compliant tubes. Refractive index matching (RIM) of the working and surrounding fluid will be used to allow clear, distortion-free images to be obtained through the tube. Past investigations (Agrawal et al. 2018) have shown that a mixture of potassium thiocyanate (KSCN) and water will be appropriate for both the quartz glass solid tube case and the compliant Sylgard tube case.

2 Experimental Setup

The bulk of the work conducted up to this point has been directed towards the development of the flow system. The keystones of this approach are the pump and its control system, the compliant tube, the RIM fluid, and the imaging chamber. Having now developed all of these components, the experiments are ready to proceed. This section will discuss how these components have been designed.

The pump, shown in Figure 1 is an ARO 70 mL diaphragm pump, modified to be driven by a Teknic stepper motor-traverse system. The stepper motor can be controlled to replicate any desired pump waveform. A linear variable differential transformer (LVDT) is attached to the traverse to confirm the motion of the pump's diaphragm.

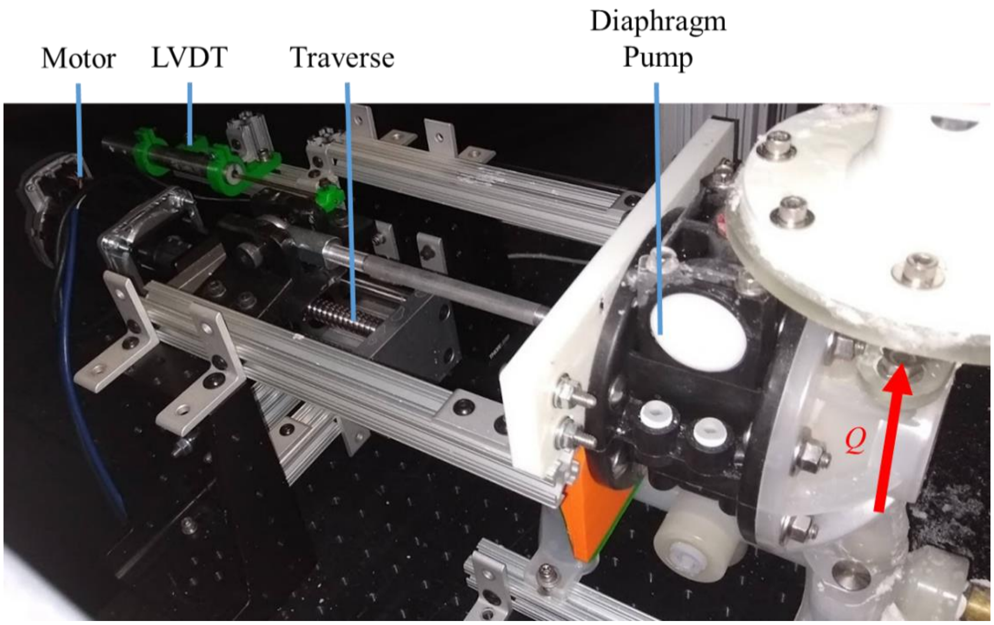


Figure 1 – Motor-traverse-pump system used to provide the flow waveform

Development of compliant tubes has been an ongoing process. The mold design for these tubes is a 5-part mold composed primarily of 3D-printed parts, with a Delrin tube at the core to precisely control the internal diameter and reduce friction during disassembly. A solid model of the mold is shown in Figure 2. The 3D-printed base is designed with tubing connections suitable for injection molding. The Delrin tube in the centre of the mold fits snugly around the peg in the base, and the side pieces are bolted together and slid around the Delrin tube. These pieces are then bolted to the base, and the top cap is slid into the Delrin tube and bolted to the sides.

