Evaluation of Particle Image Velocimetry Measurement Using Multi-wavelength Illumination

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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. Many researches are conducted on high power light emitting diode (HPLED) to replace the traditional laser illumination system in PIV. As an extended work to the research in PIV illumination system, two high power light emitting diodes (HPLED) with different wavelength are introduced as PIV illumination system. The objective of this research is using dual colours LED to directly replace laser as illumination system in order for a single frame to be captured by a normal camera instead of a high speed camera. Dual colours HPLEDs PIV are capable with single frame double pulses mode which able to plot the velocity vector of the particles after correlation. An illumination system is designed and fabricated and evaluated by measuring water flow in a small tank. The results indicates that HPLEDs promises a few advantages in terms of cost, safety and performance. It has a high potential to be develop into an alternative for PIV in the near future.

1. Introduction

Particle image velocimetry (PIV) is a technology that has benefitted the field of fluid flow measurement for decades. 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 that the contribution of PIV invention towards the fluid flow measurement field is essential and irreplaceable from the past till today. As the name of PIV itself suggest, the idea is to trace the particles in fluid flow by capturing two or more images with very small time interval. With this, reliable fluid flow properties such as the direction, velocity, vorticity and shear strain of flow can be obtained.

A PIV setup is the integration of a few systems with respective function to perform as desired. Firstly is the illumination system. A common PIV system uses laser as the light source. The Neodyme-YAG (Nd:YAG) laser is the most widely used laser source for PIV [2]. It is pulsed in the form of a thin sheet into the test section for the tracing particles to reflect the light and to be captured by the recording system. Today, the development of solid state illumination resulted in mass production of a wide range of HPLEDs available in the market. It provides alternatives that can be used to replace the laser illumination in the traditional PIV setup as laser source’s is costly in price and might cause safety issue if it is not handle with extra care during operation.

The system that works closely together with the illumination system is the recording system. The recording system basically refers to a camera or video recorder. Both systems are required to be
synchronised in order to achieve the correct timing for light pulsing and image acquisition. The quality and the capability of the recording system will basically determine the capability of the entire PIV system. For example, by fitting a camera pinhole model to the two cameras using single or multiple views of a 3D calibration plate, it is capable to perform a stereo-PIV measurement for 3D flow analysis [3].

Another essential part of a PIV is the computing system or a computer. The computer with the aid of applicable software will analyse the acquired images and results the flow characteristic of the fluid. There are many software available that can be used to perform PIV result analysis such as PIVView, OpenPIV and PIVLab, which is a Matlab-based application. Photo editing software are also sometimes required to perform colour filter on the raw images, or convert the raw images to files that are compatible for the PIV software.

Although a test section is an individual system from the PIV, it must not be neglected as it provides a platform to hold the test model with desired flow condition. A test section must be optically transparent in order for the light sheet to pass through and shone into the flow across the test model. The test section can part of wind tunnel, water channel, a transparent 3D-printed model to study the internal flow or even as simple as just a large space with desired fluid flow condition, depending on the objectives of the experiment.

Seeding particles or tracing particles are added into the fluid flow in the test section in order to visualise the flow. The main idea is to get the suitable seeding particles that have about the same density with the fluid so that it could mix well without floating or settling in the fluid. It is also worth to study the characteristics of seeding particles in order to determine its suitability for a respective experiment. Zhang [4] had performed a study on several seeding particles such as hollow glass spheres, polymer micro-spheres and solidified particles to determine their availability to perform PIV measurement in liquid helium. On the other hand, a seeding particles choice evaluation test is performed by Rafika [5] in order to choose suitable seeding particles to study the acoustic streaming flow generated by High Intensity Focused Ultrasound (HIFU). In short, the selection of seeding particles is crucial for PIV system is able to generate reliable results.

