EXPERIMENTAL STUDY OF WATER DROP PENETRATION FOLLOWING DROP IMPACT ON WATER SURFACE USING PLANAR LASER INDUCED FLUORESCENCE

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Abstract

Planar Laser Induced Fluorescence has been introduced as a method of studying water drop impacting deep water pool, specifically the penetration a drop after collision. The general formulation and law behind the PLIF method was formulated. Then, the experimental setup is described. Finally, two series of images taken from drops with different impact speeds (Weber numbers) are shown and the data that can be extracted from them are illustrated. The photos show the vortex ring produced by drop impact at low impact speeds. This ring will cause to penetrate faster and deeper than higher impact velocities without mentioned vortex ring.

Key words: Drop Impact, Optical measurement, Planar Laser Induced Fluorescence

1. Introduction

Drop impacts on solid or liquid surfaces are a really common phenomena in the nature which act a notable role in a wide variety of both natural and industrial applications. Some of these well-known technical applications are ink-jet printing, annealing, internal combustion engines, spray coating, plasma spaying, spray-cooling of hot surfaces such as turbine blades, rolling mills used in producing steel, and electronic devices. Other applications, as well as liquid atomization, cleaning, and ice accumulation on aircrafts also relate to drop impact phenomenon. That being said, having a clear understanding of the corresponding physics of drop impact is of utmost importance in relating proper boundary conditions in numerical codes to spraying simulation.[1] Moreover, the phenomena is highly important in nature. Rainfall drops impacting in the oceans generate vortices which are in charge of entraining air, necessary for the flora and fauna living in the near-surface region, to surprisingly great depths; rain-induced mixing also influences near-surface temperature and salinity; raindrop impact can initiate erosion; and mixing-induced nucleation sites produced by droplets falling back into a boiling liquid enhance heat transfer rates.[2]

Due to aforementioned importance of the phenomenon, drop impact physics have been investigated widely for about a century. However, we are still far from understanding it fully. Extreme diversity of the problem (which makes it surprising) may be one of the reasons that caused this lack of knowledge. [1]

When a drop impinges on the surface of a deep liquid, it either coalesces with the receiving liquid or splashes. In addition, impinging drops may also bounce off or float on the liquid surface. Near the transition from coalescence to splashing, different phenomena such as regular entrainment of gas bubbles along with thin high-speed jets and thick jets are found.[3]

As mentioned above, many researches have discussed drop impact but most of them have focused on the structure, considering the surface deformation and bubble entrapment. [1], [4] [5],[6],[7],[8] These researches have been based on two major approaches, experiment, photographing water surface by means of high speed cameras[9], and numerical simulation, using methods such as VOF method[10, 11] and immersed boundary method[12].

There are a few number of studies who have focused and concerned what happens after the impact within the liquid pool and discussed the mechanism by which the penetration of drop in liquid occurs. Thomson and Newall [13] were one of the first to study drop penetration into liquid pool. They state that when a drop of ink falls into water from not too great a height, it descends through the water as a ring, in which there is evidently considerable rotation about the circular axis passing through the centers of its cross sections.

Cai has studied the drop penetration of water drop, falling from different heights, impacting on deep water pool with 0.1% sodium carbonate. To make clear photos of the phenomena, thymol blue has been dissolved in the water drop, making it dark orange in color. [14] He has recorded three consequences to the drop impact. First, drops falling from a small height (impact velocities near to zero), the submerged drop cleaves in an "inverted cauliflower" below the surface where it can last for several seconds, diffuse and vanish slowly in the water. Secondly as the height increases the drop penetrates in the liquid rapidly, with a speed of several centimeters per second, in a ring-shaped form. Finally, as the falling height is increased further, penetration disappears and cleavage reappears.

Both latter articles can be discussed, as researchers have declared that solutions made visible by color dyes are not an exact replica of the water drop, since its properties have changed (drop surface tension have decreased about 35%). [14]

Rather than experimental approach, Takagaki et al. [15] have studied the drop impacts phenomena numerically. They have focused on the vortex generation below liquid surface due to drop impact. They further used this knowledge to describe the ring shape generated by drop.

