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Application of Laser Induced Fluorescence in experimental analysis of convection phenomena

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Abstract. One of the most promising technique for temperature measurement is the Laser Induced Fluorescence (LIF) which utilize basic concept of optical, non-intrusive measurements and give possibility to visualize the temperature distribution in the whole two-dimensional plane at once. A major problem of a LIF is it still unsatisfactory accuracy for temperature gradient and heat transfer measurement. The LIF fluorescent re-emission is a function of temperature but, in all measurements a lot of imperfection follow the image recording: background noises, light intensity variation, non uniformity and shadowgraph effect near the non-isothermal walls. In the present paper the influence of all key effect on the temperature measurement will be verified in order to obtain the method uncertainty. To evaluate that experimental measurement of convection phenomenon using LIF and thermocouples focussing on heat transfer measurement will be presented. Results show that all processing steps (pre-processing, processing and post-processing) are crucial for reducing the error related to the temperature measurement.

1. Introduction
Typically the velocity and its fluctuation are the primary quantities characterizing the flow field. But in the case of non-isothermal flow distribution of the velocity and temperature are equally important. In the last two decades particle image velocimetry has made possible velocity component measurements with high temporal and spatial resolution (including 2D, 2D stereo and full 3D).

At the same time laser induced fluorescence (LIF) technique has been developed in order to obtain temperature (and concentration) measurement with high resolution. However temperature measurement technique development has shown less progress.

Knowledge about temperature distribution during the prototyping phase of many application is crucial. Typically to measure fluid temperature, two main approaches are used. First, connected with contact temperature measurement is the utilization of thermocouples. For problems connected with fluid flow, this could be done only at few selected points which don't affect main fluid flow, i.e. thermocouples installed at the wall or in the near wall region [1,10]. The second approach is utilization of optical method, which only could take place when working fluid as well as considered vessel are transparent. An optical method based mainly on thermochromic liquid crystal (TLC) and on Laser Induced Fluorescence (LIF) techniques [5-8]. The TLC reflects light at visible wave length depending on local temperatures. Therefore, this method could be easily adopted with simple optical devices. In many cases a liquid crystal particles can offer relatively good resolutions, but its application is limited only to some liquids and limited due to quite small temperature range. The unencapsulated liquid crystal is sensitive to the shear stress and do not allow for quantitative temperature measurement rather than for
visualization. On the other hand, in the case of capsulated TLC the temperature response time of liquid crystal particle is an important issue and may result in a very inaccurate temperature field in convective dominating flows. The main disadvantages of TLC method are a narrow temperature range depending on chosen liquid crystals, non-linearity of emitted colour waves, size of particles and response time. The accuracy of the measurement with TLC depends largely on the calibration process. The accuracy relative to the 6°C temperature range is about 10% [3].

Another very promising and powerful technique used to measure fluid temperature is laser induced fluorescence (LIF) [1,4]. This technique involves dissolving a temperature-sensitive fluorescence dye to a gas or a liquid flow and then illuminating the fluorescent dye by an external light source. The dyes used for temperature measurement have a property to absorb primary light energy and generate re-emission at different wavelength [4]. This type of measurement assumes that the generated re-emission is a function of temperature. The method advantage is the fast planar measurement, large temperature range and relatively good accuracy, i.e. typically about 1.5 °C for a 40°C temperature range. Details about the principles of laser induced fluorescence can be found in [4].

For the temperature measurement in liquids the choice of the dye is as the following: (a) the dye has to be liquid, soluble, (b) the dye have to be stable during time period of measurement, (c) the dye have to be stable under laser excitation and provide sufficient signal, (d) the dye must have clear separated emission-absorption spectra. For the Nd:YAG laser used to illuminated dye the pulse duration is about 10ns, and the fluorescent emission time is typically similar order of magnitude. This means that the smallest time-scale for turbulent structure able to resolve is in the order of 10^{-8}s, which make this technique very attractive also for turbulent flow measurement. The size of the dye molecules about 10 nm is what makes them perfect even for microscale measurements [2].

