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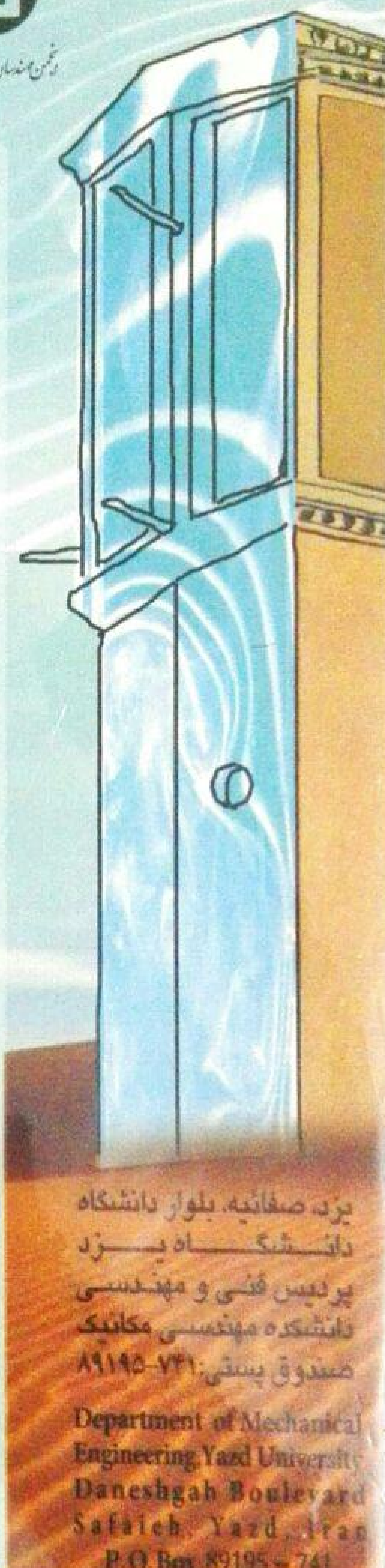

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EXPERIMENTAL STUDY OF WATER DROP PENETRATION ON WATER SURFACE USING PLANAR LASER INDUCED FLUORESCENCE

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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, three 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 the drop to penetrate faster and deeper than higher impact velocities without mentioned vortex ring.

Keywords: Drop Impact, Optical measurement, Planar Laser Induced Fluorescence

Introduction

Drop impacts on solid or liquid surfaces are 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 phenomenon 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 always surprising) may be one of the reasons that caused this lack of knowledge[١].

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 entrainment [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 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[14] 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. 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%).

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 used optical visualization methods 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 [16] and Owen [17] and Liu and Parson [18]. It was later developed by Dimotakis and Koochesfehani[19]. 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 that are 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 principles which can make researchers capable of describing the flow both qualitatively and quantitatively[20]. 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.

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).

General Fluorescence Theory

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

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

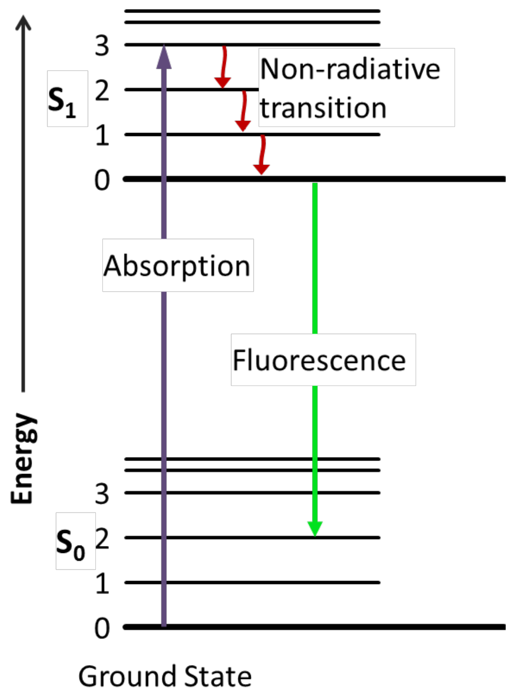
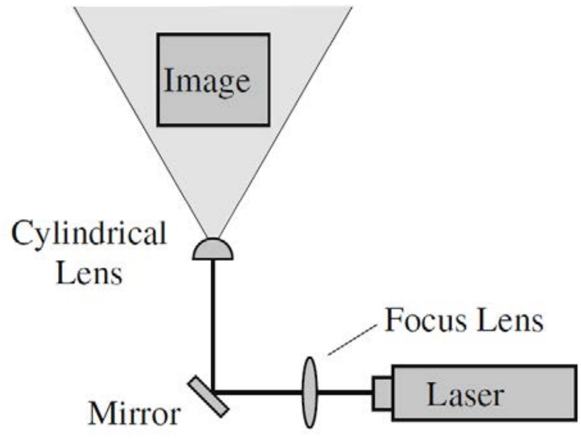