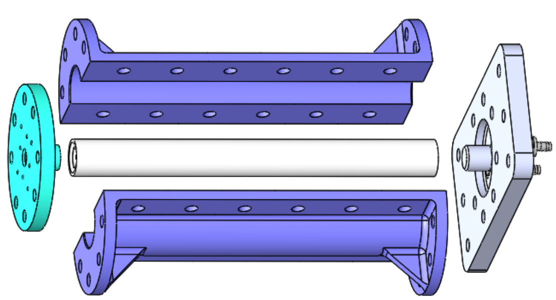
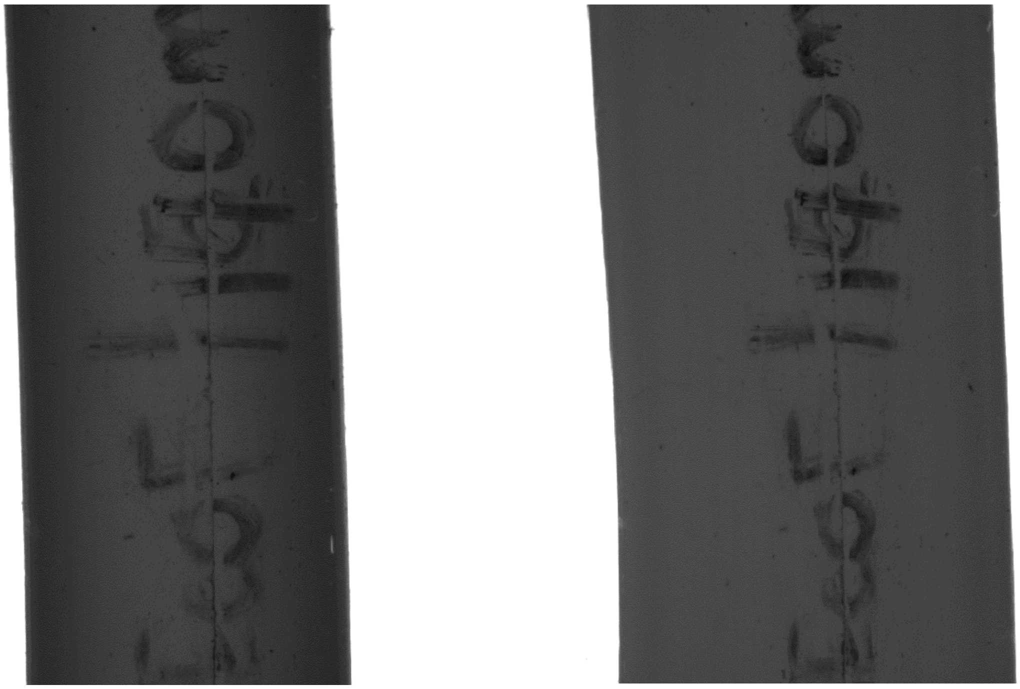


Figure 2 – Five-part silicone tube mould design, rotated to conserve space.

Past work has focused on measuring the compliant behavior of straight opaque silicone tubes as the pump was cycling with an aortic waveform. Sample images showing the expansion of one of these tubes (Ecoflex 50) have been provided here in Figure 3. The Sylgard 184 tubes are in development and are being designed to replicate the 50% pulse volume storage that is typical of a physiological system (Belz 1995).



(a) (b)

Figure 3 – Expansion of Ecoflex 50 silicone tubes at (a) minimum width and (b) maximum width over the pump cycle.

As the experiment requires imaging through the fused quartz and silicone tubes, it is important that the working and surrounding fluids are refractive index matched to the tubes. An example image of the RIM effect is shown for a quartz glass tube in Figure 4. Here, the quartz tube is immersed in a mixture of 58% KSCN and 42% water and all but vanishes below the fluid line. As the refractive index of quartz (1.46) is higher than that of Sylgard 184 that will be used to for the silicone tubes (1.42) this mixture will be need to be diluted for the compliant tests.