LIF can be used to measure temperature at a single point [8], along a single line [6] or in two dimensional plane [5]. Recently a “simple” extension of the two-dimensional techniques in order to perform three dimensional volume temperature measurement was reported. But the most common and “natural” application of a LIF is to measure temperature in a whole 2D plane (or concentration) in gaseous or aqueous flows. Depending on the nature of the fluid to be analysed and the type of measurement, there are various types of dyes that could be used for the LIF technique. Typically, fluorescent tracer is an organic dye such as acetone, toluene or rhodamine. For the temperature measurement in aqueous flows one of the widely used tracer is Rhodamine-B. It is characterized by good solubility in water, high absorption, emission, and high sensitivities when excited with 532 nm Nd:YAG laser [11,12]. The laser induced fluorescence with this configuration ensures good temperature range, gradients and acceptable temperature readings.

Presented method, it is not free from disadvantages. In order to have accurate measurement the illuminated fluid need uniform light and all optical conditions need to remain constant during measurement. But in real measurement this is very difficult to keep constant and in consequence, large number of different types of imperfection follows the image recording (background noises, laser light fluctuation, shadowgraph effect)[12]. In the present paper the influence of all key effect on the temperature gradient measurement and on the heat transfer calculation will be verified in order to obtain the method uncertainty. To evaluate that experimental measurement of natural convection flow using LIF in parallel with thermocouples measurement focussing on heat transfer measurement will be presented.

2. Principles of LIF techniques
Fluorescence is the property of some molecules that in incident light at specific wavelengths absorb an energy and get higher quantum energy level. Than after a relatively short time (or in case of some materials almost immediately) reemits additional energy in a form of light at longer wavelengths. The fluorescence $F$ depends on the excitation intensity $I_o$, the dye saturation intensity $I_{sat}$ and the concentration of the fluorescent dye $C$ as follows:

$$F \sim \frac{I_o}{1+I_o/I_{sat}} C$$ (1)
If the excitation intensity $I_o$ is much lower than the dye saturation intensity $I_{sat}$ then the eq.1 can be written in linearised form:

$$\text{if } I_o \ll I_{sat} \text{ then } F \sim I_o C$$

(2)

The above equation provides a simple relation for concentration measurement. In the real case the incident light flux $I$ and not the excitation intensity $I_o$ is know. Additionally $I_o$ may vary in space and in time. In the literature the following equation base on eq.2 for fluorescence has been proposed [3,7]:

$$F = \varepsilon AI \Phi \frac{\lambda_e}{\lambda_f}$$

(3)

where $I$ is the incident light flux, $C$ is the concentration of the fluorescent dye (in the present paper with paper $500 \mu g/dm^3$), $\varepsilon$ is the molar absorptivity, $A$ is the fraction of the collected available light and $\Phi$ is the quantum efficiency (ration of the energy emitted by the dye molecules per absorbed energy).

In the case of temperature measurement the quantum efficiency $\Phi$ may result for selected dyes in temperature dependent total emitted fluorescence and observed temperature effect on the quantum yield is possibly induced by quenching effects. This phenomena makes temperature measurement with the laser induced fluorescence method.

3. Experimental set-up and data evaluation

The experimental system employed in the current investigation is presented in figure 1. The Nd:YAG laser (Litron Lasers max 60mJ beam power) is used as a pulse light source. Light source has been equipped with the beam splitter, a energy monitor, sheet optics, mirror and a cylindrical lens. Optical system generates light sheet with a thickness about 0.1mm and a height of 40 cm.

![Figure 1](image)

**Figure 1.** The experimental set-up.

The LIF signal from measurement section presented in figure 2 has been recorded with a 2048x2048 pixels monochromatic charge coupled device (CCD) camera equipped with a long pass filter at $\lambda=540nm$ arranged perpendicular to the light sheet plane. This arrangement ensures the lowest optical distortion. To obtain the laser synchronisation with the camera and in order to get only one laser pulse during signal recording the external triggering system was used.
The test section (closed enclosure of 32x32x32mm filled with distillate water and Rhodamine-B solution) has been bounded with two copper plates attached to the water heat exchanger (right wall) and Peltier cell (left walls). The remaining walls were made of 7 mm plexi. The natural convection in the closed cavity was generated by electrical heating on the left wall with certain electrical power and cooling on the right wall at 23.5°C (temperature similar to the experimental room temperature). For the power used in presenting cases the Rayleigh number was from 5.9*10^5 up to 1.46*10^6 and result mainly in laminar flow regimes. An accurate temperature measurement was performed with thermocouples located at the walls.

