EVALUATION OF DUAL COLOURS ILLUMINATION

FOR PARTICLE IMAGE VELOCIMETRY MEASUREMENT

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Declaration

This work has not previously been accepted in substance for any degree and is not being concurrently submitted in candidature for any degree.

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Date: 5th June 2017

STATEMENT 1

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Evaluation of Dual Colours Illumination for Particle Image Velocimetry Measurement

T.F. Chew, and Norizham A. Razak

Abstract

In past decades, particle image velocimetry (PIV) has been widely used in measuring fluid flow and a lot of researches have been done to improve the PIV technique. The purpose of this research project is to evaluate the capability of dual colours high power light emitting diodes (HPLED) illumination to replace traditional PIV. Dual colours HPLEDs PIV can apply single frame double pulses which provides direction or velocity vector of the particles. The idea of dual colours PIV directly replaces lasers as illumination system and high speed camera as recording system, as a single frame can be captured by a normal camera. An illumination system is designed and fabricated to perform fluid flow analysis. The results of the experiment is promising and the feasibility of dual colours PIV is ensured.

Table of Contents

Abbreviation

CAD	Computer Aided Design
CCD	Charged Couple Devices
HPLED	High Power Light Emitting Diode
LED	Light Emitting Diode
PIV	Particle Image Velocimetry
RGB	Red, Green, Blue

1. Introduction

1.1 Particle Image Velocimetry (PIV)

Particle Image Velocimetry (PIV) is a technology which has been used in fluid flow measurement since decades ago. The name PIV was proposed to distinguish the term itself from the laser speckle mode in 1984, as there was an argument that illumination of particles in fluid flows by a light sheet would seldom create a speckle pattern in the image plane [1]. It is undeniable the creation of PIV has contributed to the field of fluid flow measurement for past few decades and today it is still an irreplaceable essential technique in the field. Just like the name of PIV itself, the idea is to trace the particles in fluid flow by capturing two or more images with very small time interval. With this, a few fluid flow properties can be obtained reliably such as the direction and velocity of flow.

A traditional PIV setup consists of a few system to perform its analysis. First of all illumination system, which traditionally is a laser source. The most common used laser source for PIV is the pulsed Neodyme-YAG (Nd:YAG) laser [2]. Today, there are a lot of alternatives in market that can be used to replace traditional PIV setup due to laser source's costly price, safety and other purposes. For example, a stereo-PIV is capable to perform 3D flow analysis by fitting a camera pinhole model to the two cameras using single or multiple views of a 3D calibration plate [3]. This shows the importance of another system of PIV setup, recording system, as the quality and functions of camera can actually change capability of a PIV system.

Another essential thing for PIV is a transparent test section. The test section can part of wind tunnel, water tank or a transparent 3D-printed model to study the internal flow, depends on the purpose of any certain experiment. In order to ensure the flow can be visualized and captured by recording system, seeding particles are added into the fluid. There are several choices of seeding particles in the market which can be used to mix with fluid. It is also worth to study the characteristics of seeding particles in order to determine its availability for a certain experiment. For example, T. Zhang, who did a study on several seeding particles such as hollow glass spheres, polymer micro-spheres and solidified particles to determine their availability to perform PIV studies of a liquid helium [4]. On the other hand, a seeding particles choice evaluation test is performed by Rafika Ben Haj Slama as for the purpose of choosing suitable seeding particles to study the acoustic streaming flow generated by High Intensity Focused Ultrasound (HIFU) [5]. In short, the selection of seeding particles are important for PIV system so that the results captured by recording system are reliable.

Lastly, a computer with suitable software is needed to process the results acquired by recording system. There are many available software that can be used to perform PIV analysis such as OpenPIV and PIVlab, which is an application of Matlab. Photo editing software can be used to filter and convert raw images.

Today, there are many researches in many fields that utilize the PIV technology to study flow measurement. Also, researchers are still seeking for improvements and availabilities of PIV in order to maximize its functions and capabilities.

1.2 Project Objective and Overview

There are two main objectives for this research project. The first objective is to replace the traditional PIV illumination system, which is lasers with high power light emitting diode (HPLED). The reason of replacing lasers source as illumination system is because of lasers are dangerous. A lot of possibilities that cause laser accidents such as lack of adequate protection, operators unfamiliar with laser equipment, fail to follow proper operating procedures, unexpected eye exposure during alignment, misaligned optics and even equipment malfunction. Not to forget the cost of a laser illumination source is costly, even its maintenance fees are not cheap. This makes PIV experiments unaffordable, which is a waste for such a great innovative creation. Therefore, the idea of replacing laser illumination system has been figured out in order to make PIV affordable and safe for everybody.

As mentioned, HPLEDs will be the replacement of laser as illumination system in this research project. Beside reduction in cost and its safety, HPLEDs have a lot of advantages in comparison to lasers. HPLEDs provides incoherent light over a rather wide wavelength range. It is extremely stable in terms of intensity and spatial intensity distribution when the HPLED is operated in pulsed mode. HPLEDs also have longer lifetime. With short pulsed operation, the temperature of the HPLEDs stay below the damage threshold while the photon generation per time unit is increased in proportion to the current increase [6]. Thus, the HPLED is worth to be studied and being used in this research project.

Another objective of this project is to reduce the cost of recording system. For a normal PIV system, a costly high speed camera is commonly used because the time interval between two pictures must be short enough to trace the fluid flow. No doubt, the maintenance fees for high speed camera is also pricey. To make PIV more affordable, an idea of replacing the recording system with a normal camera is initiated. The idea of how a normal camera can do to perform fluid flow analysis will be discussed in following chapter.

2. Literature Review

2.1 PIV's History

Ludwig Prandtl (1875-1953), a German scientist, one of the greatest aerodynamist built his flow tunnel in sunlight in which he photographed fluid flows inside the tunnel. Boundary layer and its importance for drag and streamlining has been described in his paper. The paper described the concept of flow separation and stall. Micaceous iron ore was suspended in the water to indicate the nature of the flow. Due to the technological limitations, the flow can only be visualized, no quantitative data of the structure of flow can be determined [7].

Before PIV method was introduced, there are a few methods of obtaining the fluid flow properties. Some of the earliest method of fluid flows measurements were obtained by using Pitot-static tubes. However, when pitot tubes are employed in connection with fluid, it has the potential to become clogged with foreign matter which lodges in the openings in the tubes. This incident leads to erroneous or erratic readings and may necessitate ceasing operations for period of time to remove and clean the tubes [8].

Back in 1920s, hot-wire anemometer was introduced and it was a significant advance technique during that time. In terms of probe miniaturization, frequency response and ability to measure multiple velocity components, hot-wire anemometer was once one of a good choices of measuring fluid flows [9]. The principle of a hot wire anemometer is based on a heated element which its heat will be dissipated by colder impact airflow. The temperature hot wire is meant to be kept constant by power supply. The fluid flow can be calculated based on change in temperature.

However, hot-wire anemometer has its disadvantages and limitations. Same as pitot-tube, physical probe of hot-wire anemometer requires to be inserted to fluid flow which will disturb the flow.[9] Also, hot-wire anemometer is unsuitable for measuring turbulent temperature correlations because of the highly non-linear response to temperature fluctuations. This method is then limited to measurements of mean and fluctuating mass-flow rates [10].

In 1960s, the invention of laser brought flow measurement techniques into a whole new level. Laser Doppler anemometer was introduced and successfully overcome the limitation of hot-wire anemometer and pitot-tube, which its laser probe can be operated without disturbing fluid flow [9].

Since then, the PIV technique is still developing and always being used in fluid flow measurement field. A number of researchers did surveys and studies on PIV based on its measurement technique and applications. There are a lot of helpful and informative published paper since the invention of laser which done by L Zhao and Y Zhang [11], Hertzberg and Shandas [12], AK Prasad [13] and many more. The high promising and reliability approach of PIV makes it a popular method to study the structure of flow. It is has been widely used in many field such as fluid mechanics and aerodynamics.

2.2 Application of PIV

As mentioned, PIV is a flow measurement technique that has been widely used around the world for different cases of studies. Its capability of providing accurate instantaneous velocity of flow field has become the reason of its application at many researches. Different setup of PIV system can be applied at different type of flow measurements. For example, van Doorne and Westerweel used stereoschopic-PIV to perform a fluid dynamics research, which is to measure laminar, transitional and turbulent pipe flow during 2007 [14]. The image of instantaneous turbulent flow field in a cross-section of the pipe is shown in Figure 2.1.