Improvements and exploring availabilities of PIV in order to maximize its functions and capabilities are widely conducted. Finding alternatives to replace the laser illumination system for PIV are no longer a new research topic in flow measurement field. It can be trace back to 1993, where Hshen, Ma and Zhuang [6] from Beijing, China developed a type of new PIV, which is known as the white light bubble image velocimetry (WLBIV) by modifying the traditional PIV illumination system. As the name suggest, the illumination system of the WLBIV used a flash set as the multi-pulse light sources for the PIV film while the particle tracer in the flow field are oxygen bubble generated by the electrolyzed water. High-power laser is also not required in WLBIV but as a result, the system has high signal to noise ratio.

Willert and colleagues [7]-[8] performed PIV experiment using of High Power Light Emitting Diode (HPLED) as an alternative to laser-base illumination system in PIV. In the research, it was found that HPLEDs promise some attractive advantages in comparison to laser. LEDs are able to operate beyond their continuous damage threshold when operating in short duration or pulsed. The light pulses generated by the HPLEDs are sufficient to illuminate and image micron-sized particles in flow velocimetry.

A research on colour-sequence enhanced particle streak velocimetry (CSPSV) which is a new approached introduced by Wang [9] and colleagues from China. CSPSV consists of three types of controlled flash lights of different colours and one type of white light. The change of illumination colour of the test zone in a given sequence added the time sequence information onto a single frame, which enables easier execution of the algorithm for three-dimensional reconstruction and streak pair matching. CSPSV also combines the advantages of particle tracking velocimetry and particle streak
velocimetry, which reduces the requirement of high-speed cameras. CSPSV also can be easily extended and used to measure the air flow in large space.

2. PIV illumination system with HPLEDs

As high power LED (HPLED) has been chosen as the alternative to replace the traditional laser PIV illumination source, an illumination system has to be constructed in order to support the illumination of HPLEDs in desired way. The selected HPLEDs for this research project are green and red colours as shown in Figure 1 which are capable to perform in both continuous and pulsing mode. Both HPLEDs has maximum power of 100W and 6.25cm$^2$ size of illumination area. Other main components of the illumination system include the HPLEDs electronic driving circuit, optic fibre guide, cylindrical and convex lenses, power supply and microcontroller.

Red and green HPLEDs are selected to replace laser as illumination source. Green HPLEDs is chosen because it has the highest quantum efficiency and human eyes are most sensitive to the middle of the spectral range, which is around 550nm and is in the range of green visible light wavelength. A traditional laser-based PIV also uses laser that illuminates green light. Red colour HPLED is chosen as the second colour instead of other available colour HPLEDs such as blue and yellow because red colour has a higher eye sensitivity function compare to blue colour. Yellow colour is better than red in terms of wavelength because it is more sensitive to the eyes. However, the wavelength range of green and yellow is very near which might have the tendency to cause difficulties in differentiating both green and yellow light.

![Figure 1. Green (left) and red (right) HPLEDs with maximum power of 100W.](image)

It would be simpler to connect the HPLEDs directly to power supply to lighten it but it might cause damage to the HPLEDs and the desirable pulsing are not able to be control. Therefore, an electrical control circuit is essential to be developed in order to light up the HPLEDs with desirable pulsing. The electrical components required and respective specification to construct the driving circuit of the HPLEDs is presented in Table 1 below.

| 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        |
Both HPLEDs are driven using two different circuits which draw power from different power supply but are controlled using the same microcontroller as shown in Figure 2. The MOSFET in the circuits are triggered by a microcontroller, Arduino Uno. A pulsing program is uploaded into Arduino in order to trigger the circuit as desired. In order to stabilize the electrical energy in the circuit, the presence of capacitors store extra electrical energy and discharge electrical energy when voltage is lower than usual especially during pulsing.

![Schematic diagram of HPLED electrical driving circuit for both red (left) and green (right).](image)

**Figure 2.** Schematic diagram of HPLED electrical driving circuit for both red (left) and green (right).

The entire illumination system with the circuits and optics are integrated into a box with the size of one CPU unit as shown in **Figure 3.** A beam splitter is place directly in front of both HPLEDs to reflect the light illuminated by each HPLED in two different directions. In order to minimize the light loss from the HPLEDs, convex lenses are used to focus the light that passes through the beam splitter into the optic fiber guide inlet. As the HPLEDs radiate large amount of heat during operation, cooling fans are installed to cool down the HPLEDs and circuits to avoid the components from overheating damage.

