Design of a High Speed Imaging System for Visualization and Measurement of flow fields through the Magenta Medical Turbine Pump

by

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Introduction

This report describes the design and application of a high-speed imaging system for flow visualization of the Magenta Medical blood pump turbine. I developed and patented this technique in the 1990's and have successfully applied it to many blood handling devices, including Ken Butler's original Nimbus Axipump spinning at 10,000 rpm [1-4]. With this design, you will be able to view your turbine as if it were standing still, but while spinning at 20 krpm. By synchronizing the camera and illuminations sources to your turbine, and by varying pulse delays, you will be able to view all parts of your turbine, as a flow field appears to move slowly through it.

This technique has been used by many R&D organizations developing blood handling devices. The wavelengths of optical components are chosen to completely eliminate reflections that will saturate image sensors. A schematic of the design concept is shown below in Figure 1.

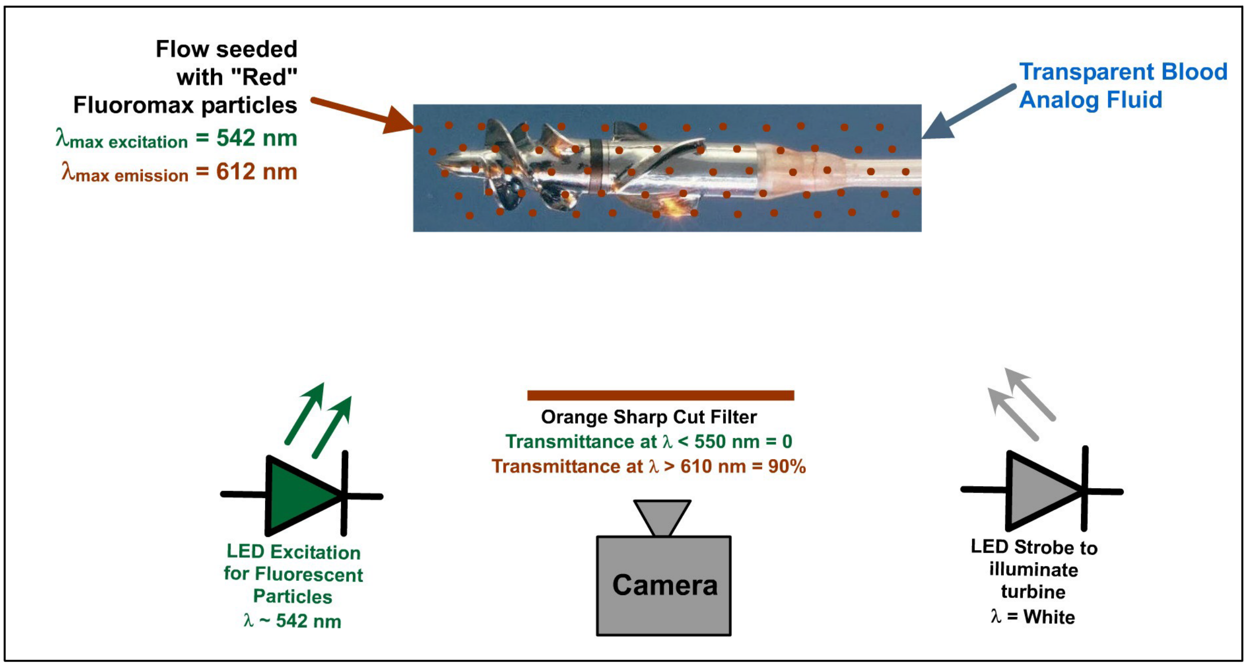


Figure* 1. *Schematic of System Design for Magenta Blood Pump

Fluorescent Particles as Flow Markers

Fluorescent particles are used as flow markers. Thermo Scientific™ Fluoro-Max Red Dry Fluorescent particles are recommended. The particles have a density of 1.05 g/cc, making them neutrally buoyant in water and blood analog fluids. The red rhodamine dye used in these particles has maximum excitation at 542 nm and maximum fluorescent emission at 612 nm. The spectral excitation and emission curves are shown in Figure 2. Appendix A shows detailed info about the particles, and where they can be purchased.