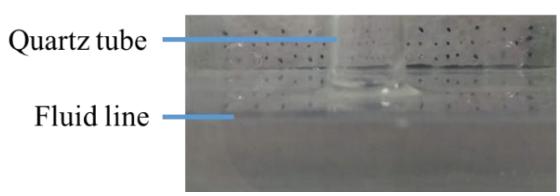


Figure 4 – Refractive index matching of quartz glass

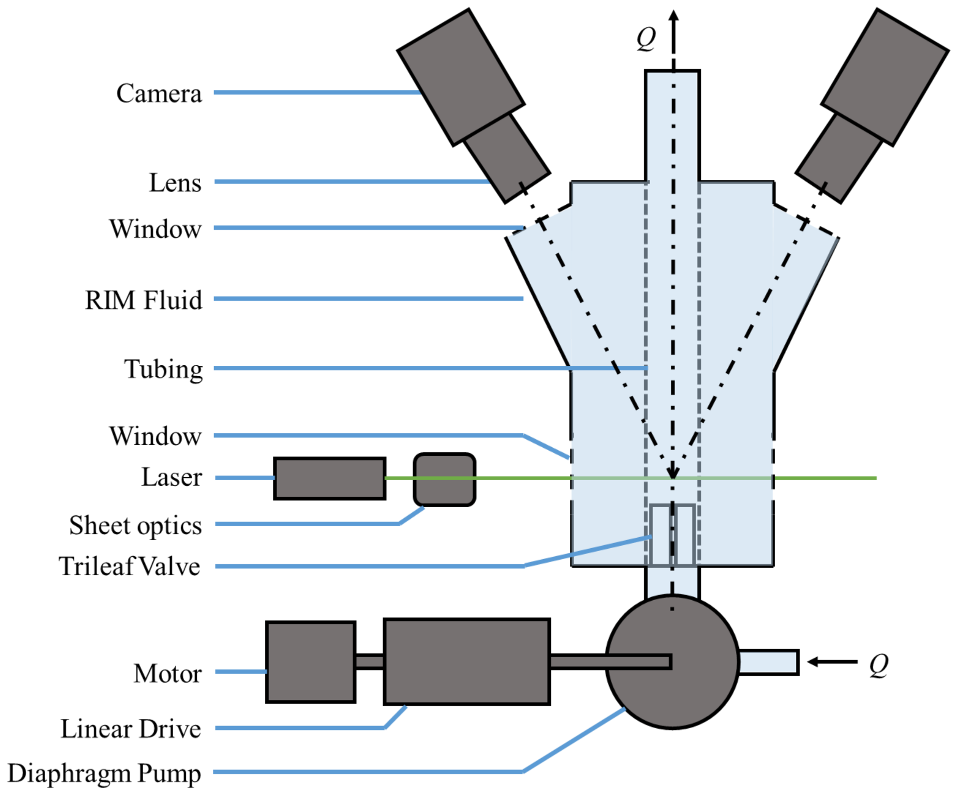


Figure 5 – Schematic of the experimental setup.

A schematic of the full experimental setup is shown in Figure 5. This shows the pulsatile pump system at the bottom of the experiment, pumping fluid upwards. A custom-made trileaf valve forms the exit valve of the pump. This valve is intended to produce a more physiological release of fluid into the compliant tube, as would be found in a cardiac system. These components are encased in an imaging chamber shown as a solid model in Figure 6. The complex geometry of this device was achieved through use of an FDM additive manufacturing technique. This figure also shows the modular base and outlet to allow switching between glass and silicone tubing while having adjustment for the location of the experimental region-of-interest. Laser illumination is accessible through widows at the bottom of the image chamber and four quartz glass windows angled at 22.5° from the horizontal are included for camera optical access. There are also multiple taps for filling and pressurizing the chamber with RIM fluid. The experiment itself, configured in stereo mode, is shown in Figure 7. Note that in Figure 7, the outlet from the system is absent. The laser enters through the lower orange window, and the cameras image through the upper orange windows.