![Final design of the illumination system platform.](image)

**Figure 3.** Final design of the illumination system platform.
2.1. HPLEDs characterization and pulsing operation

After the setup is done, the characteristics of both HPLEDs have to be studied. The light intensity of both HPLEDs are measured in terms of illuminance which its SI units is lux (lx) by varying the power supply to the HPLEDs. It is important to measure the illuminance of both HPLEDs in order to get them illuminate light with same intensity while operating as both HPLEDs illuminate light with different intensity under the same power. The measurement is performed using a digital photo sensor, BH1750 which is controlled by using a microcontroller. The microcontroller is connected to a computer for programming purpose. The coding to operate BH1750 digital light sensor is uploaded to the microcontroller [10]. The illuminated lights are shone into the photo sensor through the optic fiber guide.

The measurement is conducted in a totally dark condition to avoid stray light to introduce noise. Both HPLEDs are characterized separately under the same condition. The power towards the HPLEDs is controlled by manipulating the voltage of the power supply. The voltage is started with maximum value 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 the next reading, the HPLED will be cooled down to avoid the temperature factor which may affect the performance of the HPLED.

After the completion of characterizing the HPLEDs, it is also essential to make sure both HPLEDs pulsed appropriately with the aid of microcontroller to fulfill the operation mode of a PIV system. The microcontroller was programmed to pulse multiple LED in sequence. Both HPLEDs will be pulsed for 150 ms and then switched off while the interval between pulses is also 150 ms. Green HPLED are pulsed after the red HPLED. The interval between pulses can be set based on the flow velocity to achieve an optimum measurement condition, i.e. usually the higher the velocity, the lower the interval between pulses and vice versa. The pulsing of the HPLEDs will restart whenever the microcontroller is reset.

2.2. HPLEDs illuminance against power

Even though both HPLEDs are from the same manufacturer, both HPLEDs do not share the same properties in terms of capability to draw power from the power supply and also the intensity. The light intensity against the power of both HPLEDs are plotted and presented in Figure 4. It can be clearly seen that red HPLEDs draw more power from the power supply compare to the green HPLED, i.e. the maximum power to pulse red HPLED are higher than green HPLED. Besides, red HPLED started to emit light at higher power supply compare to green HPLED. However, green HPLED emits light with much higher intensity compare to red HPLED. When both HPLEDs are driven at maximum power available, green HPLEDs illuminate light with almost ten times the illuminance of the red HPLED. This might be caused by the sensor as it is not wavelength corrected.

From Figure 5.1, it also can be observed that the illuminance of both HPLEDs increase together with the power. It generally shows a linear trend at the beginning which fulfills the theory which states that illuminance is directly proportional to power [11]. However, deviation in illuminance is spotted when the power approaches maximum for both HPLEDs. This is because when the HPLEDs are operating in high power, large amount of heat generated by the HPLEDs increases the operating temperature which causes the internal resistance of the HPLEDs to increase. This phenomenon indirectly affects the power across the HPLEDs, causing the illuminance to be slightly reduced. The illuminance threshold of the HPLEDs might also affect the HPLEDs performance when the illuminance is approaching maximum.

From the illuminance test, the respective power required by each HPLED to provide light with the same intensity can be determined. It is crucial to achieve the same intensity for both HPLEDs while operating in PIV system. If both HPLEDs do not emit light with the same illuminance, more particles can be observed while the HPLED that illuminate light with higher intensity is pulsed. This will cause
one of the images in the image set acquired to have higher seeding particles density which lead to higher noise ratio and reduce the accuracy of the PIV measurement.

![Figure 4. Illuminance against power for both red and green HPLEDs.](image)

3. **Illumination system evaluation by non-uniform flow measurement**

After the illumination system is ready, a simple experiment is conducted in order to evaluate the reliability of the designed PIV illumination system. **Error! Reference source not found.** illustrates the setup of the HPLEDs illuminated PIV. A cylindrical lens is responsible to focus the light that emitted from optics fiber guide into a thinner sheet. A tank that contains tap water acts as the test section of the experiment. It is seeded using polyamide with a mean diameter of 50 µm. The light is shone to the water tank while the camera is located perpendicularly to the light sheet. The camera used in this experiment is Canon EOS 1300D. The lens of camera is set to focus on the particles in the plane of the light sheet. The HPLEDs are pulsed as mentioned while the camera captured the image of particles inside the tank with 1 s exposure.

