Two-Color Particle Tracking Velocimetry and Thermometry

by

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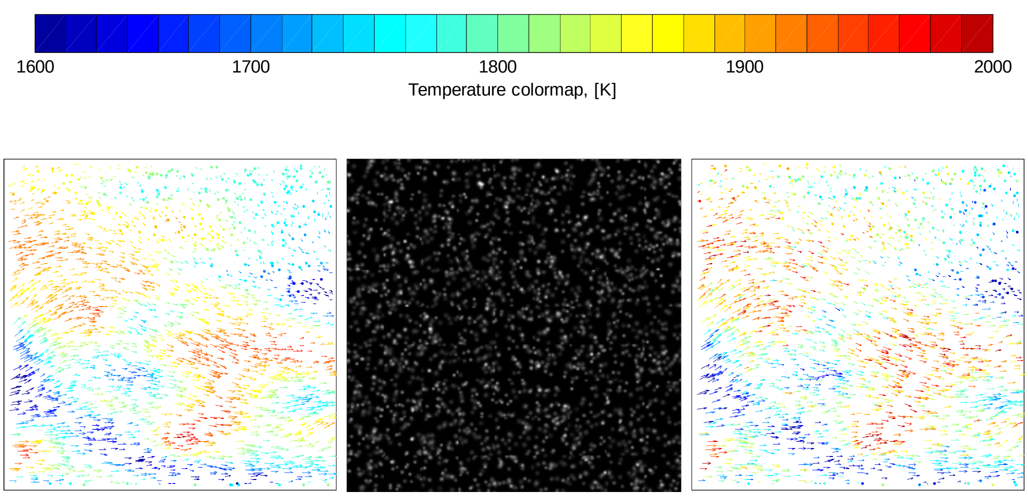
ABSTRACT

Particle Tracking Velocimetry (PTV) and Particle Image Velocimetry (PIV) originally have been established for velocity field visualization. In the meantime flow fields of interest in classical and applied fluid mechanics are essentially inseparable from thermal effects in the majority of cases. Different physical phenomena are involving for temperature field mapping depending on physical properties and data required by certain class of application, such as: Thermochromic Liquid Crystal (TLC) Digital Particle Image Velocimetry/Thermometry (DPIV/T), Planar Filtered Rayleigh Scattering (FRS) technique, Coherent anti-Stokes Raman Scattering (CARS) technique, micron-resolution particle image velocimetry (μ-PIV) for temperature measurement which based on the premise that Brownian motion will cause width-wise broadening of the cross-correlation peak, etc. Most of proposed techniques utilize different radiation sources for velocity and temperature respectively (except TLC), usually require sophisticated hardware, optical access to the interrogating flow from different directions and pretty complex calibration. In present work inherent or laser induced irradiation of individual tracer particles or distinguishable groups of molecules (injected into hot flow in the form of liquid evaporating droplets) is examined as information source of both temperature and velocity fields in an assumption of detectable relative light intensity from each tracer depending from its average temperature, similar to infrared (IR) pyrometry applied to each individual tracer within interrogation flow domain. This technique seems to be quite attractive alternative to more sophisticated aforementioned technologies for a number of particular applications most of all due to much less expensive implementation and simple calibration providing acceptable accuracy with sub-pixel spatial resolution as shown in figure 1 for an computer simulated and then recovered velocity and temperature distribution. Appropriate demonstrational experiments are carrying out.



Actual Distributions ***Firs of two sequent simulated images*** ***Recovered Distributions***

Fig. 1. Technique application for simulated velocity and temperature fields of 2489 vectors captured by noisy 8-bit 256x256 sensors, 2245 are recovered with high accuracy

1. INTRODUCTION

Flow fields of interest in classical and applied fluid mechanics are essentially inseparable from thermal effects in the majority of cases. One of the important obstacles in the way of attaining competitive with available by velocimetry spatial and temporal temperature field resolution is the completely different physical nature of characteristics desired to be measured, namely mechanical for velocimetry versus inherently statistical for thermometry.

Optical non-intrusive sensing to evaluate and optionally control temperature and velocity distribution in a variety of high temperature facilities seems to be a one of the promising diagnostics methods allowing to extract spatial distribution and temporal behavior of velocity and temperature simultaneously.

Ideal combination of velocimetry and thermometry should be able to provide approximately equal both spatial and temporal resolution as high as possible using optimal physical principles to accurately measure both, velocity and temperature, for diverse applications of appropriate technique.

We propose a novel particle tracking technique enhanced two-color particle tracking velocimetry to recover both, velocity and temperature, from each tracer particle identified within the flow interrogation domain. In this paper, the recovery algorithms both, velocity and temperature, from individual particles have been presented. The feasibility of this technique is validated by error and limitations analysis. The performances are evaluated using demonstrational numerical experimens.