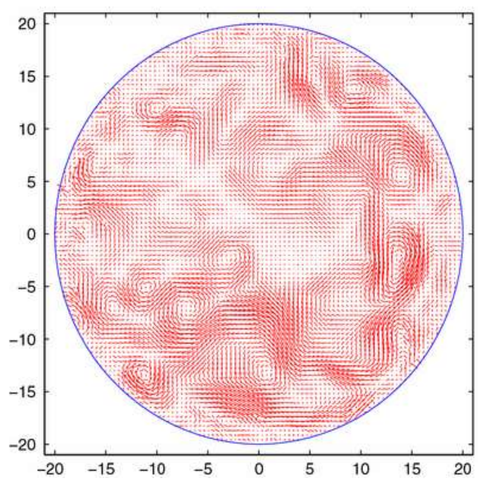

Figure 2.1: Example of the instantaneous turbulent flow field in a cross-section of the pipe. Displayed resolution is 8 × 8 px, or 0.5 × 0.5 mm2 [14]

PIV is also able to contribute in the field of aerospace. In 2011, James Bridges had conducted a PIV measurements of chevrons on F400-series tactical aircraft nozzle model [15]. The purpose of the research is to reduce the noise of tactical jet aircraft which can benefits health of military workforce and also stealthiness of the aircraft. Figure 2.2 shows the results of mean streamwise velocity contours for all different design of chevrons. The turbulence intensity is further discussed in the paper in order to determine which design is best suit the aircraft nozzle to minimize noise.

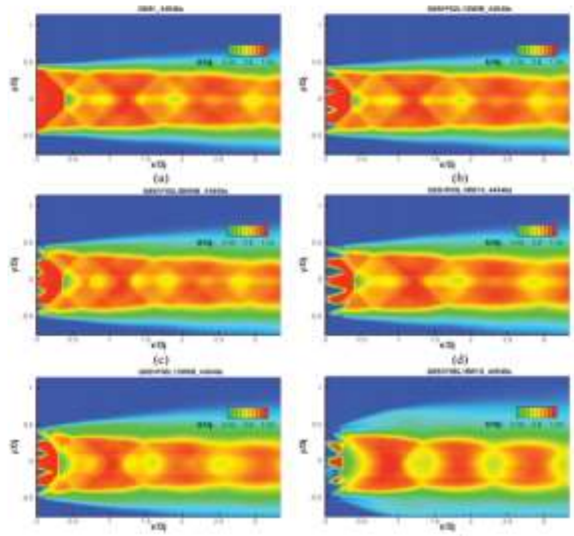

Figure 2.2: Contours of mean streamwise velocity for all chevrons configurations[15]

In terms of aerodynamics, PIV has a wider application. An excellent research on the turbulence structure of drag-reduced boundary layer flow has been done by C. M. White in 2003 [16]. The dilute addition of long-chain flexible polymers to flowing liquids can reduce turbulent friction losses. Thus, drag reduction was achieved by injection of this polymer solution to the test wall for PIV analysis. The research compared the fluid flow, with and without the drag reduction polymer solution injection and the velocity of the flow is shown in Figure 2.3.Both of the images are taken from top view. It can be said that the results taken by PIV is reasonable with the observation of higher velocity vector in picture b compared to picture a, since the fluid in picture b was injected with drag reduction polymer solution.

It is common to utilize PIV for analysing fluid flow around an airfoil. BW V. Oudheusden and F. Scarano made an assessment to determine the feasibility of using PIV velocity data to for the non-intrusive aerodynamic forces such as lift, drag and pitching moment [17]. This assessment relies on the combination of application of control-volume approaches and momentum equation after the extracting results from PIV experimental data. PIV-based force coefficients were compared with the standard pressure-based procedures in the assessment and found that the PIV approach is in acceptable accuracy.

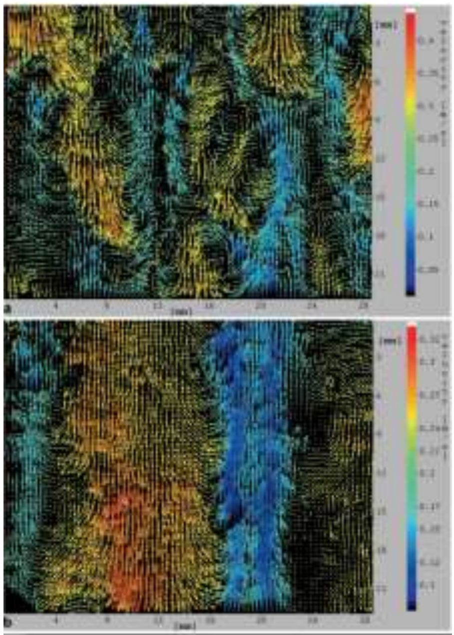

Figure 2.3: Sample PIV vector plots of the fluctuating velocity in water, with and without drag reduction polymer injection[16]

Another interesting assessment on airfoil is worth to be highlighted, that is to investigate the laminar separation bubble on a SD7003 airfoil by using PIV technique. Wei Zhang and his team found that by decreasing the Reynolds number, the laminar separation bubble has an earlier separation across the airfoil and a significantly increased reversed flow region followed by "huge" vortical structures [18].

Other than airfoil, the fluid flow around a propeller is also worth to be investigated by PIV. F. Di Felice did an investigation on a five blade propeller wake behind a ship model by using stereo PIV [19]. The longitudinal mean velocity component obtained by stereo reconstruction is shown in Figure 2.4. The results have proven the capability of stereo PIV in resolving the complexity of the flow field.

Overall, PIV has a wide range of application. As shown above, a lot of research fields such as fluid mechanics, propulsions and aerodynamics utilize PIV technologies to perform investigations. There are still a lot of researches conducted based on PIV. Thus, PIV technique should be developed continuously to enhance its capability.

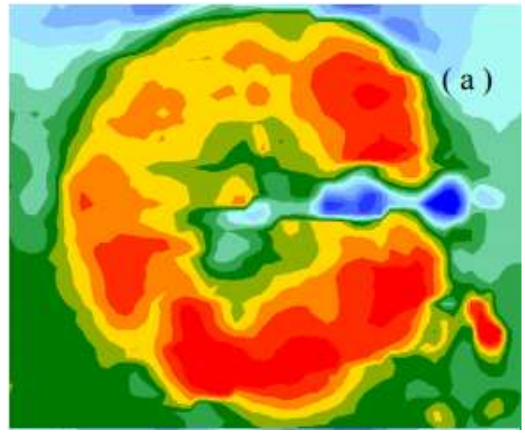

Figure 2.4: Longitudinal mean velocity component obtained by stereo reconstruction[19]

2.3 Illumination System

The illumination and recording system both play important role in PIV technique. Illumination system is the source that shines the seeding particles inside fluid so that visualized and captured by recording system. A recording system is important as its capability and specifications have to meet an experiment's demand. A traditional PIV system uses laser as the source of illumination system. Laser light can produce high intensity beams and the beams can be shaped into a 2 dimensional light sheet. Its beam pointing stability is also one of the favourable characteristics as an unstable light sheet may affect velocity measurements accuracy. A range of laser wavelengths are available depends on the sensitivity of recording system [20].

According to Northern Illinois University Laser Safety Manual [21], lasers are divided into a few classes depending on the power or energy of the beam and the wavelength of the emitted radiation. Laser classification is based on the laser's potential for causing immediate injury to body and for causing fires from direct exposure to the beam or from the reflections from reflective surfaces.

Class 1 lasers are incapable of producing damaging radiation levels which makes them exempt from most control measures or other forms of surveillance. Class 2 lasers emit radiation in the visible portion of the spectrum. Its protection is afforded by the normal human aversion response, such as blink reflex to bright radiant sources. It could be hazardous if viewed directly for a long period of time. Class 3 is divided into 2 categories. Class 3a lasers are those which would not cause injury if it is just viewed momentarily with unaided eye. They may present a hazard if viewed using collecting optics such as telescope, microscope or binoculars. Class 3b lasers may cause severe eye injuries from direct viewing of the beam or specular reflections. Class 3 lasers are usually not fire hazard. Class 4 lasers are a hazard to the eye from the direct beam and specular reflections and even from diffuse reflections. Class 4 lasers can also start fires and damage skin. The commonly used laser for PIV, neodymium-doped yttrium aluminium garnet (Nd:YAG) falls in Class 4 [22].

For Class 3b and Class 4 lasers operators, they must be trained and qualified which they have to meet both training requirements and operational qualifications established by PI [21]. Lasers operators must receive written safety instructions to properly utilize the equipment and follow all the safety procedures. The training include basic instruction on a few topics such as biological effects of laser radiation, access control, use of protective eyewear and emergency response procedures.

It can be seen that lasers is a powerful but dangerous illumination source, thus a few alternatives source was tried by researchers to replace the laser. In February of 1993, a paper namely White Light Bubble Image Velocimetry was published by Shen Gongxin and Ma Guangyun from Beijing University of Aeronautics and Astronautics [23]. It is a kind of PIV in which a flash set and a plane sheet like-bubble mass to replace the traditional laser light and seeding particles. The results show that the instantaneous 2-dimensional velocity vector field at more than 1000 points with accepted accuracy for a starting vortex flow in low-speed water channel is obtained. It has a few attractive advantages such as lower cost and no dusty pollution in the testing facilities.

In the past decade, a few researches have been done on replacing illumination source with high power light-emitting diode (HPLED). In 2010, N.A. Buchmann and his colleagues investigated the use of HPLED as a replacement to traditional laser-based illumination source. Other than ensuring the feasibility of LED-based illumination source, some attractive advantages of LED over laser was discovered. The usage of LED dramatically reduces costs, has considerable long lifetimes, provide extremely stable pulse-to-pulse intensity as well as prevention of speckle related artefacts due to their incoherent light emission. Furthermore, HPLEDs can be operated beyond their damage threshold by using high current and short pulsing duration. In PIV, green LEDs are mainly used because present day imaging sensors exhibit peak quantum efficiencies in the yellow and green range, which is around 530 to 550nm, similar to the response of human eyes [24, 25].