![Figure 5. HPLEDs PIV setup to conduct flow measurement.](image)
To evaluate the capability and reliability of the new designed PIV illumination system, the experiment is carried out by simply measuring the flow inside the tank. The mixture of water and seeding particles inside the test section are randomly disturbed using a wooden stick before any images are acquired. As the intention of this research is to prove the concept of multi-wavelength illumination system in PIV, no measurement was conducted on any known flow model for the time being.

The acquired images are required to undergo an image post-process before it is able to be analysed by any PIV analysis software available. Colour filtering function in the graphic editor, IrfanView are used to filter the acquired image into two separated red and green images. Both filtered images are converted into greyscale images which are then imported to PIVLab, a MATLAB based PIV analysis software for analysis. To reduce the time of analysis, only a section at the centre of the tank where the flow is significant known as region of interest (ROI) are selected to perform the analysis. PIVLab performed cross-correlation on the acquired images and plot the velocity flow field which will be further discuss in the next session.

3.1. Image Analysis

The acquired raw image before any post process was performed is shown in Figure 6. It can be observed that streaks are present and the particles can also be seen at both ends of the streaks. Each particle appears in both red and green colour in the streak, as it scattered the red and green light illuminated from the HPLEDs. The present of streaks aid to validate the accuracy of the velocity vector plotted by PIVLab. The streaks are not present after the raw image acquired undergoes colour filter process and each particle can be clearly seen. It has no doubt that correlation can be performed by PIV analysis software.

Cross-correlation was performed by PIVLab and the result is presented in the form of velocity vector as shown in Figure 7. The result represents the instantaneous flow condition inside the water tank. Vectors with higher magnitude indicate higher velocity of the flow. As the flow is randomly disturbed so it is reasonable that the velocity vector plotted appear in random direction. The plotted velocity vector can be verified by comparing with the streak present in the raw image acquired. By comparing the plotted velocity vector with the streak in the raw image acquired, it can be said that the result obtained is reliable and promising. This proves that multi-wavelength HPLEDs are capable as the illumination system of a PIV system.
3.2. Multi-wavelength HPLEDs illumination advantages

The evaluation of multi-wavelength HPLEDs illumination system in PIV does not only rely on the results. Attractive advantages by the multi-wavelength illumination system also added value to it. First of all, HPLEDs’ cost is relatively lower compare to laser-based illumination system. Using multi-wavelength HPLEDs illumination system also allows the high-speed camera to be replaced by a normal DSLR camera, which also reduce the cost of the entire PIV system. A multi-wavelength illumination PIV system is might be quarter the cost of the traditional laser based PIV.

Besides, from the previous findings, HPLEDs provide incoherent light source with a wider wavelength range, which alleviates several issues to speckle artifacts found in laser-based illumination system. HPLEDs are also safer to operate and maintain compare to lasers. This is because PIV usually used a Class IV laser which is eye hazard if direct, reflected or diffusely-reflected beam is viewed and also possible to cause skin and fire hazard. Although HPLEDs is not hazardous, it does not mean that it is eye-friendly especially when operating at extended period.

The only disadvantage of HPLEDs is large amount of heat is generated in operation. Even though the maximum power available for the HPLEDs is 100W and it will be damaged due to over power during operation, the increase in temperature causes the internal resistance of the HPLEDs to increase which lead to a drastic decrease in the illuminated light intensity. This might affect the results obtained from the PIV measurement. Hence, effective cooling measurements are required to increase the effective operation time of the HPLEDs at maximum power and avoid the heat generated from damaging the components in the driving circuit.

4. 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 reduces 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 extracted for low speed flow applications. Thus, the feasibility of dual colours PIV is ensured.
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5. References
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