Figure١ electron excitement and emission of a Fluorescent dye in LIF



Transformation of laser beam to a plane using a ٢ Figure cylindrical lens

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

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

Increase in amount of fluorescent dyes will lead to non-linearity in equation (2) [21] 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, If.[22]

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

where Kopt is a constant optical factor of the camera, Φ is quantum efficiency factor, I_0 is Laser intensity and b is laser diffusion. ε1 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 Kspec. [23]

$$\Phi = K_{spec} e^{\frac{\beta}{T}} \quad (6)$$

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

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

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.

$$I_{f_0} = \delta C_0 \quad (8)$$

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

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

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.

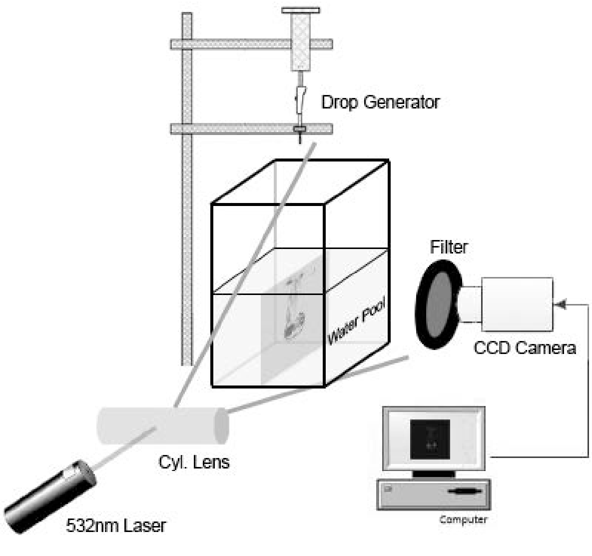


Figure 3 Experimental Setup

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. Takagaki and Komori [24] reported the effect of Rhodamine B concentration on water surface tension(Figure 4). Due to extracted trend-line the surface tension of a 12mg/l-solution will reduce about 6% relative to pure water.

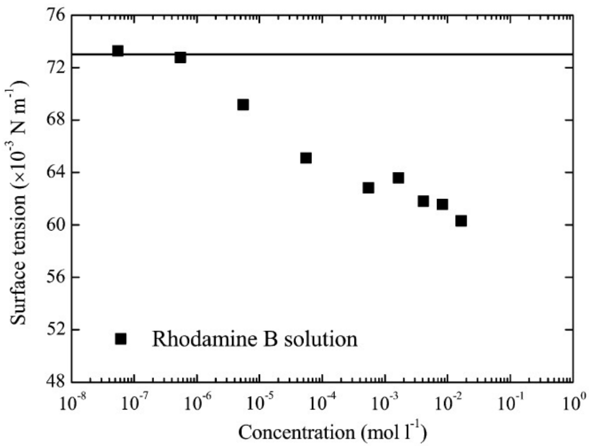


Figure 4 Surface tension water-RhdB solution in different concentrations

Rhodamine B is a beneficial and common dye used in Fluorescence-based visualization techniques with quantum efficiency of about 95% which enhances the visualization. Properties of Rhodamine B is presented in Table1.

Table 1 Properties of Rhodamine B dye[21]

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

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 [19] in 1985 but has been further calibrated for radial effect of beam expansion utilizing the equation illustrated by Crimaldi et al [21] 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.