3. Theoretical Background

As the name suggests, particle image velocimetry (PIV) is an optical method of flow visualization that is able to record the position of a small tracer particles that introduced into the flow over time in order to extract the local fluid velocity [26]. A complete integrated PIV system consists of illumination system, transparent test section, recording system and a computer that contains image processing software. Figure 3.1 illustrates a setup of a PIV. Light is illuminated to the test section that has the mixture of fluid and seeding particles. The light will be reflected by seeding particles and the movement of these particles will be traced by recording system which is located perpendicularly to the light sheet. The captured images will be imported into computer and processed by software to obtain qualitative and quantitative results.

In traditional PIV system, high power laser as illumination system and high speed camera as recording system are essential in order to capture the fluid flow. However, safety issues and high cost of both of these equipment are often raised. Therefore, the idea of dual colours PIV is introduced. Two different colour HPLEDs are used to replace the high cost and dangerous high power laser. It is expected that dual colours PIV illustration system will be able to capture the fluid flow with normal camera which has lower fps has a longer shutter time compared to high speed camera. With this, the cost of the PIV system can be reduced.

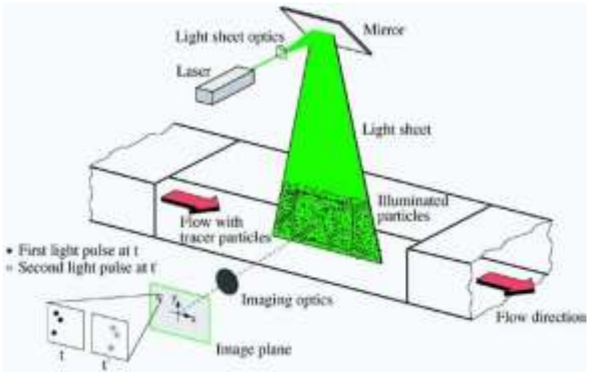

Figure 3.1: Simple setup of PIV [27]

In this research project, green and red HPLEDs are selected to replace laser as illumination source. Figure 3.2 shows eye sensitivity function against color wavelength graph and this can explain the reason of selecting red and green HPLEDs instead of any other color. According to the graph, human eyes are most sensitive to the middle of the spectral range, which is around 550nm and similar to green color's wavelength. This is why green color HPLED is one of the best options for this project. Red color HPLED is chosen as the second choice instead of other available color HPLEDs such as blue and yellow. Refer to Figure 3.2, red color is definitely a better choice than blue color because of the higher eye sensitivity function to red color. Yellow color is better than red in terms of wavelength because it is more sensitive to the eyes. However, the wavelength range of green and yellow are very near which makes observer difficult to differentiate both colors. These reasons make red color HPLED a better option.

Before the experiments are conducted, the characteristics of both HPLEDs have to be determined. HPLEDs intensity test was conducted with the aid of microcontroller to record illuminance lux that can be produced by HPLEDs. Illuminance is the total amount of visible light illuminating a point on a surface from all directions above the surface, which is lumens per square meter (lm/m^2) [29]. It is a measure of intensity of the incident light, wavelength-weighted by the luminosity function to correlate with human brightness perception. In short, illuminance is the quantitative term of brightness. As the intensity test of HPLEDs will be conducted by manipulating voltage (or power), it is worth to study the relationship between illuminance and power.

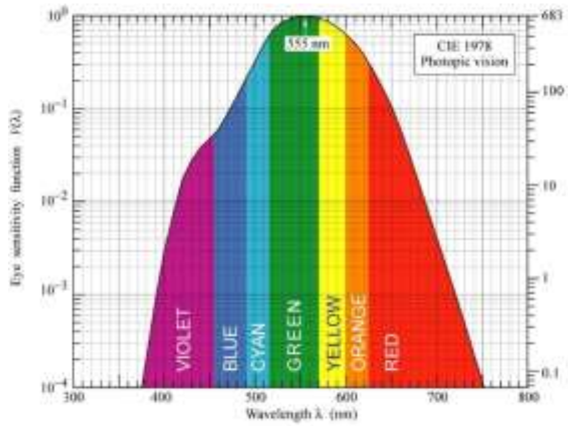

Figure 3.2: Human eyes sensitivity function against wavelength [28]

The luminous flux, Φ_V in lumens (lm), is the product of power P in watts (W) and the luminous efficacy η in lumens per watt (lm/W):

$$\Phi_{v(lm)} = P_{(W)}\ x\ \eta_{(\frac{lm}{W})} \qquad (1)$$

The illuminance, E_v in lux (lx), is the ratio of luminous flux Φ_V in lumens (lm) to the surface area A in square meters (m^2):

$$E_{v(lx)} = \frac{\Phi_{v(lm)}}{A_{(m^2)}} \qquad (2)$$

So the relationship between illuminance and power is:

$$E_{v(lx)} = P_{(W)}\ x\ \frac{\eta_{(\frac{lm}{W})}}{A_{(m^2)}} \qquad (3)$$

In this case, the luminous efficiency and surface area will be constant because the HPLEDs are identical. Thus, illuminance is directly proportional to power supply to the HPLED. Another interesting finding of brightness or illuminance is its sensitivity RGB color. According to Darel Rex Finley [30], the brightness or illuminance can be calculated as follow, which stating green color relatively contributes more to illuminance, followed by red and green color:

$$Brightness = sqrt(0.299\,R^2 + 0.587\,G^2 + 0.114\,B^2) \quad (4)$$

The intensity test for both HPLEDs used in this project research will be done and its results will be discussed in later chapter.

The idea of studying fluid flow by using PIV technique relies on capturing the movement of seeding particles by visualizing the reflected light from them. For most experiments, it is desirable that seeding particles are non-toxic, non-corrosive, non-abrasive, non-volatile and chemically inert [31]. The seeding particles also need to have some characteristics to fit the experiment, such as similar density with fluid, large enough to be visible, fairly distributed in the flow and adequate mass quantities. A few solid seeding particles are commonly used in PIV study in liquid application such as polystyrene (10-100μm), polyamide (aluminum flakes (2-7 μm), hollow glass spheres (10-100 μm) and granules for synthetic coatings (10-500 μm). For gas application, seeding particles often used are alumina (0.2-5 μm), titania (0.1-5 μm), glass micro-spheres (0.2-3 μm) and smoke (<1 μm) [32]. Before the experiment started, it is crucial to select suitable seeding particles in order to obtain reliable results.

There are two reasons for optimizing particle image diameter. First is to minimize the error in velocity measurements. An analysis shows that the error of velocity measurement strongly depends on particle image diameter. Second, sharp and small particle images are essential in order to obtain a high particle image intensity, since at constant light energy scattered by the tracer particle the light energy per unit area increases quadratically with decreasing image areas [32].

Next, the mass quantity of the seeding particles that introduced to the fluid needs to be appropriate. In 2012, Z. Driss and his colleagues did an experimental study of the seeding mass quantity effect on the PIV measurements [33]. The purpose of the study is to quantify adequate mass quantity of spherical polyamide particles in order to reduce errors in two-dimensional PIV. Four different mass quantity of seeding particles which their mass were 0.04g, 0.08g, 0.16g and 0.24g were used and the results obtained by PIV system is shown in Figure 3.3.

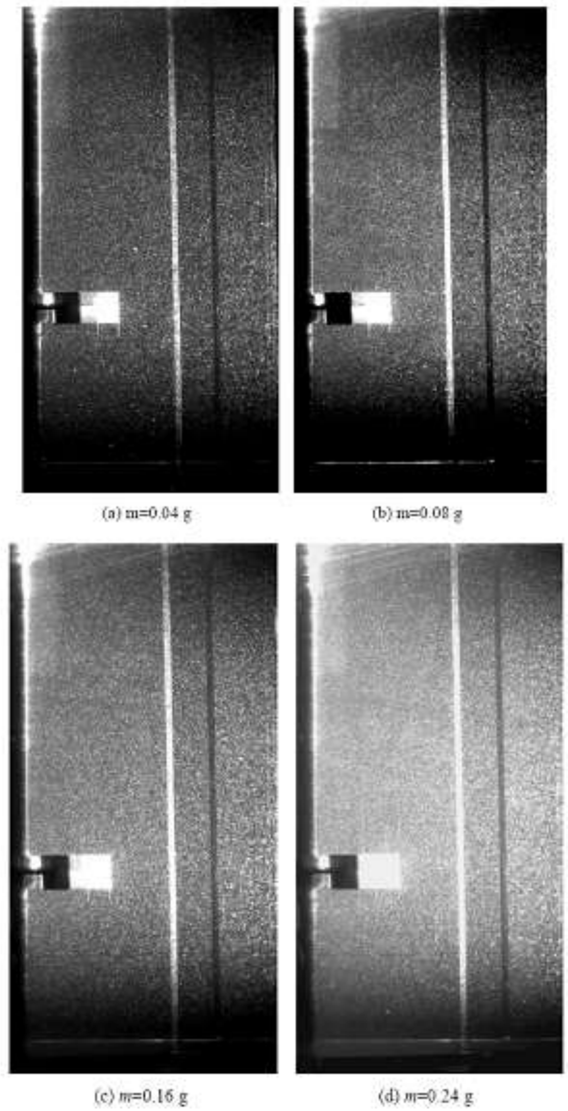

Figure 3.3: Data acquisition of different mass quantities seeding particles [33]

In this research project, polyamide with size of 50μm is chosen to be seeding particles due to its similar density to water, affordable price and its visibility under the light by recording system.