It has been found that the laser energy pulse to pulse variation depends strongly on the laser power used. Laser energy fluctuation measured before the final measurement for the different laser power levels is presented in figure 3. It can be seen that for the laser power level 80% (in reference to the maximum laser power) mean normalised laser energy is about 2746.7 with rms. 41.05 which gives approximately 3% laser energy variation. On the other hand, for the maximum laser power (100%) mean normalised laser energy is about 3321.9 with rms. 2.2 which gives approximately only 0.13% laser energy variation. This shows that the laser power supply system as well as laser itself prefers working (for its stability) at nominal conditions (100%). It has to be notified that working with the maximum laser power beam in the case of small laser distance and small cavity may generate light intensity higher than dye saturation intensity. In order to avoid that the laser was located about 1m from the measurement section and the large part of light sheet was not used. For the single frame the temperature evaluation uncertainty related to the laser light fluctuation is about 0.248K. For further correction mean laser intensity was used by averaging results over 20 recording frames. In this case the influence of the laser intensity variation is decreasing to about 0.03%.
The CCD camera background noise (dark noise) has been reduced by averaging over 50 images. The typical image representing background noise together with its statistical analysis has been presented in figure 4. The average background noise value of full recorded domain is 96.03 counts with rms. equal 5.05. The maximum and minimum recorded intensity of black noise is about 122 and 68 respectively. The dark noise constant component can be relatively easy removed from recorded imaged but the fluctuation component not. For the single frame the temperature evaluation uncertainty related to the dark noise single pixel variation is about 0.569K and can be reduced using spatial filter.

![Figure 4. The image of the background noise and its statistic.](image1)

Recorded frames (experimental, calibration and sheet) due to several types of distortions and impurities (tiny particles, small bubbles or impurities in the wall material) show spatial noise which has to be reduced. It was found that the best solution has been obtained using spatial filter from 3x3 up to 5x5 pixels. This slightly smooth the results and significantly reduce spatial noise (see figure 5).

![Figure 5. The influence of the spatial noise filtering method.](image2)

To convert the fluorescent signal into the real temperatures the calibration curve need to be used. In order to construct this curve a series of measurements at uniform temperatures was done. The uniform temperature was achieved cooling or heating, vertical walls to the same temperature.

![Figure 6. Intensity to temperature the calibration curves.](image3)
In Figure 6(a) the calibration curves are presented for full image and for different images sub-regions showing a monotonic intensity decrease with the increasing temperature. In order to ensure repeatability, the calibration was repeated for the same temperature range and for different sub-regions and spatial resolutions. In figure 6(b) calibration curves for different laser power and different set-up arrangement are shown. It can be seen that for lower laser power lower fluorescence signal is detected and what is more important for measurement error the ratio signal to the temperature are also decreasing. In the case of 100% power and presented temperatures signal intensity range is about 237 while for 60% power is only 98 and has a value similar to the constant component of the dark noise.

The experimental measurement evaluation procedure, consisting of seven steps, and is presented in Figure 7. In the first step a series of raw images is averaged, then the background image (dark noise) is subtracted from the raw images. After this procedure the LIF signal is obtained. The effect of light, spatial inhomogeneities is corrected in the next step, i.e. sheet correction. After these steps a highly uniform output LIF signal is obtained. Normalised images contain spatial noise and it is recommended to filter-out this noise. This is done with 3x3 smooth filter. In the last step, base on the calibration curve (see figure 5a) intensity has been mapped into temperature. It is important to notice that some sources of errors are reduced with statistical operations or by taking into account laser energy measurement, while some other effects (still not all), can be reduced through employing filters.

![Figure 7. LIF image evaluation procedure.](image)

4. Experimental results

In order to estimate heat loss, conduction experiment was carried out. The experimental vessel was positioned with electrically heated plate on the top and cooled plate on bottom. At first step, a specific temperature difference between horizontal walls was selected. In the second step, after thermal stabilization the heating power was measured. The theoretical heat flux was obtained from Fourier’s law. That allows estimation of heat loss:

\[ Q_{\text{loss}} = Q_{\text{cond}} - Q_{\text{theor-cond}} \]  
\[ Q_{\text{theor-cond}} = D\lambda(\theta_h - \theta_c) \]

where: \(\theta_h\) – hot wall temperature, \(\theta_c\) – cold wall temperature. Heat loss was calculated according to eq. (4) and could be linearly approximated for various heating rates \(\Delta\theta = \theta_h - \theta_c = 1.0\div43 \ [\text{K}]\), where the temperature of cold wall was kept at ambient temperature), according to the following relation:

\[ Q_{\text{loss}} = 0.0545\Delta\theta \]