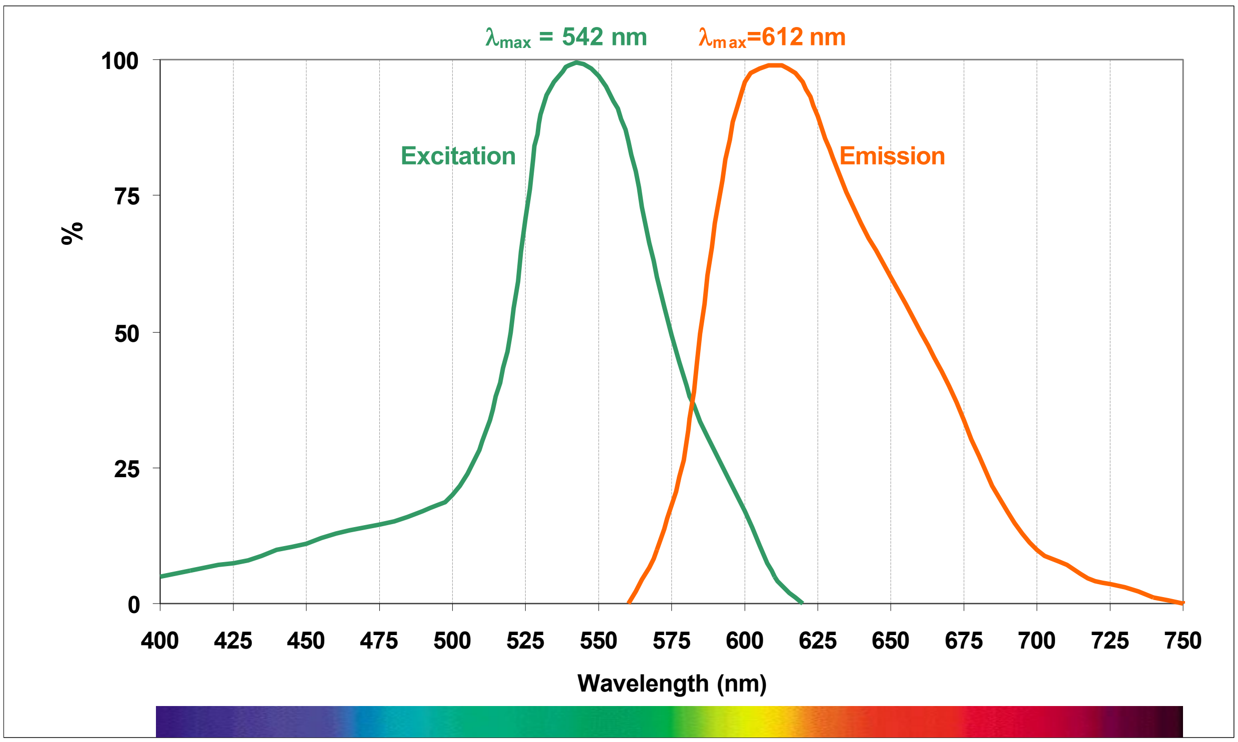


Figure 2. Spectral Excitation and Emission of FluoroMax red dyed particles.

I recommend starting with 100 μm FluoroMax particles while developing your imaging system, because they are very bright. The cost is around $300/gram. Each gram of 100 μm particles contains 1.8 million particles. After your imaging system is working well, you can switch to 30 μm FluoroMox particles, which are near the size of white blood cells. The cost of 30 micron FluoroMax particles is also around $300/gram. Each gram contains 6.7 x 10^7 particles.

Will the FluoroMax particles follow the flow accurately?

