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INVESTIGATION OF NATURAL CONVECTION IN CUBICAL ENCLOSURE USING LASER INDUCED FLUORESCENCE

Temperature measurements are extremely important and they are used in many technical and engineering processes, including the analysis of natural convection. In contrast to the commonly used thermocouples and Pt100 temperature sensors, which allow point temperature measurements, laser induced fluorescence technique (LIF) allows the imaging of temperature fields throughout the area. An obvious disadvantage of thermocouples and Pt100 sensors is the possibility that the probes can affect the fluid flow, changing its structure. This problem does not appear in LIF measurements and better accuracy of temperature mapping is obtained. This work focuses on describing one-color LIF technique (using one fluorescent dye) in theoretical and practical terms. The experimental set-up is described, as well as a number of operations required to get the temperature field of the whole domain. The results of the natural convection process analysis in the configuration of one side wall heated and the opposite one cooled, with the use of laser induced fluorescence technique are presented.

Keywords: temperature measurement, visualization techniques, LIF, fluorescence

1. Introduction

Temperature measurement is essential in many technical and engineering applications, i.e. devices designing, characterizing flows, CFD codes validations. Also, numerous experimental situations require temperature and velocity measurements in liquid flow, i.e. thermal convection, in which buoyancy is the primary motive force. And while techniques such as particle image velocimetry are relatively well developed for the measurement of the velocity field, there are many flows in which the temperature field is of greater importance than the

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velocity. Temperature, being a scalar, is also a simple marker that is often used for visualizing the structure of the flow.

One of the most popular and widely used probes are thermocouples and Pt100 sensors. Properly calibrated thermocouples can measure temperature with accuracy better than 0.1K, and Pt100 sensors can be at least ten times more accurate. But both sensors have relatively large spatial resolution and may significantly disturb the fluid flow. Also, those types of probes make point-measurement, and mapping the whole area requires traversed systems or large number of sensors. An obvious disadvantage of those techniques is the possibility that the probes can affect the fluid flow, changing its structure. To avoid this, thermo-chromic liquid crystals have been used to non-intrusively measure full flow field [8]. The color of white light scattered from the thermo-chromic particles can be calibrated against temperature and scattering angle.

Another possibility in temperature measurements is utilization of temperature-sensitive fluorescent dyes excited by laser light - laser induced fluorescence (LIF), where temperature mapping includes the whole domain. Many studies have used LIF as a diagnostic technique to measure fluid flow scalars. Temperature measurements, in particular, are commonly made to acquire specific information about physical processes, i.e. natural convection [1, 9, 10]; tribological flows [3]; heat transfer and turbulent mixing [2, 5-7]; evaporating and combusting droplets [4]. This paper presents an experimental procedure and LIF measurement of natural convection in vertically heated cubical enclosure.

2. Principle

Fluorescence is a radiative decay process that occurs by electronic transitions in molecules. A fluorescent dye molecule is exposed to an electromagnetic field and photons entering the molecule cause displacements of electrons from one region to another. This displacement of electrons causes an increase in potential energy of the molecule from the ground state to the first electronic excited state resulting in fluorescent light emission [8]. The ratio of the total energy emitted per quantum of energy absorbed by the molecule is called the quantum efficiency Φ. The fluorescence energy I [$W \cdot m^{-3}$] emitted per unit volume is defined as [8]:

$$I = I_0 C \Phi \varepsilon \tag{1}$$

where I_0 is the incident light flux [$W \cdot m^{-2}$], C is the concentration of the dye solution [$kg \cdot m^{-3}$] and ε is an absorption coefficient [$m^2 \cdot kg^{-1}$].

In most organic dyes quantum efficiency is temperature dependent. And although the change in fluorescence intensity is normally small, there are some types of dyes that have significant sensitivity to temperature. In Rhodamine B, the fluorescence intensity strongly depends on the temperature, and LIF signal decreases about 25% for each 10K temperature increase. This feature can be used to measure the temperature of the liquid, if both the exciting light intensity and concentration of the dye can be kept constant.