Another important factor to obtain good image of flow is the timing calibration between illumination source pulsing and recording system shutter time. Usually the pulsing and capturing time is very short, thus the calibration task will be done by computer to control the operation between two systems. Figure 3.4 illustrates the timing of camera shutter and laser pulsing time. The laser will be pulsed in between the time of camera shutter open [34]. For high speed camera, the shutter will usually closed for a very short period of time, which is about micro to nano seconds. The camera shutter will be open again for capturing the second image. The time interval between the two images is very short. The two images will be used for fluid flow analysis.

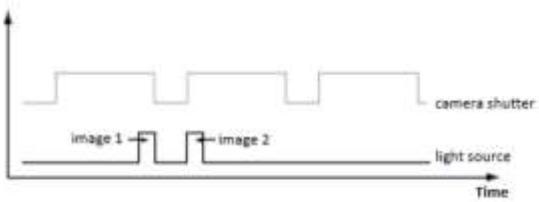

Figure 3.4: Timing of laser illumination and camera shutter time for PIV system [34]

One of the purposes of this project is to replace high speed camera with normal camera. The limitation of a normal CCD camera to this project is that it needs longer time interval between shutters, which means the time interval between the images will be too long and leads to inaccurate results. Thus, the idea of using dual colours PIV is introduced. The shutter opening time is set to be longer to capture two pulsing LED light in one shutter. There is an interval time between both pulsing LED light so that the movement of particles can be visualized. Figure 3.5 shows the relationship between camera shutter time and light source illumination time.

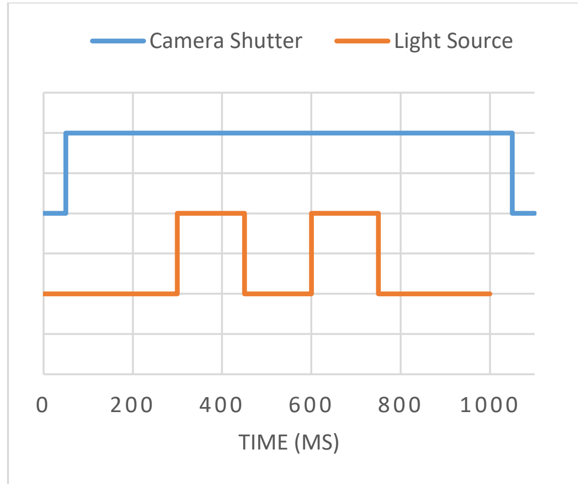

Figure 3.5: Timing of HPLEDs illumination and camera shutter time for dual colours PIV system

After taking the images, the images have to be processed to get qualitative and quantitative results. There are two types of method for analyzing images acquired from flow, which are cross-correlation and auto-correlation respectively. A single frame double exposure image will undergo auto-correlation while a double frame single exposure image will undergo cross-correlation [35, 36]. There are a lot of available correlation software in the market for PIV images analysis such as PIV View, OpenPIV and PIVlab which is one of the application of MATLAB. Christian A. Hviid has published an interesting paper of visualizing and characterize air flow patterns in a classroom and the captured image is being processed by PIVlab. The results are shown in Figure 3.6 [37].

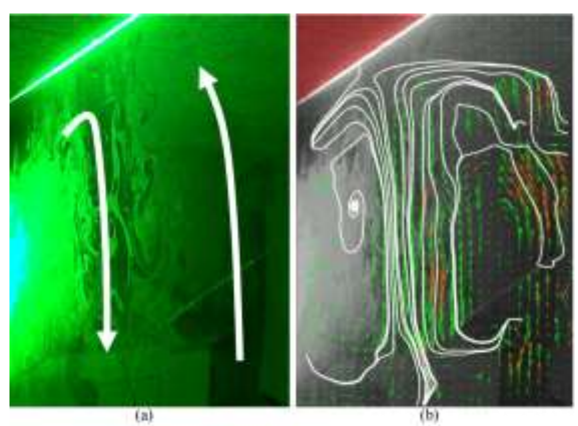

Figure 3.6: a) Raw image b) Image with velocity vector after processed by PIVlab [37]

With the aid of image processing software, the analysis of fluid flow velocity become simpler, easier and more accurate. However, because of PIV is based on statistical correlation of imaged subregions to determine local flow velocities, it is possible that errors can occur from finite tracer particle numbers, sample volume size and image resolution. To correct the errors, there are a few methods can be done. A correlation of two or more adjacent correlation tables, improves subpixel accuracy and eliminates spurious vectors resulting from unmatched particle pairs, out-of-boundary motion, particle overlap, inter-particle correlations, and electronic and optical imaging noise [38].

4. Methodology

In this chapter, the methodology of this project will be discussed in detail. The design of the project will be discussed and explained. A CAD software, Solidworks is used throughout the design process in order to illustrate the idea for the ease of fabrication.

4.1 Control Circuit

For this research project, high power LED (HPLED) has been chosen as the alternative to replace the traditional PIV illumination source, which is laser. An illumination system has to develop in order to support the illustration of HPLEDs in desired way. The selected HPLEDs for this research project are green and red colors, which shown in Figure 4.1, both capable to perform in continuous mode. Both HPLEDs has maximum power of 100W and 6.25cm^2 size of illumination area.

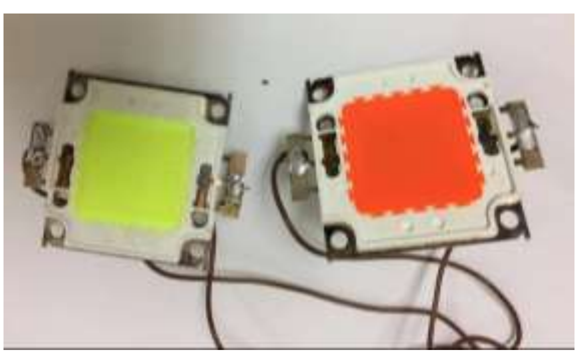

Figure 4.1 : Red and green HPLEDs with maximum power of 100W

The main components of the illumination system are electronics circuit, illumination sources which are red and green HPLEDs, optical parts which are optics fiber guide, cylindrical lens and convex lens, power supply, microcontroller for pulsing purpose and the casing for the illumination system.

The electrical control circuit is essential because it controls and ensure the HPLEDs are able to perform as desired. It would be easy to connect the HPLEDs straight away to power supply to enlighten it but it might damage the HPLEDs and it is not easy to control the desirable pulsing of the HPLEDs. Therefore, an electrical control circuit is developed in order to light up the HPLEDs with desirable pulsing, driving by a power supply. The electrical control circuit consists of resistors, capacitors, HPLEDs, MOFSETs and power supply. The main function of MOFSETs power transistor in this circuit is to control pulsing of the HPLED, which the MOFSETs will be triggered by microcontroller. All the electrical components in the circuit are shown in Table 4.1.

Table 4.1: Components in electrical control circuit

Symbol in Circuit	Components
R1,R3	1 Ω resistors
C1,C3	10 μF capacitors
C2,C4	2200 μF capacitors
L1	Red Colour HPLED
L2	Green Colour HPLED
Q1, Q2	IRF540N MOSFET
S1, S2	Switch
R2	0.165Ω resistor
R4	0.110Ω resistor

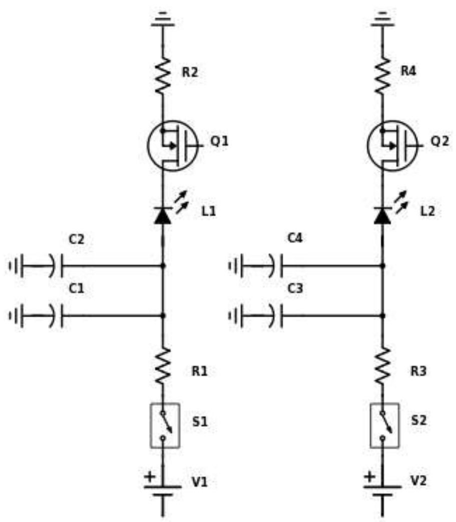

Figure 4.2: Schematic diagram of electrical control circuit

The circuit on the left is for red HPLED while the other is for green HPLED. Both of the circuits are almost the same, the only difference between two circuit is the resistance of R2 and R4. R2 resistance is designed to be lower compared to R4 because of the red HPLED required more current, in other words, more power to produce sufficient illuminance. In order to get resistance as small as R2 and R4, a few resistors with small resistance are connected in parallel.