2. BACKGROUND

In the present section the essence and relevant recent results of temporally and spatially sensitive velocimetry and thermometry are briefly introduced. This is not an exhaustive review of recent work on both topics. It is author's view of some recent work that they have found interesting and believe to be important and promising to couple both together in a manner required by the majority of possible diverse applications.

2.1 Particle tracking velocimetry (PTV) and particle image velocimetry (PIV)

Particle Tracking Velocimetry (PTV) and Particle Image Velocimetry (PIV) are well-established extremes of the general class of Particle Imaging Techniques (PIT) for visualization over extended regions of a flow with high spatial and temporal resolution (e.g. Adrian, 1991 and Adrian and Yao, 1985). Particle Imaging Techniques imply the flow visualization by recording the images of tracer particles at two or more times on a film or a Charge Coupled Device (CCD) array. PTV is the low-image-density mode of PIT when each displacement vector is obtained from the consequent images of individual tracer particle as opposed to PIV, the high-image-density mode of PIT when every velocity vector is obtained by averaging the displacements of many images inside the certain small interrogation spot. Tracer particles are supposed to accurately follows the motion (and here the temperature too) of the flow. Both extremes of PIT, PTV and PIV, originally have been established for velocity field visualization. PIV essentially tracks groups of particles within small regions of the image (interrogation areas) at higher particle density, e.g., about 15 particles per 32 x 32 pixels. Usually the correlation between the interrogation areas in both images is computed and the displacement is determined from the location of the correlation peak. PTV, in contrast, tracks individual particles at rather low particle image density.

PIV techniques estimate an average velocity over the chosen interrogation area, and resolution is limited to the size of this area. A theoretical limit for the resolution of all particle imaging techniques is the maximum of the average distance between particles and the average displacement of the individual particles between exposures. PIV does not reach this limit due to the additional averaging over interrogation areas. PTV, in opposite, traditionally required large distance between particles to correctly identify the same particle in both exposures.To increase resolution, PIV and PTV have been combined by using velocity estimates predicted using PIV to help track particles and correctly pair them in the two images (Keane, Adrian and Zhang, 1995, and Tan and Hart, 2002). The spatial resolution of such combined PIV\PTV technique allow to obtain up to 5 vectors of velocity within interrogation area with an average displacement error of 0.1 pixels (Keane, Adrian and Zhang, 1995, and Tan and Hart, 2002).

It should be concluded that PIV/PTV techniques family allows perform quiet precise measurement of particle displacement. For extensive review refer to (Adrian, 1991, Adrian and Yao, 1985, Keane, Adrian and Zhang, 1995, and Tan and Hart, 2002) and others references in present paper.

2.2 Simultaneous dynamic spatially sensitive velocimetry and thermometry

Thermochromic Liquid Crystal (TLC) Digital Particle Image Velocimetry/Thermometry (DPIV/T) employs TLC seeding particles in water (Dabiri and Gharib, 1991). The temperature visualization is based on the property of TLC to refract light of selected wavelength as a function of the temperature and viewing angle. The dependence on color to temperature allows obtain quantitatively temperature distribution in flow. Large uncertainties are encountered when the temperature is measured from individual TLC particles (Park, Dabiri and Gharib, 2001). The uncertainty is reduced by computing the average temperature of the particles within the common specified sampling window used for standard DPIV (Park, Dabiri and Gharib, 2001).

The PIV works recently published and based on TLC are excellent example of most preferred prototype of the tracers being the same for both velocimetry and thermometry measurements. But it should be noted that the imaging techniques with use TLC have some drawbacks. A major shortcoming is that one has short range of measurable temperature (0 to 100 OC), and application of TLC restricts itself generally to liquid flows. Additional drawback is concluded in necessity of calibrating each point of the test field to compensate for the influence of the illuminating light variations. Nevertheless it seems that simultaneous velocimetry and thermometry measurements with use of tracers techniques are quiet possible not only for pure TLC applications but also for gasogenous media seeded with illuminating solid/liquid tracers.

2.3 Spatially sensitive thermometry

Due to the expanding diversity of practical applications of PIT different physical phenomena are involving for temperature field mapping depending on physical properties and data required by certain class of application.

To date a few novel laser diagnostic techniques have been proposed to measure temperature field distributions.

With the planar Filtered Raleigh Scattering (FRS) technique, for measuring the temperature field, and simultaneous application of particle image velocimetry (PIV), combined 2D information about the instantaneous velocity field and the temperature structure of hot flows is achievable (Most and Leipertz, 1999, and Most, Dinkelacker and Leipertz, 2000). The basic idea of FRS is to use the fast and statistically distributed thermal movement of molecules, causing large Doppler broadening, to separate the Rayleigh signal from Mie.