3. Experimental set-up and procedure

In order to map the temperature, the classical benchmark for natural convection of water with addition of 3mg of Rhodamine B in a cubical cavity was investigated. A cubical enclosure of 210x210x210 mm, presented in figure 1, with one vertical wall hot and opposite one cold, was considered. Other walls were adiabatic. The non-adiabatic walls' temperature was kept constant by means of two water bath thermostats and the wall temperature difference was set at 5°C. The experimental set-up used in the present investigation is shown in figure 2 and figure 3. The excitation source was Nd:YAG laser (*Litron Lasers*), which was connected to energy monitor in order to register laser energy fluctuations. CCD camera (*LaVision*), with a set of lances, was recording the LIF images.

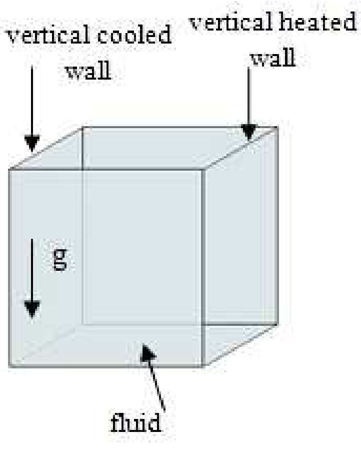

Fig. 1. Geometry of the cubical cavity

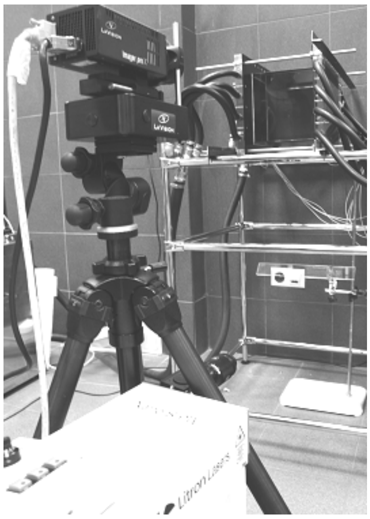

Fig. 2. Experimental set-up

In LIF measurements the preferred setup of laser light sheet and the camera is perpendicular (as shown in figure 3). So after adjusting the laser to form a light sheet at the desired place and positioning camera, calibration and scaling took place in order to correct the distorted image. Then image recording process started. Because camera's dark current (dark image) and surrounding light (background image) add an offset to the signal from the actual experiment, those effects must be subtracted in order to extract pure LIF image. This is achieved by recording a Background Image (with camera's lenses closed). Moreover, all lasers show a certain spatial profile normal to the beam axis when the laser is formed to a sheet. These local laser sheet inhomogeneities will introduce systematic errors. These effects were corrected with the Sheet Correction process - recording the sheet image, which gives information about the spatial laser energy distribution and the optical transmission behaviour of the detected system, and subtracting it from experimental images, which were recorded next (with temperature difference between heated and cooled walls 5°C).