The most important blind spot that can be observed among previous experimental researches is lack of a reliable visual system. By reliable, it is meant that reviewed articles have used seeds like colorful matters to make the drop visible and traceable within the pool, which significantly changes the properties of water, while there are other visualization methods known to non-intrusive. Furthermore, aforementioned experiments present a qualitative description of drop penetration. One of the most well-known optical visualization methods that are used in fluid mechanics is Planar Laser Induced Fluorescence (PLIF) that can be utilized for studying the mentioned phenomenon.

Laser induced fluorescence is one of the optical visualization based on laser and light sensitive dyes, which is widely used in diagnosis and measurements of scalar parameters within fluid field. This method was presented by Dewey and Owen (1976) and Liu (1977). It was later developed by Dimotakis and Koochesfehani (1986).[16] This method is increasingly used in multiphase flow diagnosis, both for measuring parameters directly or as a reliable method to validate numerical results. Due to dyes used the parameters that are measured vary, for example it can be concentration, pressure, temperature, PH, or OH concentration.

According to the geometry and flow regime, LIF can be utilized 1D, 2D, and 3D but all of them follow same principle which can make researchers capable of describing the flow both qualitatively and quantitatively[17]. Due to common principle of LIF fluorescent dyes (such as

Rhodamine B or Fluorescein) are solved in the fluid and get deployed within the flow, then a Laser source is used to excite the dyes. Excited electrons in dyes start to return to their original place while emitting light (Figure 1). The emitted light is then filtered, photographed, and analyzed. The intensity of captured light in every point can help us extract valuable information about specific features of the flow, since the fluorescence emission can be sensitive to temperature, PH, and other flow characteristics. The 2D LIF method is called Planar Laser Induced Fluorescence.

In the coming text, first PLIF method and its principles are illustrated and then some results taken from drop impact diagnosis using PLIF method are presented. Then the results and picture are compared with previous results.

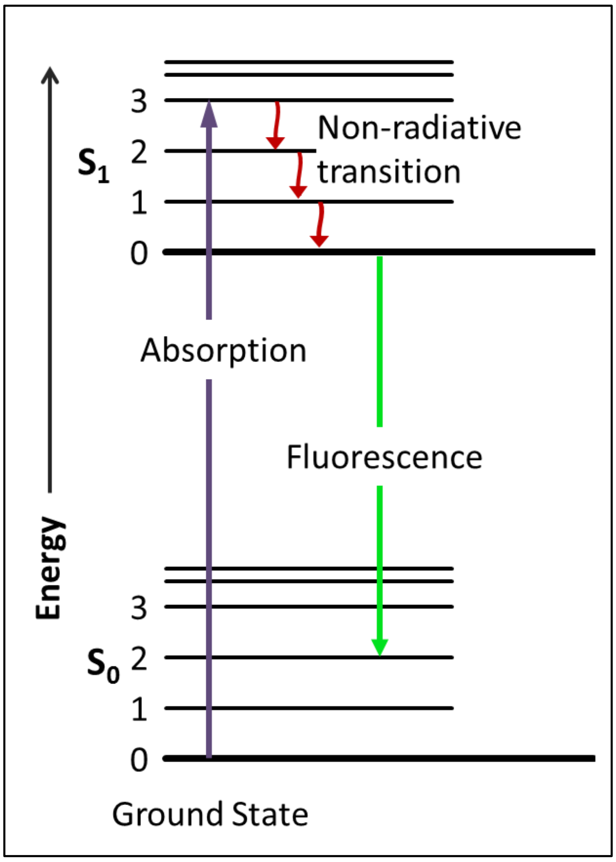


Figure 1 electron excitement and emission of a Fluorescent dye in LIF

2. Planar Laser Induced Fluorescence

Laser induced fluorescence is the excitement property of a fluorescent dye in presence of Laser. PLIF is one of the branches in which the laser beam is transformed into a sheet using a cylindrical lens (Figure2).