The function of both different capacitance capacitors are different. The capacitors with bigger capacitance are connected in the circuit for pulsing purpose. The power supply will not be fast enough to react and provide sufficient power when the circuit is triggered by microcontroller in the unit of milliseconds. Capacitors store electrical energy and ready to discharge immediately when the circuit is triggered by microcontroller. With this, capacitors can be said as essential components for these circuits in order to provide enough electrical energy to HPLEDs, especially during pulsing. On the other hand, the small capacitance capacitors have another function. These small capacitance capacitors which act as voltage stabilizers in the circuits. The voltage given by power supply will fluctuate in small magnitude from time to time. In order to stabilize the electrical energy in the circuit, these capacitors will store extra electrical energy when voltage is over than usual and discharge electrical energy when voltage is lower than usual.

The MOSFET power transistors of the circuits are triggered by microcontroller, Arduino. A simple LED pulsing program is uploaded into Arduino in order to trigger the circuit as desired. Figure 4.3 illustrates the schematic symbol of the selected MOFSET in this project. Symbol G, D and S represent gate, drain and source respectively. When voltage is applied between gate and source, current is allowed to flow between drain and source. MOFSET has variable resistance which can be controlled by voltage applied between gate and source. When the voltage between gate and source is low, the resistance between drain and source is very high that no current will be allowed to flow between them. As the voltage between gate and source increased, the resistance between drain and source decreases and current is allowed to flow between them. With the change of the voltage applied on gate and source, the resistance of drain and source can be changed rapidly. In other words, MOFSETs act as rapid switch which controlled by microcontroller with desired pulsing time in the circuit.

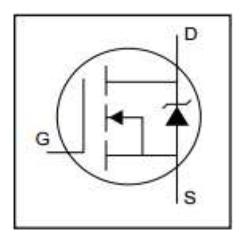

Figure 4.3: Schematic symbol of MOFSET irf540n

4.2 Design and Fabrication

The electronic control circuit is only a part of the illumination system. A casing is designed as a platform in order to hold and locate all the illumination system components, such as HPLEDs, beam splitter, and lenses. The design must ensure the light produced by HPLEDs can enter into the optic fiber guide as much as possible so that losses of the light energy can be minimized. The function of a beam splitter is to reflect the light of both HPLEDs into two difference direction. The intensity of each HPLED will be decreased to 50% at the output of the beam splitter. The output of the light from the beam splitter will be directed to the optic fiber guide. Optic fiber guide allows the light to be illustrated in sheet form.

Figure 4.4 shows the exploded view of the initial design of the platform. It is basically a circuit box that holds electronic circuit, HPLEDs and beam splitter. The perspex platform is designed to hold HPLEDs and beam splitter so that they can be fixed such that the lights from the HPLEDs can be illuminated directly to the beam splitter. The perspex platform is fabricated by using milling machine and connected with the circuit box casing with bolts and nuts. A cooling fan is installed to cool down the HPLEDs which will radiate large amount of heat during high power so that HPLEDs can be avoided from overheating damage. Two optic fiber guide inlets will be slide into the holes where the output of light from beam splitter is illuminated. Figure 4.5 shows the location of the components inside the platform of illumination system.

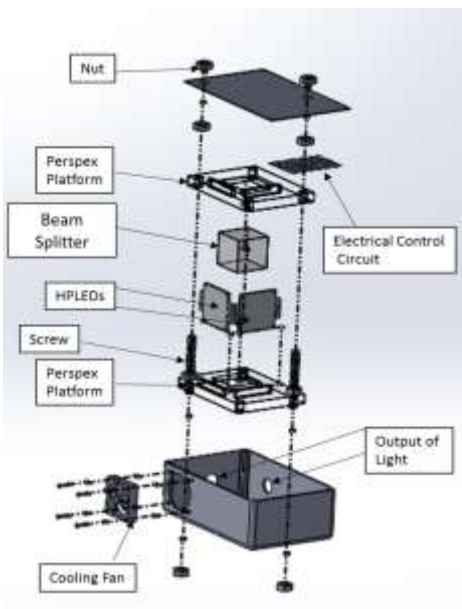

Figure 4.4: Exploded view of initial platform design

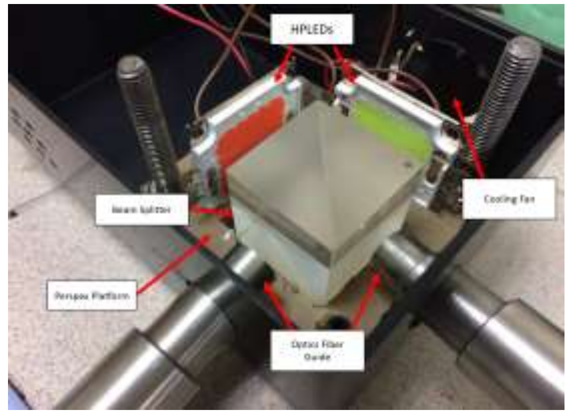

Figure 4.5: Initial interior design of illumination system platform

However, the initial design is not good enough to perform the desired experiment because the light of the HPLEDs needed to be focus more to the optics fiber guide. With this, convex lens with 12 cm focal length are used to focus the lights on the optics fiber guide in order to prevent losses of light. Thus, the design of the illumination system platform has to be changed such that the spaces inside the illumination system platform has to be increased. Of course one of the reason for that is to give space to place the convex lens and their holders. Another reason of doing that is to give sufficient distance between beam splitter, convex lens and optics fiber guide due to the focal length of convex lens.

A bigger size platform is required and a CPU casing is chosen to replace the circuit box. All the components inside the CPU is removed and modified in order to fit the expected design as shown in Figure 4.6. The previous cooling fan is replaced by a bigger one by taking the advantage of the bigger size casing. Two switches are added to the new design so that both red and green HPLEDs can be switched on and off without unplugging power supply.

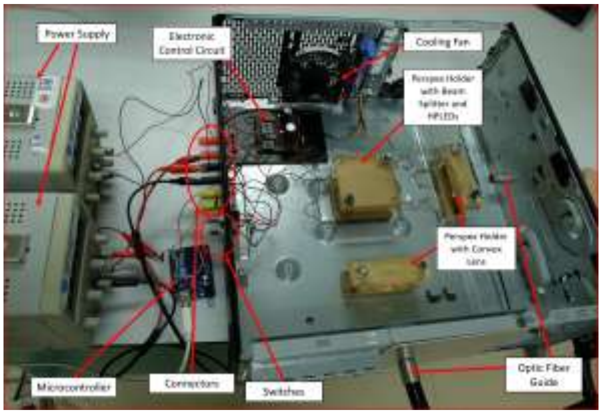

Figure 4.6: Final design of illumination system platform

4.3 HPLEDs Characterization and Pulsing Operation

After the fabrication is done, the characteristics of both HPLEDs have to be determined. The light intensity of both HPLEDs will be studied in terms of illuminance which its SI units is lux (lx) with the changes of power.

The microcontroller must first be connected with digital light sensor, BH1750 according to Figure 4.7. Next, the microcontroller will be connected to a computer for programming purpose. The coding of BH1750 digital light sensor is uploaded to the microcontroller [39].

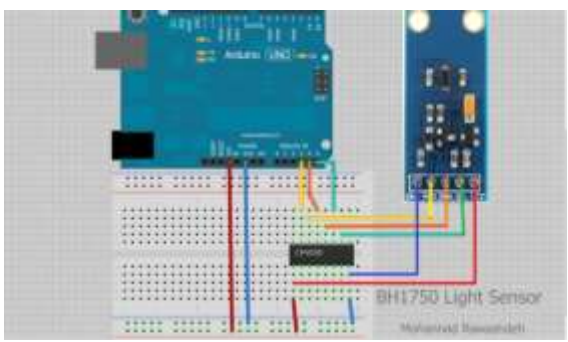

Figure 4.7: Connection between microcontroller and digital light sensor [39]

After uploading the code into microcontroller, the setup for HPLEDs characterization is done according to Figure 4.8 and Figure 4.9 where the lights from the HPLEDs travel through the optic fiber guide and shine to the digital light sensor. A paper is put between microcontroller and optics fiber guide to prevent short circuit.