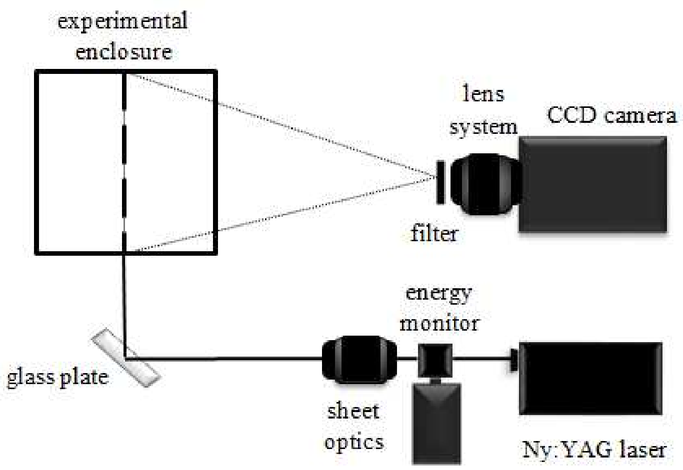

Fig. 3. Side view of the experimental set-up

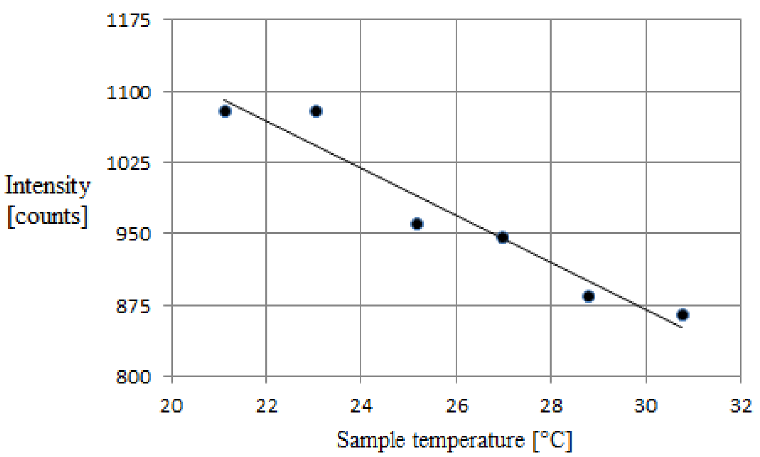

Fig. 4. Calibration curve

In order to extract absolute temperature from experimental images, it is necessary to map the image intensities to physical units. For this purpose, a set of calibration images was recorded at known values of temperature, matching intensities to specific temperature and creating a calibration curve, shown in figure 4. This curve was used to determine temperature values in experimental images.

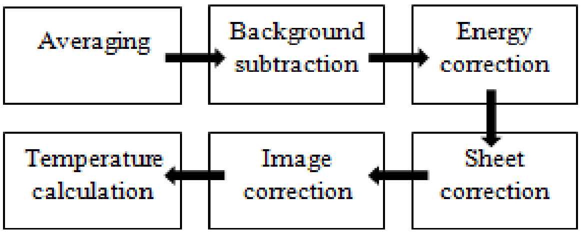

Fig. 5. Workflow for post processing of experimental images

All recorded images include the LIF signal with systematic errors, mentioned above. Therefore, for an optimum result it is necessary to correct these inaccuracies using post processing functions and procedures, shown schematically in figure 5. For experimental images processing, the first step is averaging of the images. This operation calculates basic statistical values, such as average, rms etc. for each pixel position, storing it in a new image set. Then background subtraction takes place - reducing dark current signals and light reflections to achieve pure LIF signal information. Next step is energy correction, which applies an image normalization using the read-out data from Energy Monitor. Then sheet correction is applied, correcting laser sheet inhomogeneities. Furthermore, images are polished through employing smoothing filters, which reject noises from the laser and remove small particles from the images. The last step in image processing is temperature calculation. This function re-scales recorded intensity values of an image to temperature. As a result, temperature map of recorded experimental image is achieved.

4. Results

Figure 8 presents raw image obtained during LIF experiment. After post processing temperature distribution, presented in figure 7, is obtained (darker grey color on the right side symbolizes higher temperature). *LaVision* software, used in this work, provides many options and one of them is automatic profile of the temperature at desired position. Vertical temperature profile at the middle height of the experimental enclosure is presented in figure 8. The temperature profile, in investigated domain, changes almost linearly from left side (wall temperature 21.02°C) to right side (wall temperature 26.06°C). There are visible boundary layers near the walls, where intensive temperature changes occur.

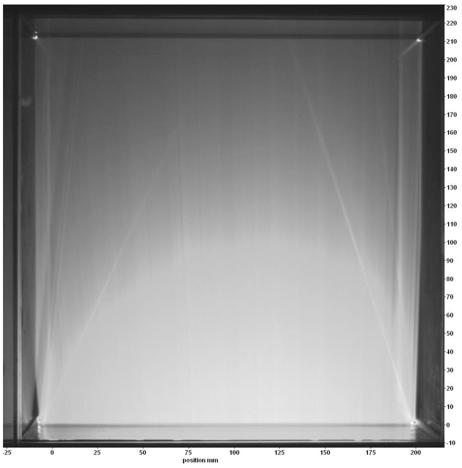

Fig. 6. Raw image obtained in LIF experiment

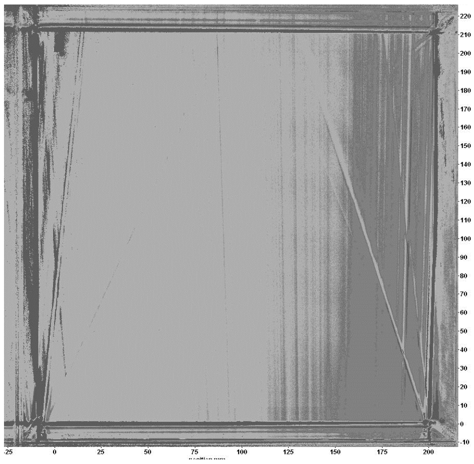

Fig. 7. LIF-temperature map (left wall cooled, right wall heated)