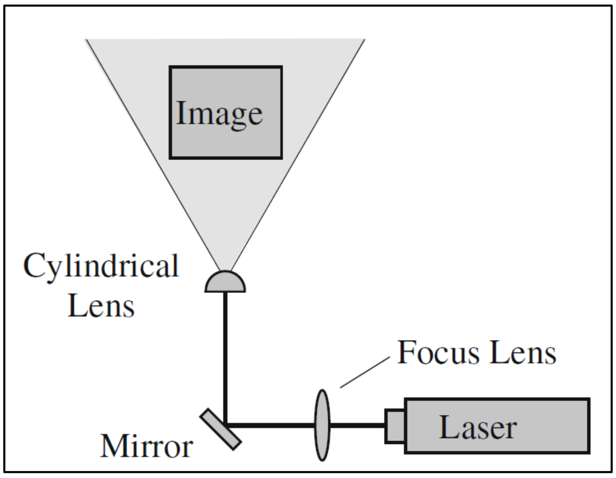


Figure 2 Transformation of laser beam to a plane using a cylindrical lens

2.1 General Fluorescence Theory

General formulation of local fluorescence, F, due to local excitement intensity, I_0, and local concentration, C, is

$$F \propto \frac{C.I_0}{1+\left(\frac{I_0}{I_{sat}}\right)} \quad (1)$$

where I_{sat} is saturated intensity. As in most of experiments, if Laser incident light intensity is small, the equation (1) will be simplified as

$$F \propto I_0 C \quad (2)$$

Increase in amount of fluorescent dyes will lead to non-linearity in equation (2) [16] that is predicted by Bier equation. The Bier's is simplified as Bier-Lambert equation (eq 3) to predict the Fluorescence intensity captures in every pixel of captured photo by camera, I_f.[18]

$$I_f = k_{opt}\epsilon_1 \Phi C I_0 e^{-C(\epsilon_1 b+\epsilon_2 e)} \quad (3)$$

where K_{opt} is a constant optical factor of the camera, Φ is quantum efficiency factor, I_0 is Laser intensity and b is laser diffusion. ε_1 is the absorption coefficient of fluorescent dye and $\varepsilon_2 e$ stands for absorption of emitted light of fluorescent dye by itself so that the term of $I_0 e^{-C(\varepsilon_1 b+\varepsilon_2 e)}$ indicated the exciting light intensity in every section.

If the concentration is negligible, as it usually is to the extent that non-intrusive criteria is satisfied, $C \to 0$, then

$$I_0 e^{-C(\varepsilon_1 b+\varepsilon_2 e)} \to I_0 \quad (4)$$

and we can assume that the light intensity is uniform in the section. Equation (3) can be rewritten as

$$I_f = K_{opt}\varepsilon_1 \Phi C I_0 \quad (5)$$

The terms ε_1 and Φ are properties of dye. As will be presented the fluorescent dye used in this research is Rhodamine B which is a temperature sensitive dye. The coefficient Φ in previous equation can be written as an exponential function of temperature for this dye with a coefficient of K_{spec}. [19]

$$\Phi = K_{spec} e^{\frac{\beta}{T}} \tag{6}$$

Taking effect of equation (6), equation (5) can be written as,

$$I_f = K_{opt} K_{spec} \varepsilon_1 Q C I_0 e^{\frac{\beta}{T}} = \delta C \tag{7}$$

In this research it is assumed that an isothermal drop impact is investigated so that coefficient δ can be assumed to be constant. To remove the unknown parameter, δ, we can use a reference concentration.

$$I_{f_0} = \delta C_0 \tag{8}$$

Using the reference concentration, the concentration in the flow field can be calculated by equation (9).

$$C = C_0 . (\frac{I_f}{I_{f_0}}) \tag{9}$$

3. Experimental Setup

According to the PLIF technique used and the physics and parameters under study different equipment may be used but they possess certain apparatus in common; Laser, light sensitive dyes, camera, and cylindrical lens. The experimental setup used in this research is presented in figure 3.