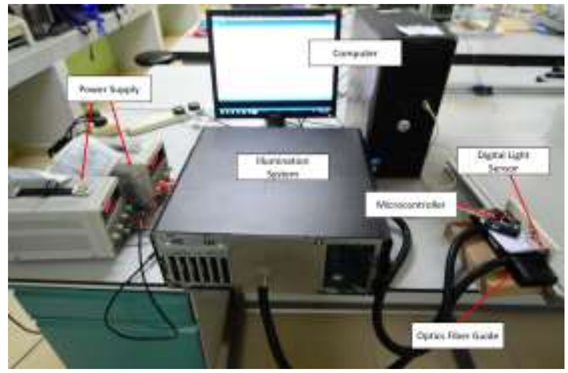

Figure 4.8: HPLEDs characterization setup

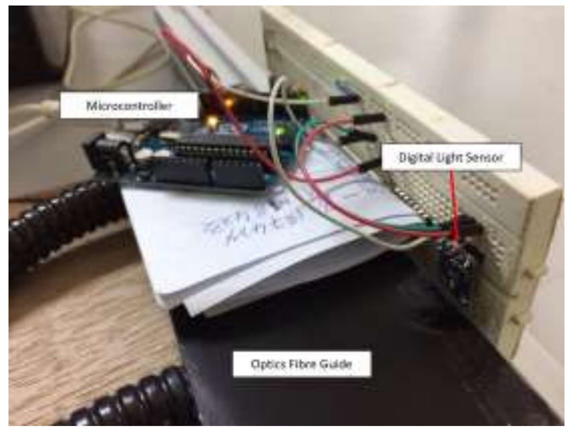

Figure 4.9: Close up to digital light sensor

The test is conducted in a dark room to avoid stray light causing noise. Both HPLEDs characteristic tests are conducted separately. The power of HPLEDs is altered by changing the voltage of the power supply. The voltage is first operated at maximum and slowly decreased to the point where the illuminance reading is zero. At each voltage, the average illuminance reading for ten seconds will be taken and recorded. Before taking any reading at any voltage, the HPLED will be cooled down to avoid overheating which may affect the brightness of the HPLED. The current reading at each voltage will be taken for the purpose of calculating the power of HPLEDs. The results for both HPLEDs at various voltage or power will be presented and discussed in following chapter.

After characterizing HPLEDs, another essential step for this project is to make sure both HPLEDs can be pulsed appropriately with the aid of microcontroller. The code for multiple LED pulsing will be uploaded to the microcontroller.

The connection between microcontroller and illumination system is shown in Figure 4.10. White wire is connecting both microcontroller and illumination system ground. Red wire is connecting the red HPLED's pulsing connector and channel 13 of microcontroller, while green wire is connecting the green HPLED's pulsing connector and channel 12 of microcontroller [40]. The microcontroller will pulse both the HPLED according to the timing shown in Table 4.2. The red HPLED will first be pulsed for 150ms and switched off. After a time interval of 150ms with both HPLEDs remained off, green HPLED will be pulsed for 150ms and switched off. The purpose of setting the time interval after red HPLED being pulsed is to allow the particles inside the flow move significantly before the green HPLED being pulsed on the test section. HPLEDs will be pulsed all over again if the microcontroller is reset.

Table 4.2: HPLEDs pulsing timing

Time (ms)	HPLEDs	
	Red	Green
0	ON	OFF
150	OFF	OFF
300	OFF	ON
450	OFF	OFF

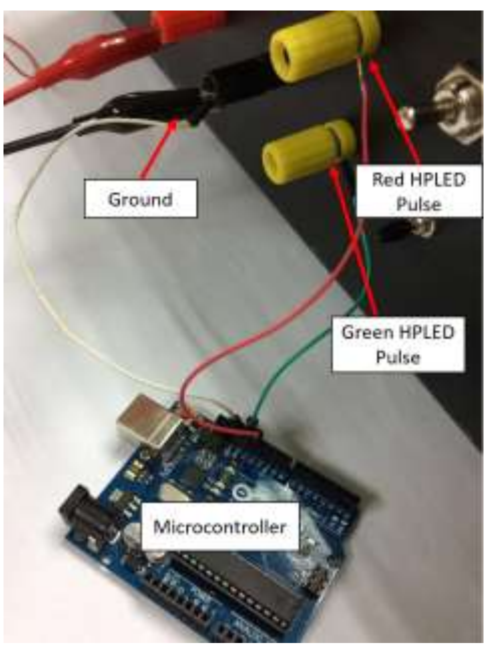

Figure 4.10: Connection between microcontroller and illumination system

4.4 Experimental Setup for Non Uniform Flow Measurement

After the illumination system is ready, a few experiments are conducted in order to evaluate the designed PIV system is reliable. Figure 4.11 illustrates the setup of the HPLEDs illuminated PIV. Cylindrical lens is responsible to focus the light that emitted from optics fiber guide into a thinner sheet. Water tank is the test section of the experiment. The water tank contains water and seeding particles which is polyamide. Polyamide has average diameter of 50 µm and has similar density with water which allows observer to visualize water flow. The light is shone to the water tank while the camera is located perpendicularly to light sheet. The camera used in this experiment is Canon EOS 1300D. The lens of camera has to be set and focus properly on the particles inside test section before the experiment starts. The light will be pulsed according to Table 4.2 and the camera will capture the image of particles inside the test section with 1 second of shutter time. The mixture of water and seeding particles inside the test section will be disturbed before the results are captured.

The mixture is disturbed by using a wooden stick. Three different results with different method of disturbing the flow are taken, which are translational, random stir and flow across a tip of a plate. The reason of choosing a wooden stick as a tool to disturb the flow because it will not reflect the light which causes inaccuracy of results.

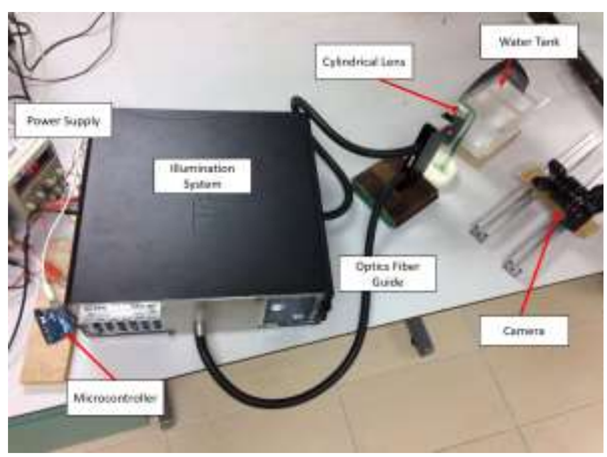

Figure 4.11: HPLEDs PIV setup

4.5 Post-Processing of Acquired Images

The taken results have to be processed before being analysed. Figure 4.13 is a flow chart on how a post-processing results will be done for analysing purpose. First of all, the raw image taken from the experiment will be filtered by using graphic viewer IrfanView into red and green color images separately. Both filtered images will be converted into greyscale respectively and the greyscale images will be imported into PIVLab for analysis.

PIVLab is a PIV software that performs PIV correlation and yields the results as the velocity flow field. It is a user-friendly GUI application of MATLAB. After importing the processed greyscale images into PIVLab, some procedures have to be done before the analysis started. Firstly, the region in the images that does not involve any fluid flow has to be drawn with mask so that the software will not take that region into flow analysis. Refer to Figure 4.12, select the button draw mask(s) for current frame and draw mask on those regions. Next, select region of interested (ROI) in the picture so that the software will only focus on analysis of the selected region.

Next, go to PIV Settings to set interrogation area before the analysis started. After the analysis is done, go to Statistics to check the histogram of the results.

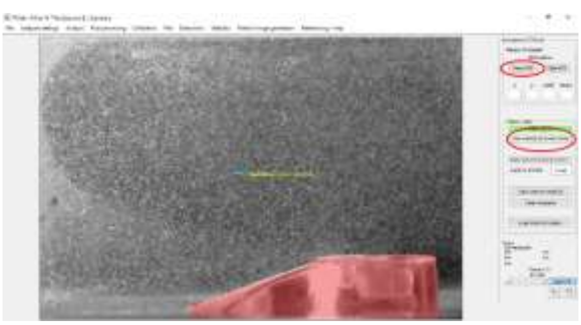

Figure 4.12: Drawing mask and select ROI in PIVLab

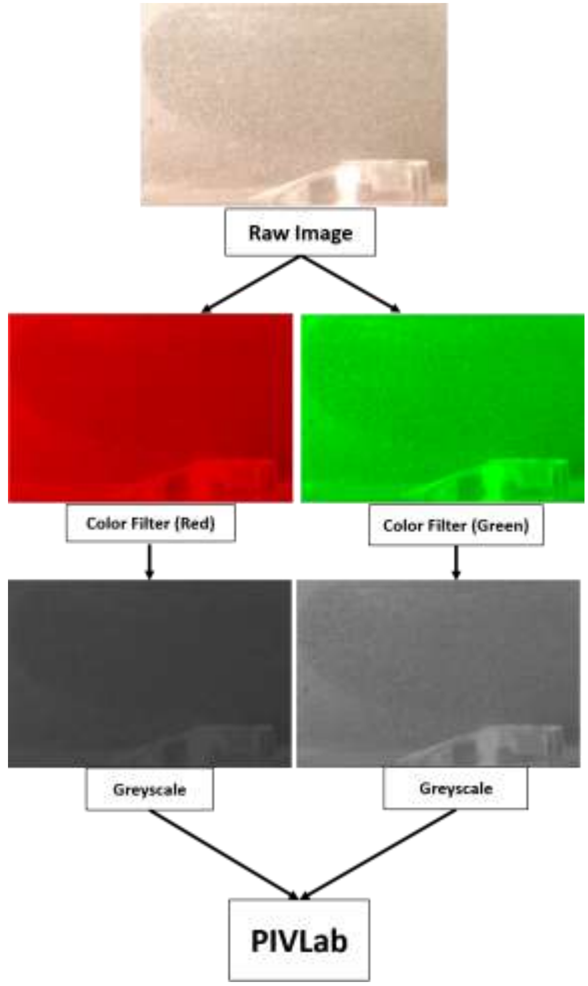

Figure 4.13: Post-processing flow chart

5. Results & Discussions

5.1 HPLEDs Characteristics Results

A simple setup that shown in Figure 4.8 is used to investigate how the power across HPLEDs will affect its illuminance (lx). The intensity, or the illuminance at each power is an averaged 10 seconds illuminance value at each power. The changes of power is by manipulating voltage of from power supply by decreasing 1V at each power. Figure 5.1 shows the relationship between the power across green HPLED and its illuminance.