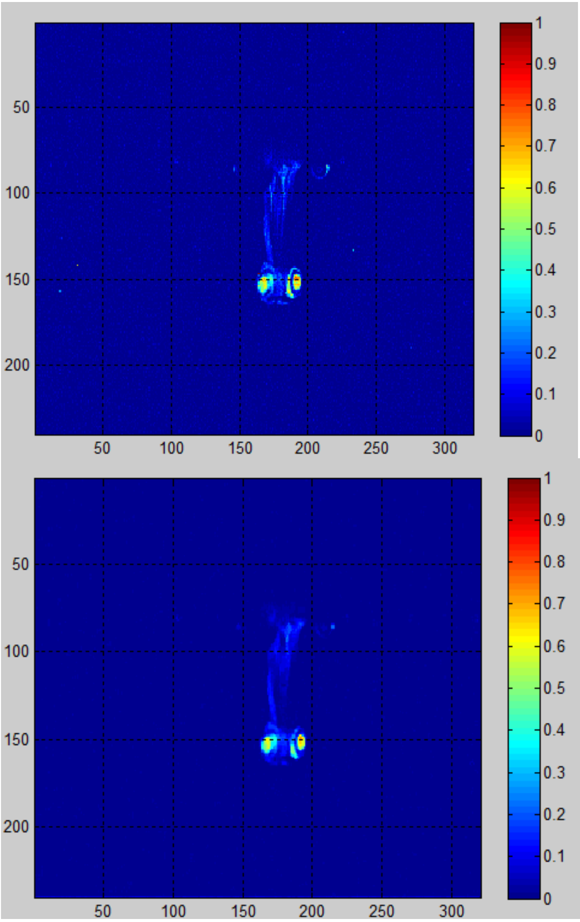


Figure 5 Effect of median filter in image dark noise reduction before (a) and after (b) utilization

Figure 5 shows the noise reduction done by median filtering in Matlab code.

Results and Discussion

Figure 6 displays three sample series of images resulted from PLIF method in the first 30 seconds after impact. The images are taken from drops of the same size (2.2mm) impacting same liquid pool with different impacting speeds which lead to different impact Weber numbers. Impacting drop of figure 6a impinges the air-water interface with speed of 0.54 m/s and We=8.87. The speed of drop shown in Figure 6b at the moment of collision is about 1 m/s which represents Weber number of 30.13, while Figure 6c presents the penetration of droplet impacting with speed of about 1.4 m/s or the Weber number of 60.26.

Figure 6a and 6b clearly illustrates the penetration of drops of low impacting Weber number of 8.87 and 30.13 and 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".

Figure 6 represents the fact that higher impact speeds in the range observed results in slightly deeper penetration in first steps when the drop has not penetrated further than 2cm.