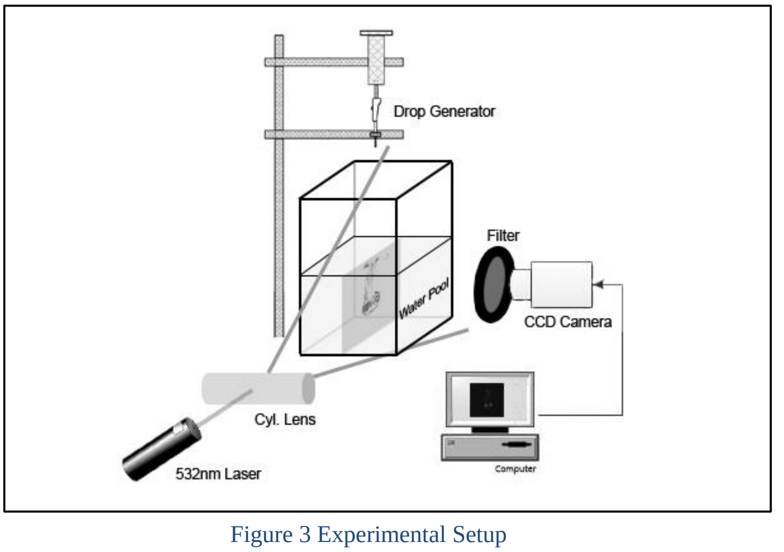


Figure 3 Experimental Setup

Laser source used in this research is a 100mw diode source producing beam of green (532nm) light which excited Rhodamine B dyes in the drop. The advantage of Diode laser source over Nd:Yag is its constant beam that improves photographing. The photos are taken using a mono-color high-speed CCD camera (Pointgrey Grasshoper) with constant frame rate of 333 fps and a micro lens. The drop solution concentration was set to be 12mg of Rhodamine B in 1 Liter of water. Rhodamine B is a beneficial with quantum efficiency of about 95% which enhances the visualization. Properties of Rhodamine B is presented if Table1.

Table 1 Properties of Rhodamine B dye[16]

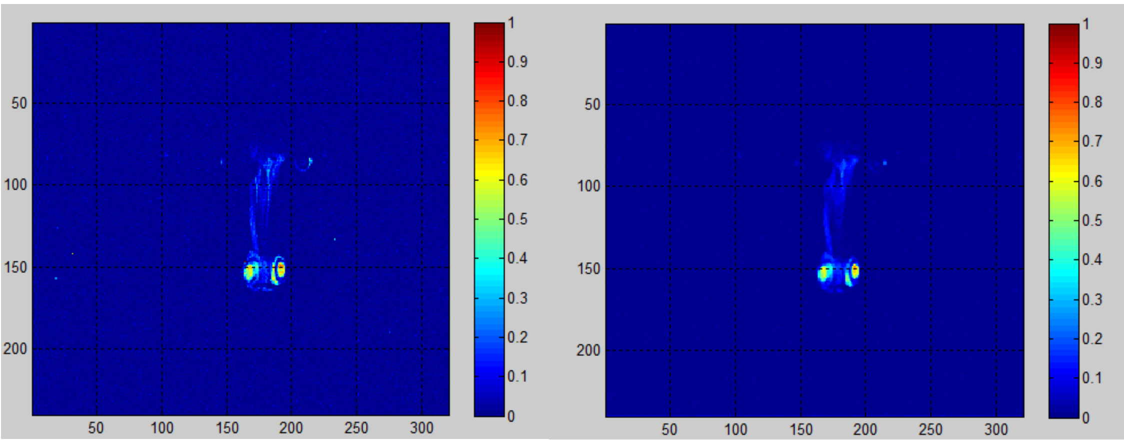
Dye	$\lambda_{abs_{max}}$ (nm)	$\lambda_{emi_{max}}$ (nm)	ε (cm M)$^{-1}$	Increment per ◦C
Rh. B	555	580	8.6E4	-1.8