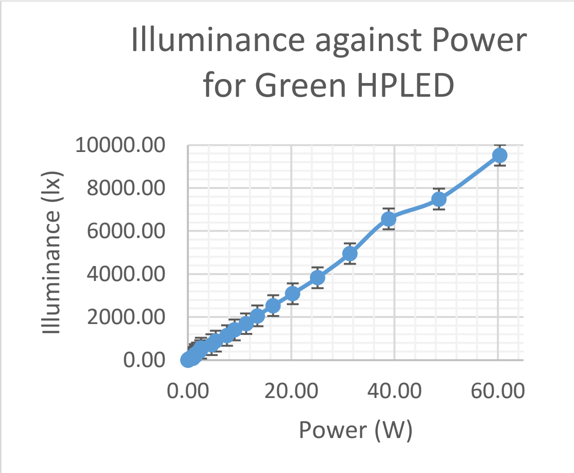

Figure 5.1: Illuminance against power for green HPLED

The result shows a trend that the relationship between illuminance lux and power is linear. Refer to Eq.3, the illuminance lux is directly proportional to power. In this intensity test, the only variable for illuminance lux is power, with the same luminous efficiency and surface area. Thus, the results is reliable. However, the result in Figure 5.1 shows some deflections at some points, especially at high power. This is because when the HPLED is operating at high power, the temperature of HPLED is very high which causes the internal resistance of HPLED increases. The power across the HPLED will be affected which causes unstable illuminance performance.

Figure 5.2 shows the relationship between the power across red HPLED and its illuminance. Compared to green HPLED, the illuminance of red HPLED is relatively smaller at each power and this can be explained by the Eq.4. Refer to the result in Figure 5.2, the curve shows linear trend at low power and slowly deviates as power increases. The reason of the deviation at high power is due to the threshold of the HPLED as its illuminance is approaching its maximum. Another reason of deviation is because of high operating temperature which caused by high power which in results affect its illuminance.

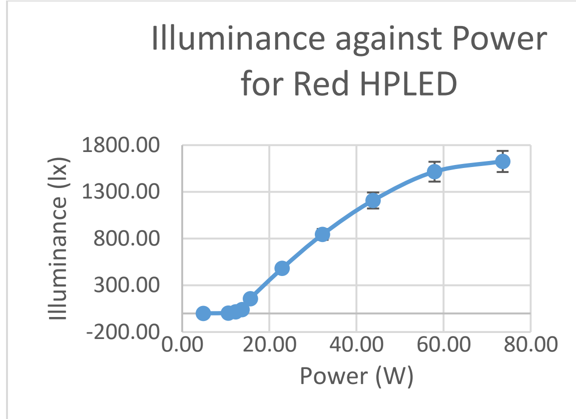

Figure 5.2: Illuminance against power for red HPLED

One of the purposes of performing this experiment is to get similar illuminance of both HPLEDs at their respective power supply. With this, the light of both HPLEDs will be shone into the test section at similar illuminance so that the results of the flow in test section can be analysed.

5.2 Case 1: Analysis of Non-Uniform Flow – Random Disturbance

In order to verify the reliability of the developed PIV system, it is essential to perform a few experiments to ensure the system can replace traditional PIV system. After the PIV setup is ready, the mixture of water and seeding particles is stirred to make sure the particles mixed with water without sinking. Next, the flow is left undisturbed until it is steady, the image is acquired by using a camera.

The raw image is shown in Figure 5.3. Figure 5.4 shows the velocity vector field plotted by using PIVlab, a PIV analysis application of Matlab. The flow is randomly disturbed so it is reasonable that the flow can be in any direction. A region of interest (ROI) is selected for the software analysis, which is shown in the red box of Figure 5.3. The vectors with higher magnitude are having higher velocities compared to vectors with lower magnitude. The velocity vectors indicate the actual instantaneous flow inside the water tank. Figure 5.5 shows the histogram of the displacement in the flow field. It shows no sign of peak locking.

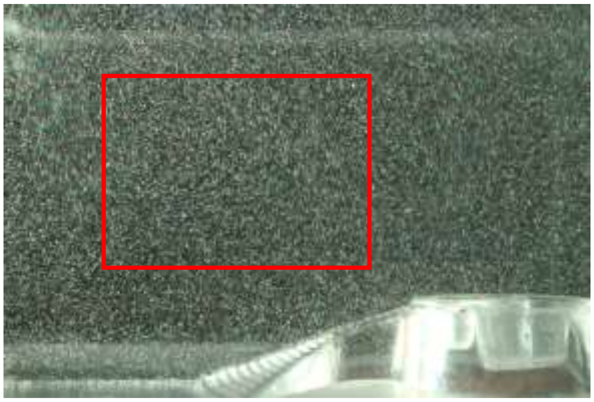

Figure 5.3: Raw image of random flow in the water tank

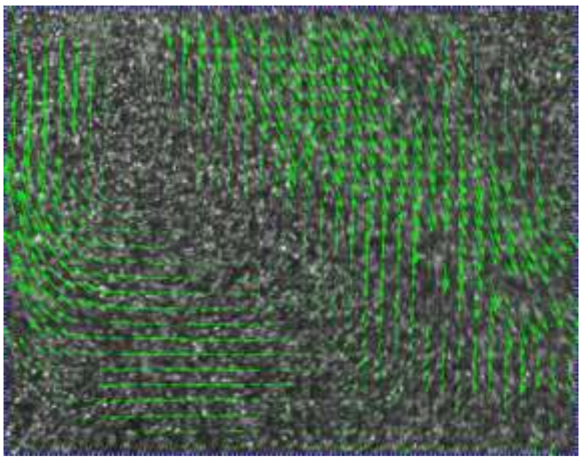

Figure 5.4: Velocity flow field of a random flow in the water tank

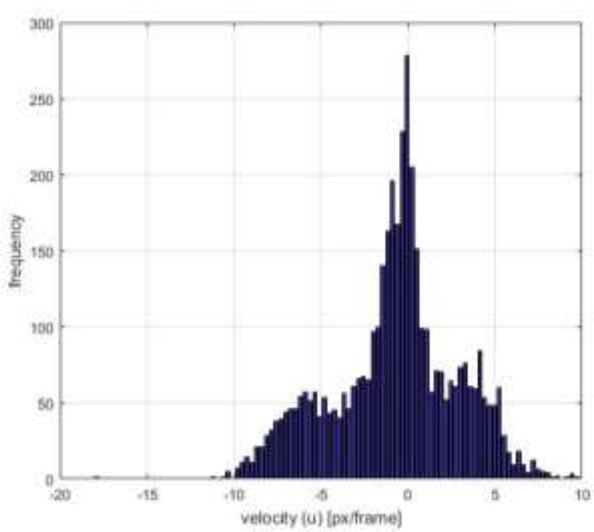

Figure 5.5: Histogram of random flow

5.3 Case 2: Analysis of Non-uniform Flow – Translational Disturbance

Another experiment is conducted in such a way that a wooden stick is used to disturb the flow in translational motion. The flow is captured and the image is filtered by photo editing software, just like previous case. The raw image is shown in Figure 5.6 and ROI is the red box. The analysis result which done by PIVlab is shown in Figure 5.7. There is a region in figure above which its flow is messy and not convincing. These inaccurate vectors can be removed and replace by interpolated velocity vector. In PIVlab, there is a function called vector validation can be used to correct the inaccurate velocity vector which is shown in Figure 5.8. The compacted area of the picture is selected for vector validation. The software will then remove inaccurate vectors and replace them with interpolated velocity vectors. The final result is shown in Figure 5.9 where the orange vectors are interpolated velocity vectors that replace inaccurate velocity vectors. Figure 5.10 shows the histogram of the displacement in the flow field. It indicates low noise and shows no sign of peak locking.