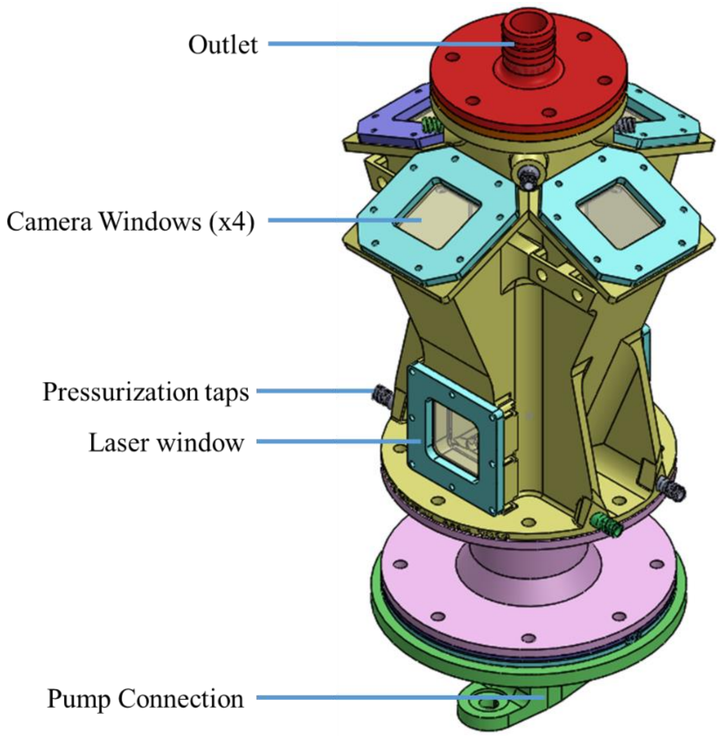


Figure 6 – Solid model of the imaging chamber

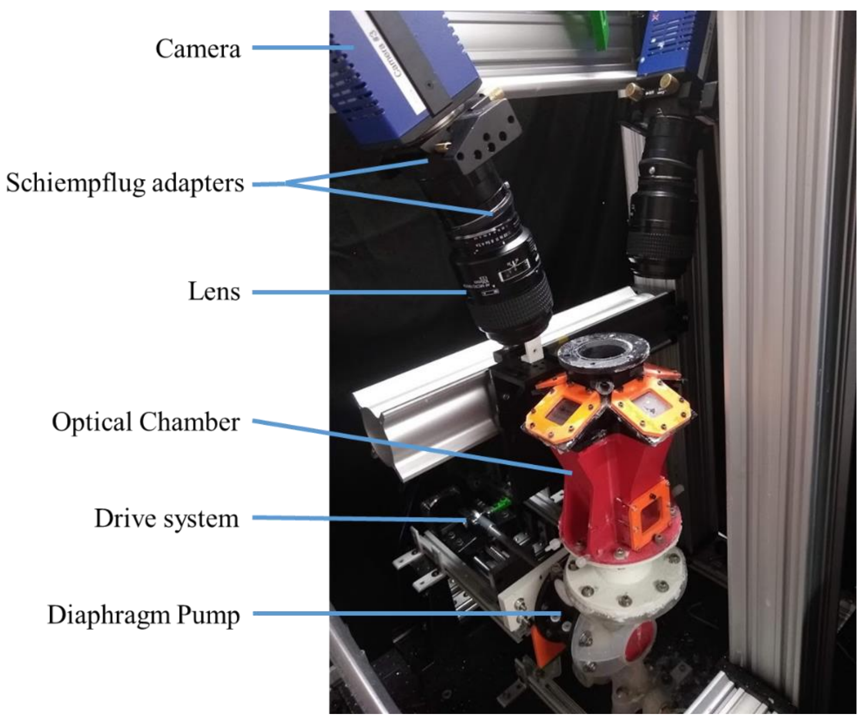


Figure 7 – The experimental setup, configured in stereo mode.

3 Preliminary Results

Preliminary results were collected on a similar flow field in an earlier setup, which was using a Left Ventricular Assist Device (LVAD) as its pump. In this case, a Phantom v611 high-speed camera was used to image the flow's axial behavior. The data was then analyzed using time-resolved PIV. The results are shown in Figure 8. Figure 8a indicates that the LVAD is prone to significant reverse flow, which is not physiologically correct. It is suspected that the butterfly-style valve in this pump has a slow response time and allows more backflow than a physiological system. The key results are that the flow field is relatively uniform while accelerating (b), but appears to start breaking up into turbulent eddies at its peak (c). These eddies seem to remain during the deceleration phase (d). These results inspired the further development of the system as discussed. Complete turbulence measurements will require 3C data at a minimum, and the transverse plane orientation of the new system was selected to provide measurements for a characteristic cross-section of the flow.