4. Image Processing

Raw pictures taken by PLIF method are formed of points with different light intensities which need to be processed in a way translatable for scientific investigation. This Process seeks for calibration, determination, and correction of Data. The image process in most articles are based on algorithm presented by Koochesfahani [20] in 1985 but has been further calibrated for radial effect of beam expansion utilizing the equation illustrated by Crimaldi et al [16] for aqueous flows.

The image processing procedure which is written as a Matlab code gets the target file and two bunches of photos. The first group of photos are background photos which gives environmental information to prevent background errors. The second group are reference photos which are used to translate target photo, as explained in theory. Photo correction is also done by utilizing Median filtering of photos to remove gain and dark noises.

Figure 4 shows the noise reduction done by median filtering in Matlab code.



(a) (b)

Figure 4 Effect of median filter in image dark noise reduction before (a) and after (b) utilization

2.4. Results and Discussion

Figures 5 and 6 are two sample series of images resulted from PLIF method. The images are taken from drops of the same size impacting same liquid pool with different impacting speeds which lead to different impact Weber numbers. The speed of drop shown in Figure5 at the moment of collision is about 1 m/s which represents Weber number of 40.937 while Figure 6 presents the penetration of droplet impacting with speed of about 1.4 m/s or the Weber number of 81.874. The physical properties of water used are presented in Table 2.

Figure 5 clearly illustrates the penetration of drop of impacting Weber number of 40.937and vortices following the collision. These images are two dimensional but can also give us a three dimensional idea about what is produced. Rotating the image, it can be seen that the drop turns into a donut and penetrates the liquid pool. The coalescence phenomenon predicted by Ray et al[3] is observed, too.

On the other hand, the PLIF shows that as the velocity of drop increases at the moment of collision, it penetrates into the liquid with shape of a “reversed flower”. It can also be claimed that the penetration speed of the drop, which is the furthest point that noticeable amount of drop has gone through the pool at a specific time, decreases as the impact speed increases. In this comparison selected time is 180ms after collision.