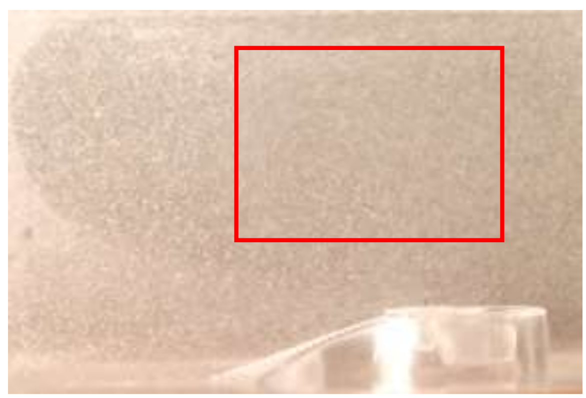

Figure 5.6: Raw image of translational disturbance flow

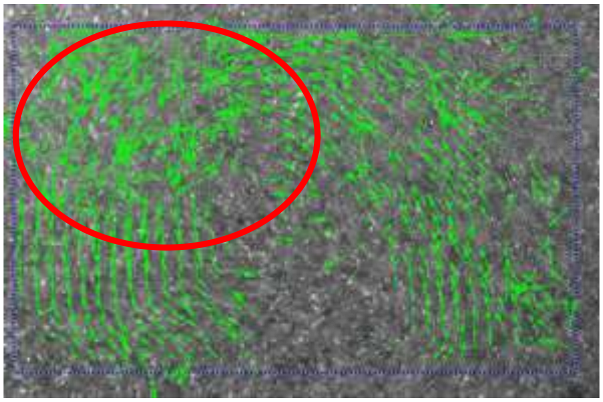

Figure 5.7: Velocity flow field of a translational disturbance flow in the water tank

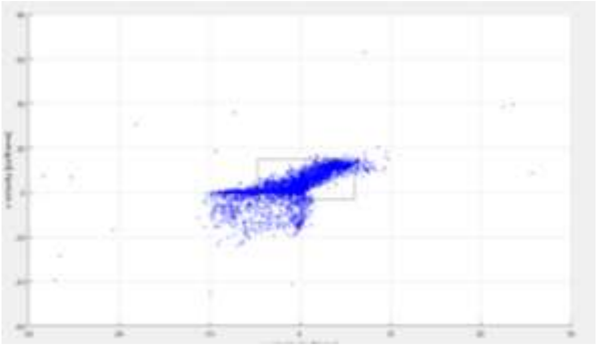

Figure 5.8: PIVlab velocity vector validation

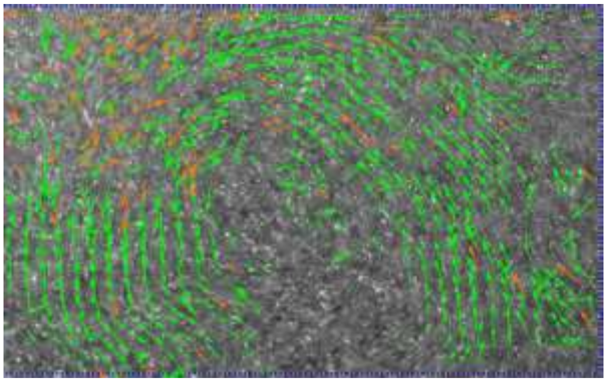

Figure 5.9: Velocity flow field of a translational disturbance random flow in the water tank after vector validation

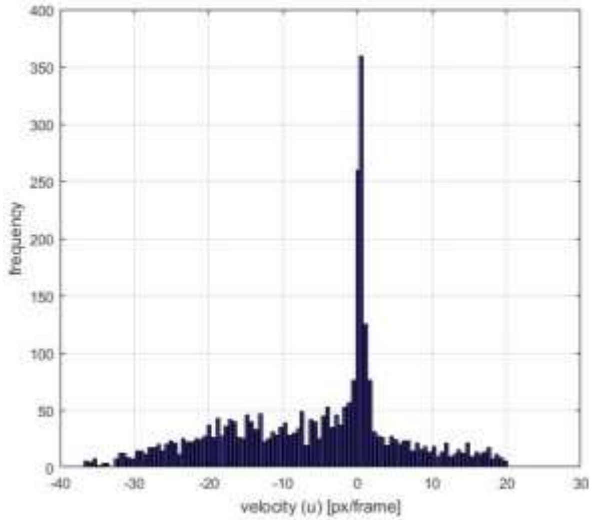

Figure 5.10: Histogram of translational flow

5.4 Case 3: Analysis of Flow Across Tip of a Plate

The last experiment for this project in such a way that a wooden stick is used to disturb the flow in translational motion. The picture is taken when the wooden stick is still in the water tank so that the vortex formed at the tip of the stick can be captured. Again the raw image, which is shown in Figure 5.11, will be filtered for further analysis.

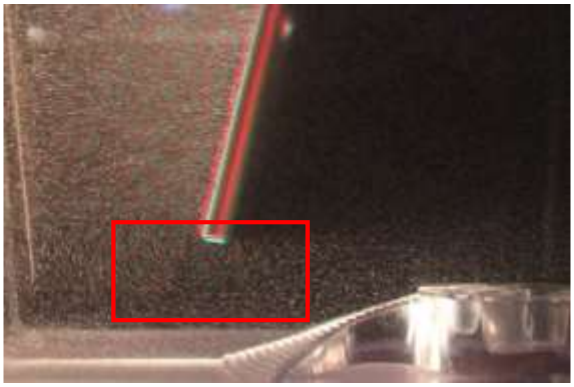

Figure 5.11: Raw image of flow across a wooden stick

The procedure is almost the same as previous case. However in this case, a mask is drawn at non-interested part inside ROI. The non-interested region is the wooden stick and the flow behind it. The analysed results is shown in Figure 5.12. Again there are some abnormal velocity vectors in the analysed image. Figure 5.13 shows vector validation is applied to replace these abnormal velocity vectors with interpolated velocity vectors. Figure 5.14 shows the results after vector validation where the orange color vectors are interpolated velocity vectors. Figure 5.15 shows the histogram of the displacement in the flow field. It illustrates that noise ratio of the result is relatively high. This is because some of the original velocity vectors are removed after vector validation. New interpolated velocity vectors are plotted which caused the increment of noise ratio.

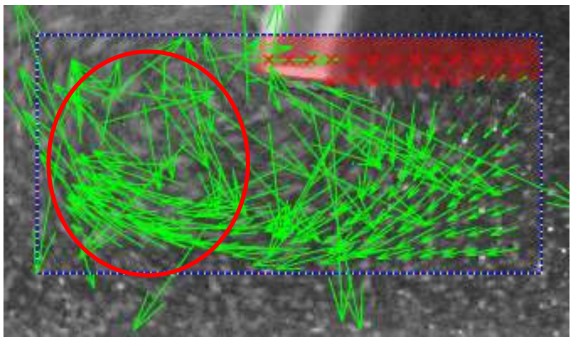

Figure 5.12: Velocity flow field of flow across a wooden stick in the water tank

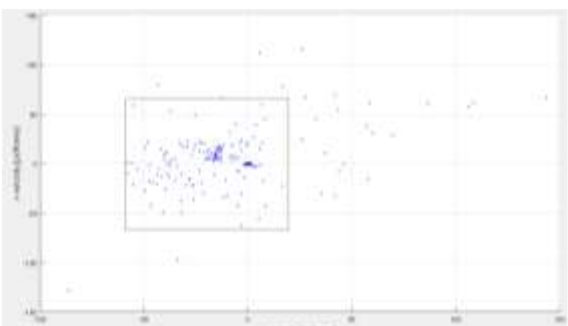

Figure 5.13: PIVlab velocity vector validation

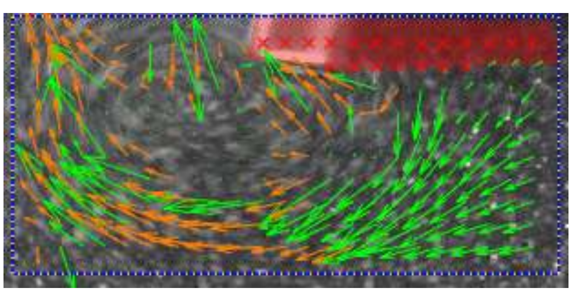

Figure 5.14; Velocity flow field across a wooden stick in the water tank after vector validation

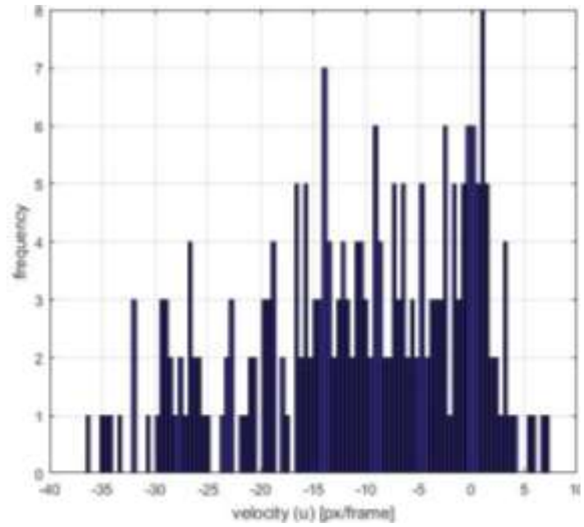

Figure 5.15: Histogram of flow across a wooden stick

6. Conclusion

In conclusion, the idea of replacing traditional illumination source with HPLEDs is possible according to the reliable results shown in previous chapter. Its advantages over lasers source which are reduction in cost, longer lifespan and acceptable performance are attractive. The only disadvantage of HPLEDs is that they will dissipate large amount of heat with high operating power and caused unsteady illuminance. The introduction of dual colours HPLEDs also successfully reduce the cost of the experiment by replacing high speed camera with normal recording system. Correlations are able to perform and velocity vectors of fluid flow are able to be plotted by PIVlab. Thus, the feasibility of dual colours PIV is ensured.

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