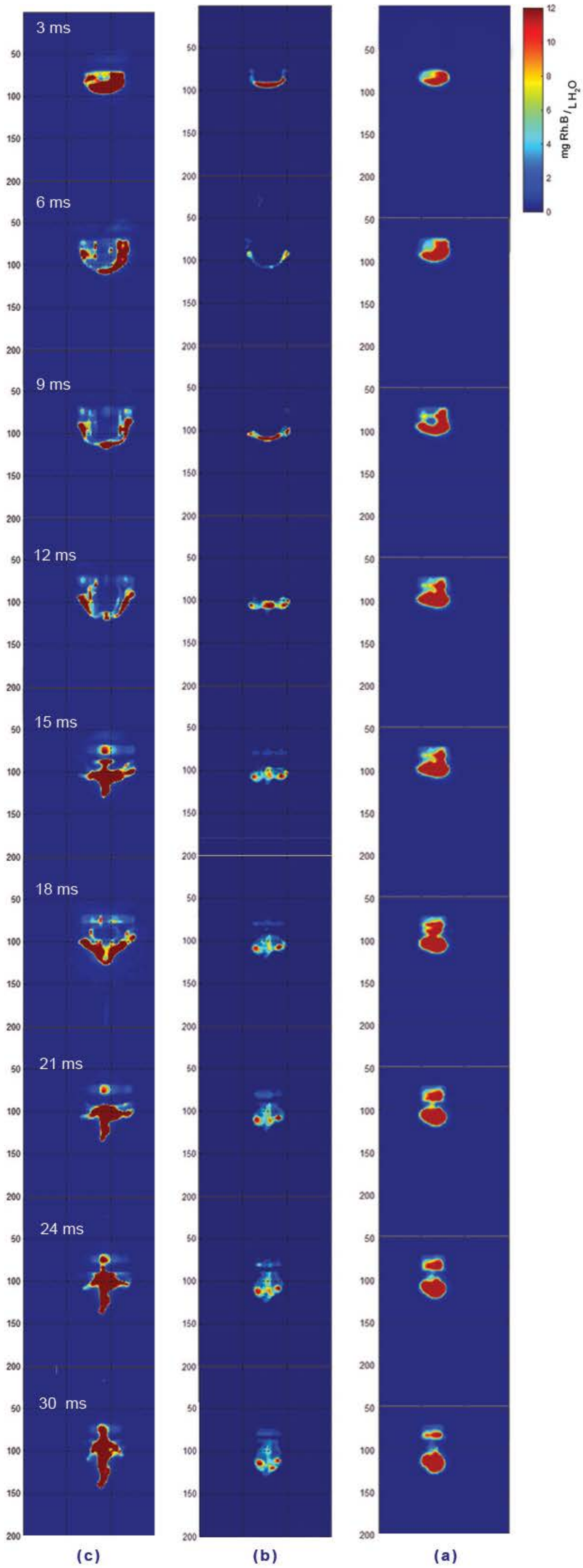


Figure 6 impinging drop evolution in the first 30 seconds after impact. Drop Webber numbers are a) 8.87, b) 30.13, and c) 60.26.

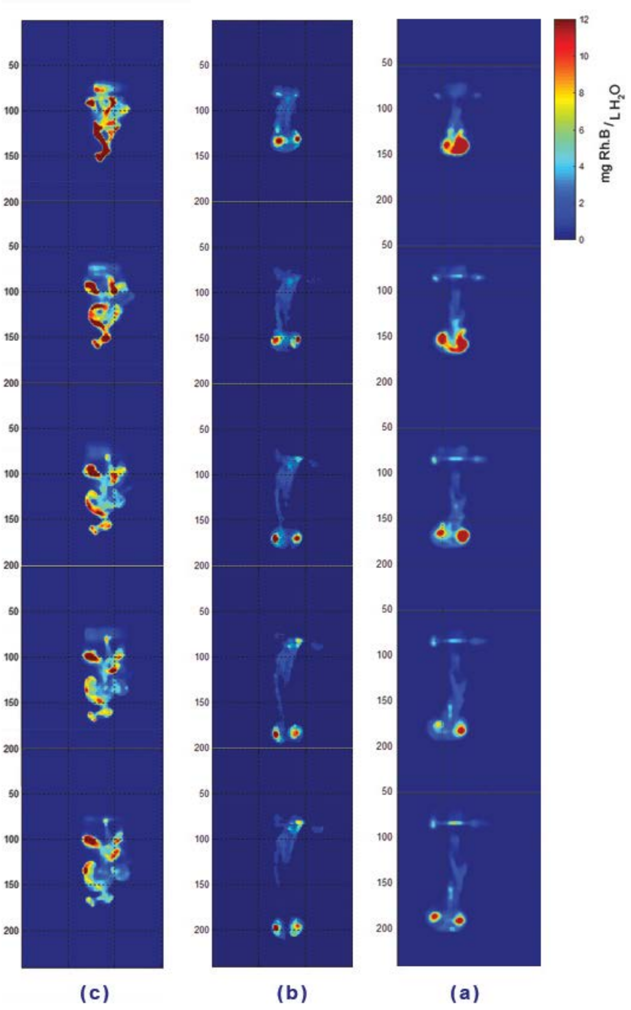


Figure 7 impinging drop evolution from t=60s to t=180s after impact in 30s steps. Drop Webber numbers are a) 8.87, b) 30.13, and c) 60.26.

Figure7 illustrates the impinging drop evolution in a longer period after impact. This figure, in contrast with Figure7 shows that drops with less Weber number at impact drop faster in long term.

The impact vortex ring are also completely visible in lower weber numbers, which has caused the drops penetrate faster.

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 three series of pictures taken and processed from three 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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