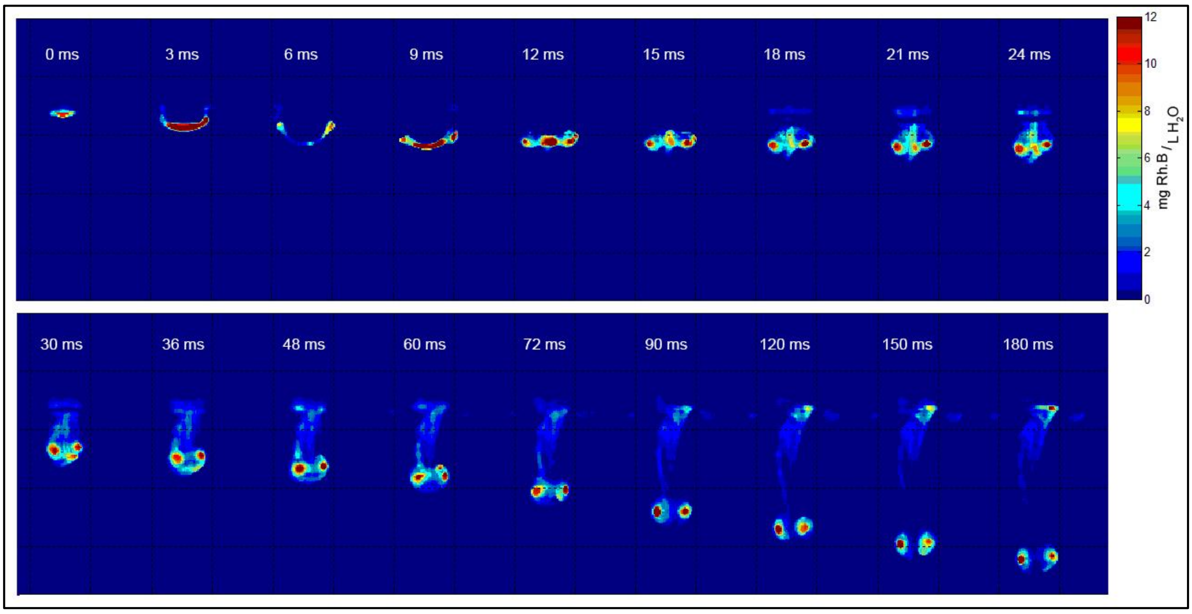


Figure 5 Penetration of a drop impacting of We=40.937

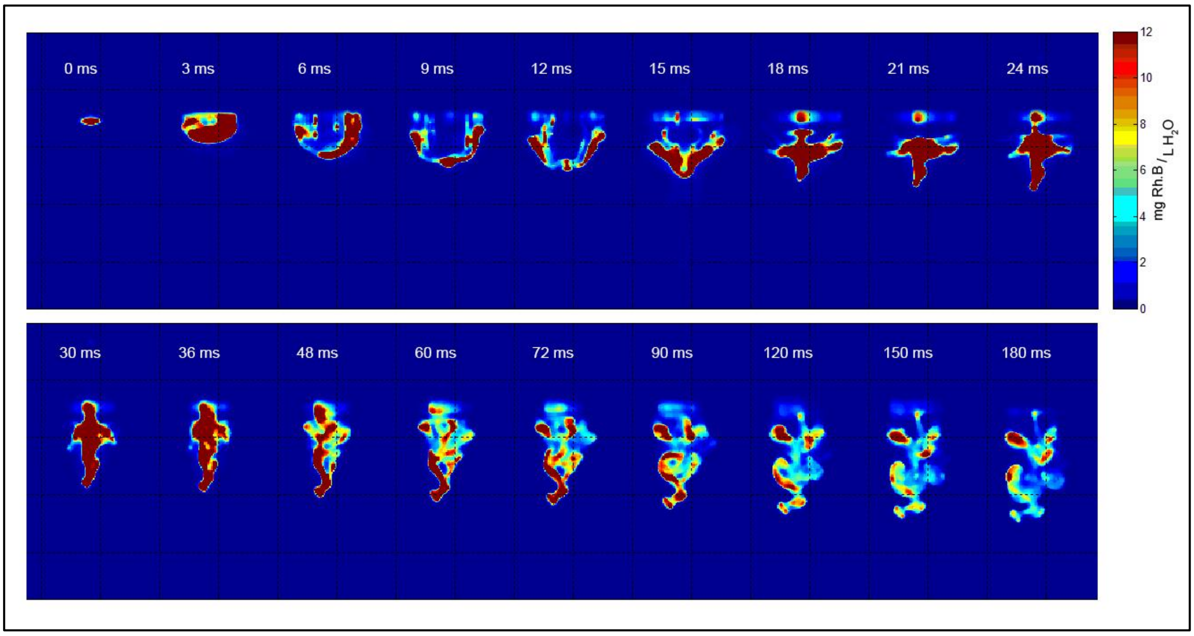


Figure۶ Penetration of a drop impacting of We=81.874

3. Conclusions

This work presents Planar Laser Induced Fluorescence Technique as a feasible method to visualize water drop impacting deep water pool from which both quantitative and qualitative data may be extracted. The governing law of Fluorescence which rules PLIF is fully presented. Furthermore, the experimental setup which was used to utilize PLIF for this purpose, i.e. visualization of drop impact phenomena was described. Introduction of the method is then followed by two series of pictures taken and processed from two different drops released from different heights. These different heights lead to different impact speed and Weber number. Weber number which was known to be a governing number on drop impact interface deflection structure is shown to be a governing number on drop penetration, too.

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