Heat losses calculated for conduction experiment are shown on Figure 8. The natural convection can be characterized by a group of non-dimensional parameters such as Nusselt, Prandtl and Rayleigh number. Nusselt number was calculated as a ratio between the net convective heat transfer rate and the net pure conduction contribution with applied method invented by Ozoe and Churchill [9]:

\[ \text{Nu} = \frac{Q_{\text{net_conv}}}{Q_{\text{net_cond}}} = \frac{Q_{\text{conv}} - Q_{\text{loss}}}{Q_{\text{cond}} - Q_{\text{loss}}} \]

Assuming that convection heat flux was equal to heater heat flux \(Q_{\text{net_conv}} = Q_{\text{heater}}\) and applying eq. (4) and (5) to eq. (7) it could be rewritten in following form:
\[
\text{Nu} = \frac{Q_{\text{heater}} - Q_{\text{loss}}}{Q_{\text{theor, cond}}} = \frac{IU - Q_{\text{loss}}}{D \lambda (\theta_h - \theta_c)}
\]
(8)

The Prandtl number and Rayleigh number was defined as follow:

\[
\text{Pr} = \frac{\nu}{\alpha} \quad \text{Ra} = \frac{\beta g \Delta \theta D^3}{\nu \alpha}
\]
(7)

where \(\beta\) is the thermal expansion coefficient, \(g\) is the gravitational vector, \(\Delta \theta\) is the temperature difference between horizontal thermally active walls, \(D\) is the enclosure size (\(D = 0.032\) [m]), \(\nu\) is the kinematic viscosity coefficient and \(\alpha\) is the thermal diffusivity.

**Figure 8.** Heat losses calculated for conduction experiment.

In the figure 9 comparison between experimental results for Nusselt number calculated using temperatures measured with thermocouples and LIF technique are shown. In this plot theoretical value for convective flow is this configuration is also presented. It can be seen that for small temperature difference uncertainty of temperature measurement is quite large. This is caused mainly due to laser light fluctuation and camera noise fluctuation. For lower temperature difference those components are significant. With statistical analysis and time averaging this effect can reduced, but mainly for steady flows. It has been found that for very narrow temperature range calibration curve for suitable range only should be constructed.

**Figure 9.** Nusselt number from LIF and thermocouples measurement.

5. Conclusion

In the present paper the results of temperature and the heat transfer measurement in a closed cavity together with the data evaluation procedure were presented. The final temperature evaluation with LIF method depends on a large number of steps. In order to have an accurate temperature evaluation the
illuminated fluid need uniform light (in time and space), optical conditions need to remain constant. In a real measurement number of different types of imperfection follows the image recording.

The fluorescent dye intensity to temperature conversion is one of the most important steps in data evaluation and finally this is the main source of errors. The error in the calibration curve generates the error in the calculated value of temperature. Calibration images as well as experimental images use the same evaluation procedure and they all are influenced by the similar optical imperfections and noises. When the level of errors in calibration and in target experimental measurements remains the similar final accuracy can be obtained. The above assumes that the experimental conditions during relatively different time periods are the same. This required that laser power output, rhodamine concentration and stability (absorption, emission), shadowgraph effect and fluid self-absorption were the same at the time of calibration and experimental measurement. In presenting configuration base on single frame analysis the temperature evaluation uncertainty related to the light and dark noise fluctuation is about 0.569K and 0.248K respectively and for statistically steady analysis can be reduced by factor 10 using averaging procedure and energy monitor correction. Nusselt number evaluation uncertainty related to temperature gradient without such analysis depends strongly on the temperature range. For the lowest temperature difference 1K and 2K the total error was 42% and 36%, respectively, but for the larger temperature difference 40K only 7%.

In the case of heat transfer measurement closer to the hot or cold wall relatively large temperature gradient may occur. This gradient influence fluid density and refractive index. For this reason local laser light intensity (local excitation intensity) will change which significant local fluorescent influence intensity signal and finally results temperature. That effect, unlike others, cannot be minimized by averaging or any statistical analysis.

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