Since the specific gravity of the Fluoro-Max particles (1.05 g/cc) is nearly equal to that of water or a blood-analog fluid, and since the Stokes number of the particles is <<1, the 100 μm particles will accurately follow the fluid flow through your turbine, even while spinning at >20 kRPM. The Stokes number (St) represents the ability of particles to follow an accelerating fluid flow. It is a dimensionless parameter describing the time it takes a particle to accelerate from zero velocity to a steady-state velocity due to drag in a flow field. Particles in a flow field with Stokes numbers less than 1 will accurately follow the fluid flow. The Stokes number of the 100 μm Fluoro-Max particles is << 1. See Appendix B for calculation of the Stokes number.

Light Sources for Excitation of FluoroMax Particles

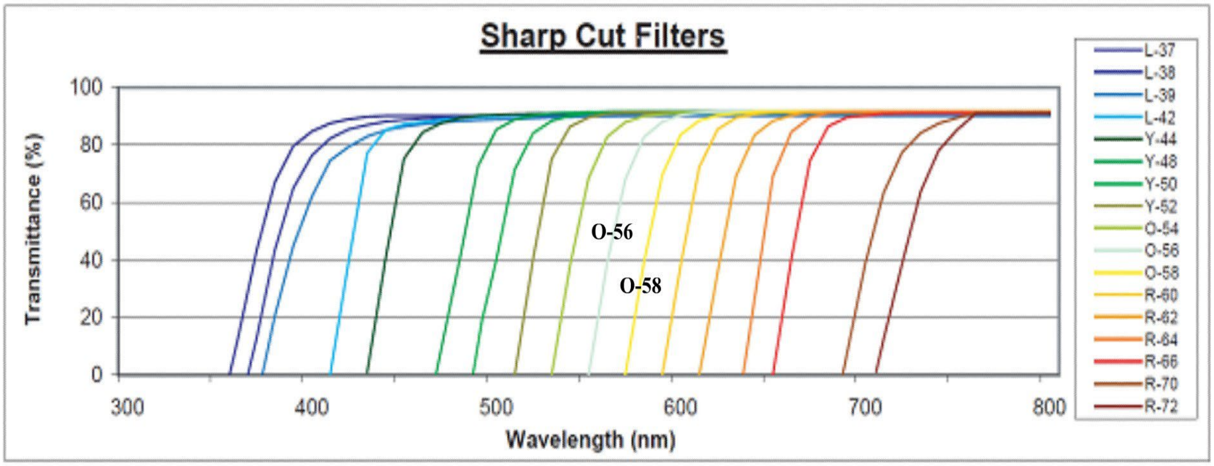
The 488 nm and 514 nm lines of an Argon laser, or the 511 nm line of a copper vapor laser, work exceptionally well for exciting the Fluoro-Max particles. However, these lasers with adequate optical power, >5 W, cost more than $25,000. There are also safety concerns. They are Class IV lasers, the most dangerous classification for lasers. Even diffuse reflections from the beam can cause eye damage. This requires the highest level of laser safety, which is difficult and expensive. So unless you already have an Argon or CuV laser, and the appropriate safety controls, I don't recommend them.

LED's will also work well for exciting the FluoroMax particles. They are far less expensive and much safer than Class IV lasers. They are also capable of being driven by pulsed input signal. There are several companies that make strobed LED illumination systems for high-speed photography.

I am talking with several companies that make pulsed LED's for high speed flow visualization. I will send you my recommendations this week.