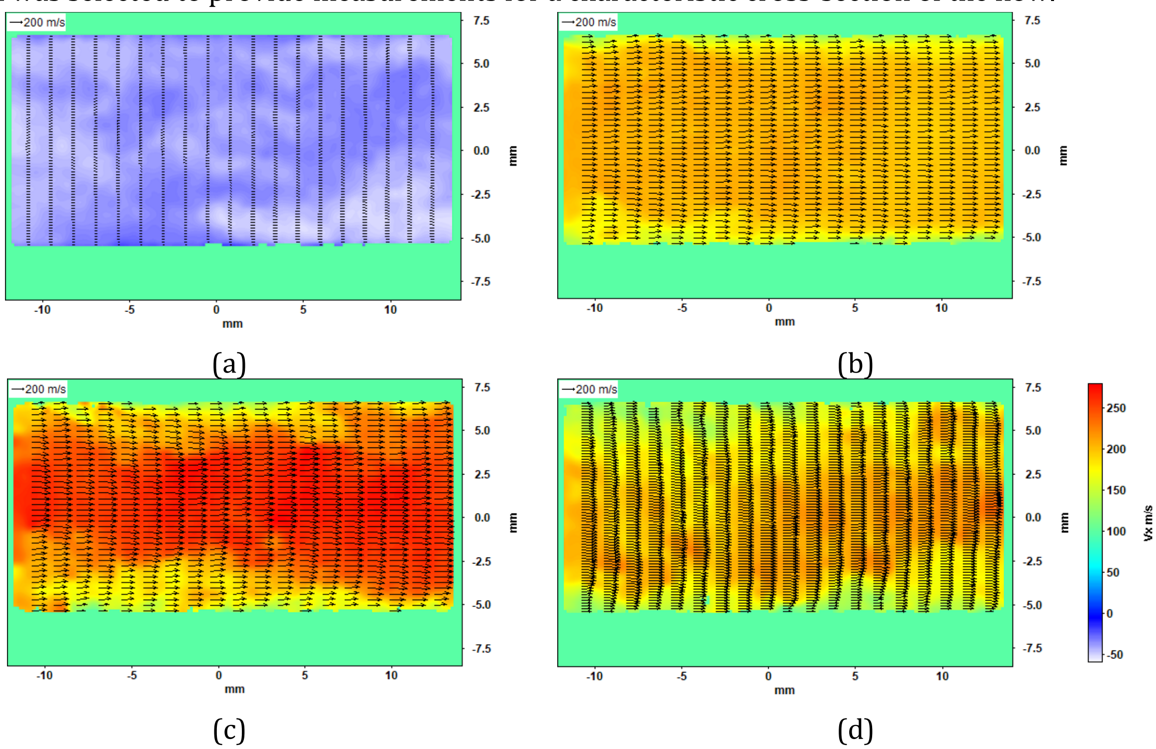


Figure 8 – Preliminary PIV results. (a) shows lowest flow rate, reverse flow observed. (b) shows accelerating flow, (c) shows peak flow rate, (d) shows decelerating flow

4 Conclusion

Progress has been made towards the ultimate goal of designing a system for tomographic imaging inside a compliant tube. The stereo version of the system has been setup and preliminary tests show promise. This builds on earlier work investigating the axial plane of the pulsating flow field. 2D3C measurements on the transverse plane of the solid glass tube are the next goal. This will allow for development of an appropriate processing string to interpret the behavior of turbulence in the system. The Sylgard 184 tubing will be developed concurrently with this process, and will be installed in the system and the 2D3C experiments will be repeated to investigate the effects of compliance. Once a high-speed tomographic system becomes available, it will be similarly applied to both cases for time-resolved 3D3C measurements. The results, up to the newest available, will be presented at the conference.

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