Also, the recorded temperature is much higher at the nodes and edges, due to laser distribution disturbances. Those effects should be avoided in future works.

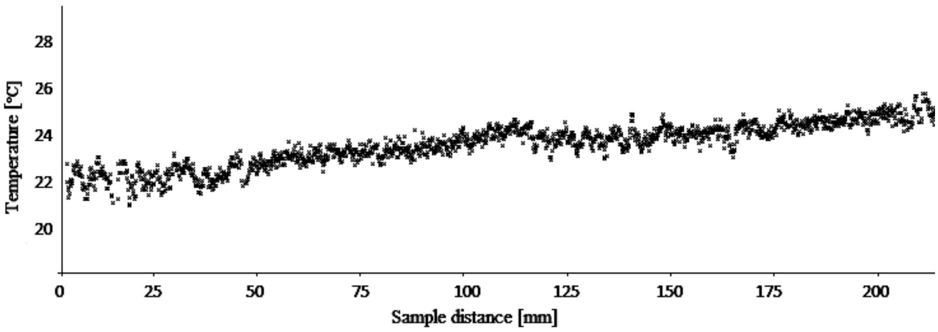

Fig. 8. Temperature profile in the middle of the sample

5. Conclusions

Temperature mapping with the use of laser induced fluorescence was investigated. Procedure and post processing processes were briefly described, and one case of investigated natural convection was shown. Temperature distribution was obtained, but presented technique has to be improved. Firstly, post processing must be uprated. To obtain clear field of view and to remove small disturbances caused by light reflections, more filters must be used. Moreover, better and more accurate dyes could be implemented. This also creates an opportunity to investigate in the future natural convection process using two-color laser induced fluorescence.

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ANALIZA PROCESU KONWEKCJI NATURALNEJ PRZY UŻYCIU TECHNIKI FLUORESCENCJI WZBUDZANEJ LASEROWO

Streszczenie

Pomiary temperatury są niezwykle istotne i mają zastosowanie w wielu technicznych i inżynieryjnych procesach, m.in. w analizowaniu konwekcji naturalnej. W odróżnieniu od popularnie używanych termopar i sensorów temperatury Pt100, pozwalających na punktowe pomiary temperatury, technika fluorescencji laserowej LIF pozwala na zobrazowanie pola temperatury w całym badanym obszarze. Oczywistą wadą termopar i czujników Pt100 jest możliwy wpływ sondy na przepływ płynu, zmieniając jego strukturę. Ponadto na dokładność pomiarową w technice LIF wpływa także fakt, że w układzie nie występują zaburzenia przepływu spowodowane wprowadzeniem do analizowanego obszaru stałych czujników. Problem ten nie pojawia się w pomiarach techniką LIF. Ponadto, odwzorowanie temperatury jest bardziej dokładne przy pomiarach techniką fluorescencji laserowej. Poniższa praca skupia się na opisaniu jednokolorowej techniki LIF (z wykorzystaniem jednego barwnika fluorescencyjnego) pod względem teoretycznym oraz praktycznym. Opisane zostało stanowisko pomiarowe oraz szereg kolejnych operacji składających się na uzyskanie obszarowego pola temperatury. Przedstawione zostały wyniki analizy procesu konwekcji naturalnej wody w konfiguracji z jedną ścianą boczną grzaną i naprzeciwległą chłodzoną poprzez zamieszczenie wyników pomiarowych uzyskanych techniką fluorescencji laserowej.

Keywords: pomiar temperatury, techniki wizualizacyjne, LIF, fluorescencja

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