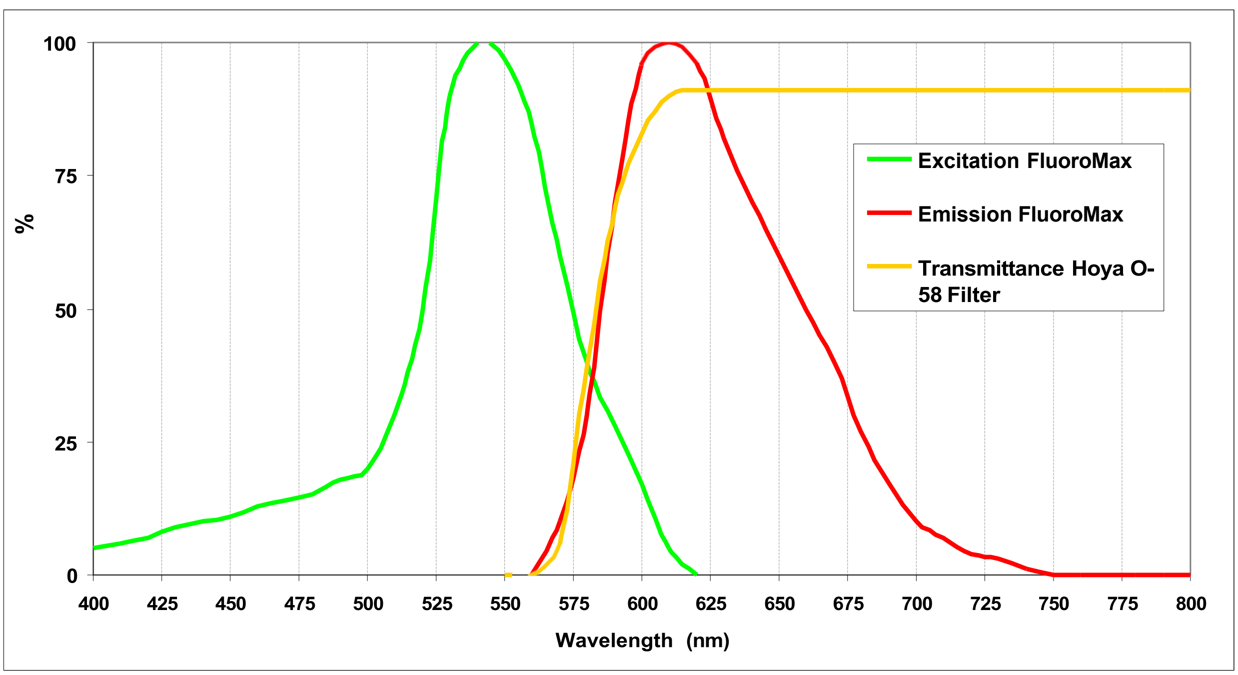
Optical Filters to Block Excitation Light from Camera

Hoya Optical makes colored glass filters that are inexpensive and work well for this



application. Figure 5 shows transmission curves for various Hoya Sharp Cut Filters.

Figure 3. Transmission curves for various optical filters from Hoya



Sharp Cut Filter (Orange)

Catalog Thickness t= 2.5 mm | Reflection Factor P_d=0.916 | Diagram-1

0-58

Transmittance (T) & Internal Transmittance (τ) units:(%)

λ_{nm}	200	210	220	230	240	250	260	270	280	290	300	310	320	330	340	350	360	370	380	390	400	410	420	430	440
T																									
τ																									
λ_{nm}	450	460	470	480	490	500	510	520	530	540	550	560	570	580	590	600	610	620	630	640	650	660	670	680	690
T												.10	6.4	39.1	69.5	83.5	88.4	90.2	90.9	91.4	91.5				
τ												.11	7.0	42.7	75.9	91.2	96.5	98.5	99.2	99.8	99.9				

Figure 4. Transmittance of fluorescent emission by Hoya O-58 optical filter

Synchronizing System Components

It helps to synchronize the system components. Figure 6 shows a basic schematic of synchronizing the system components. This allows pulse coding and multiple pulse per camera frame. When the turbine is being illuminated by the LED strobe, it should appear as it is standing still, not moving. By varying the timing of the LED strobe, the turbine can be "rotated" in the camera image, allowing different parts of the turbine to be examined.

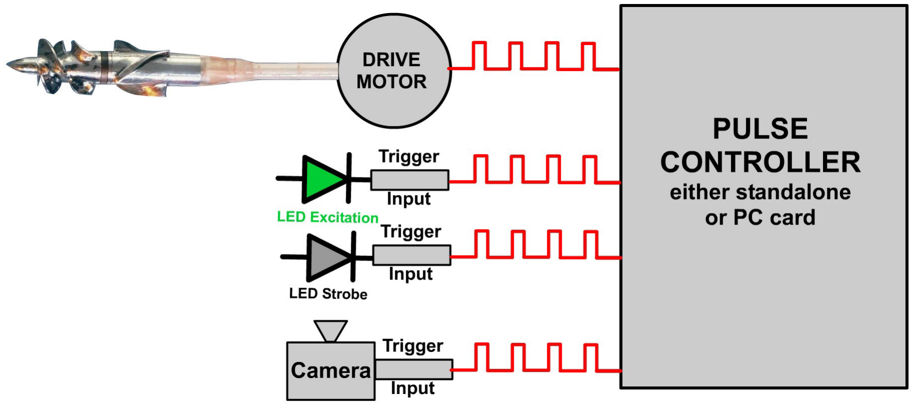
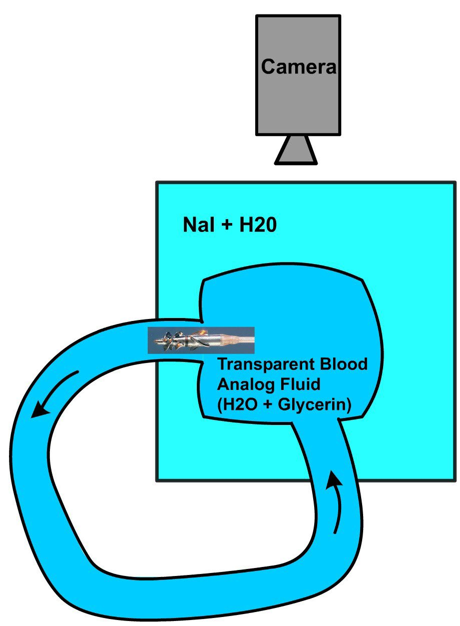


Figure 5. Synchronization of system components

Flow Circuit, Blood Analog Fluid, Refractive Index Matching

Assuming the turbine pump will be studied in a flow circuit with transparent curved walls that are similar to the anatomical walls in which the turbine pump will be inserted, refractive index matching must be used to negate the "lens effect" of the curved walls.

The figure shows a schematic of a refractive index matching flow circuit. A water and NaI solution is used to match the refractive index of the transparent curved walls of the flow loop.



References

1. "Fluorescent Image Tracking Velocimeter," US Patent 5,333,044. Franklin Shaffer, USDOE, 1994
2. "Fluorescent Image Tracking Velocimetry Applied to the Novacor Left Ventricular Assist Device," ASME Cavitation & Multiphase Flow Forum, FED Vol. 135, Shaffer et al., 1992
3. "Respitory Dialysis: A New Concept in Pulmonary Support," J. American Society of Artificial Internal Organs, Hattler, B. et al. 1992
4. "Fluorescent Image Tracking Velocimetry of the Nimbus AxiPump," J. American Society of Artificial Internal Organs, Vol. 39, No. 1, Kerrigen. et al., 1993

Appendix A: FluoroMax Red Fluorescent Microspheres

FluoroMax particles are polystyrene with a red fluorescing dye, from the Rhodamine family of fluorines. Rhodamine in liquid form, is considered by California to be a suspected carcinogen. However, since the Rhodamine is bonded to the molecular structure of polystyrene in the FluoroMax particles, they are not listed in the Safety Data Sheet as a carcinogen. The Safety Data Sheet from the manufacturer of FluoroMax particles can be found at this link.

Purchasing from the manufacturer, ThermoFischer:

https://www.thermofisher.com/order/catalog/product/35-10B

Fluoro-Max Green and Red Beads Dry	Nominal Diameter Range	Bottle Size	Dye Color/Type	Catalog Number Range*	Price
	~5 µm – 160 µm	1 gm	Green Fluorescent (Dry)	35-2 – 35-14	$276.00
	~5 µm – 160 µm	5 gm	Green Fluorescent (Dry)	35-2B – 35-14B	$1,019.00
	~5 µm – 100 µm	1 gm	Red Fluorescent (Dry)	36-2 – 36-11	$276.00
	~5 µm – 100 µm	5 gm	Red Fluorescent (Dry)	36-2B – 36-11B	$1,019.00

Additive May contain trace amount of dispersant
Color Red
Composition Polystyrene Divinlybenzene
Contents Dry dyed polystyrene (DVB) microspheres
Count 1.81×10^6/gram for 100 micron particles; 6.7×10^7/gram for 30 micron particles
Diameter (Metric) Mean 100µm, 30 µm
Dye Type Firefli Fluorescent Red (542/612nm)
Particle Density 1.05g/cm^3
Refractive Index 1.59 at 589nm (25°C)
Stability Product stable for a minimum of 24 months
Storage Requirements Store at room temperature in a dry area. Store upright and keep bottle tightly sealed. Respiratory protection from dust is recommended.
Uniformity <7%

Purchasing through the distributor, Fischer Scientific:

https://www.fishersci.com/us/en/home.html

Fluoro-Max Fluorescent Beads: Green, Red, and Blue Aqueous / Green and Red Dry

Specifications		Green & Red Dry
Composition		Polystyrene divinylbenzene
Dye		Green (468/508 nm), Red (542/612 nm)
Nominal diameter		~ 5 µm - 100 µm
% solids		100%
Additives		N/A
Index of Refraction		1.59 @ 589 nm (25°C)
Density		1.05 g/cm³
Documentation		
Storage and Handling	Unless otherwise stated, refrigerate (2-8°C) aqueous product when not in use, but do not freeze. Store upright and keep bottle tightly sealed. For aqueous products, mix with gentle inversion by hand or vortex mixer. Keep in original bottle and do not expose to light which can deteriorate the product.	

Fluoro-Max Green and Red (Dry)

Nominal Diameter Range*	Bottle Size	Dye Color	Catalog Number Range
~5 µm - 160 µm	1 gram	Green	35-2 – 35-14
~5 µm - 160 µm	5 grams	Green	35-2B – 35-14B
~5 µm - 100 µm	1 gram	Red	36-2 – 36-11
~5 µm - 100 µm	5 grams	Red	36-2B – 36-11B

*The complete list of available products is too extensive to show here, so a Nominal Diameter Range (which includes several different diameters) and its corresponding Catalog Number Range (which includes several different SKUs) is provided as a guide. Contact us or visit thermofisher.com/particletechnology for the complete list.

Appendix B: Stokes Number of FluoroMax Particles

The Stokes number (St) is a dimensionless parameter describing the time it takes a particle to respond (accelerate) to a steady-state velocity due to drag in a flow field. The Stokes number represents the ability of particles to follow an accelerating fluid flow. The Stokes number is defined as the ratio of the characteristic response time of a particle to the time available for acceleration in a fluid flow

$$\tau = \frac{\tau_{particle\_response\_time}}{\tau_{available}}$$

The response time of a particle is

$$\tau_{particle\_response\_time} = \frac{\rho_p d_p^2}{18\mu_f}$$

where ρ_p is the particle density, d_p is the particle diameter, and μ_f is the fluid viscosity. The density of the Fluoro-Max particles is 1.05 g/cm^3. Assuming particles are accelerating from rest to 10 m/s in fluid with the viscosity of blood, ~ 2 mPa-S (https://wiki.anton-paar.com/en/whole- blood/) , the Stokes number as a function of the size of FluoroMax particles well below zero for particle sizes up to 100 microns