In the Coherent Anti-Stokes Raman Scattering (CARS) technique two or three laser beams at two different wavelengths are focused and crossed in the measurement region. When the frequency difference of the laser beams is equal to a Raman-allowed vibrational or rotational transition, a new laser beam, the CARS beam, is generated, containing information on the temperature as well as the species number density of the probed species at the crossing point. The CARS technique was developed in Lund Institute of Technology (Sweden).

Another from them is most promising laser-induced fluorescence (LIF) technique being one of the most useful laser diagnostics in combustion analysis. Because of its strong signal intensity, LIF can be applied to 2D recovering of temperature and species concentration in various research and industrial devices. LIF has also been applied to flow and plasma diagnostics and the technique is quiet applicable for temperature and species visualization inside industrial combustors (Deguchi et al., 2002). LIF thermometry can be based either on seeded species (indium, gallium) or on native molecules (OH or NO radicals) in the depending on studied process. Two-line atomic LIF thermometry is based on suitable metal atoms being seeded into the combustion region and indium has been pointed out to be an attractive candidate for practical combustion, since it is sensitive over a wide temperature range (700-3000 K).

The common base of the mentioned thermometry techniques is a measuring of induced or inherent radiation of species in flow. The measurements are performed averaging radiation along optical axis and tend to the employing of uniform number densities distribution of species. Spectral separating of light (inherent, laser scattered, laser induced and etc.) emission from species (seeded into flow or not) by two or more wavelength channels is often used. Such approach allows avoid careful and quantitative calibration relative to the variation of mole fraction and collisional quenching in flow that it's almost impossible for single channel systems, for instance, in highly sooting and turbulent flames.

The thermal flow diagnostics with seeds is based on assumption that small submicroscopic particles should have almost the same temperature relative medium. In the case of a sufficiently small size of particle and high thermal conductivity of flow it allows neglect temperature difference between seed and flow. Note also when tracer species are seeded into the flow, it is essential that their influence on the studied process or phenomena should be negligible too.

3. OUTLINE OF DEVELOPING TECHNIQUE

Most of laser diagnostic techniques, which have been proposed as addition to traditional PIT, usually require sophisticated hardware, optical access to the interrogating flow from different directions and pretty complex calibration.

Involving additional parameter (e.g. temperature) recovery into conventional Particle Imaging Techniques arise a few problems needed to be clarified and solved regardless the nature of the flow, tracers, and theirs radiation. Those problems, associated primarily with images data processing, are:

- PIV has been originally developed to recover velocity map only and is based on statistical data processing when every velocity vector is obtained by averaging the displacements of many images inside the certain small interrogation spot. There is no way to extract additional flow parameter such as the temperature being within conventional PIV techniques, therefore temperature mapping require independent hardware & software development. Extraction of the additional, for instance, temperature information associates in practice with experimental challenges, most of the techniques usually require sophisticated hardware, optical access to the interrogating flow from different directions and pretty complex calibration.

- PTV potentially can be expanded to recover additional flow parameter (e.g. temperature) because it tracks individual particles (at the cost of lower image density compared with PIV). In any case additional parameter recovery (tracer image spot intensity) require appropriate algorithm development, estimating and minimizing recovery error.

This paper presents the basis of coupling both, PTV and thermometry, together, which comprises of:

1) Individual particles identification and simultaneous recovery theirs position and temperature on sequent two-color images.

2) A novel particle tracking algorithm by pairs matching based on particle size variety.

3) Principal technique implementation and limitations analysis.

4) Demonstration experiments

4. THEORETICAL BACKGROUND

It is often said that it becomes impossible to match pairs of particle images by PTV technology when particle displacement exceeds half of average distance between particle images. However, this is not precisely true: it is only when individual particles do not distinguishable.

This section of the paper presents a method of accurately determining the displacement of tracer particles between two images using introduced enhanced pairs matching procedure based on random particle size distribution. Individual particle images pair identification is arrived at through most close particle size search as opposed to traditional PTV technique based on nearest neighbour searches. This methodology being properly realized allows overcome most crucial limitation inherent to traditional PTV technique concerning particle displacement which can exceed half of average distance between particle images. It means that in such a manner Enhanced Particle Tracking Velocimetry and Thermometry (EPTV/T) has now gone beyond a low-image-density variant of Particle Imaging Techniques (PIT), as it usually associated with PTV, enabling tracking velocimetry alone to be applied for high-image-density data (0.04 particles/pixel), which were so far processed exclusively using correlation based based PIV methods. Compare with traditional auto- or cross-correlation PIV, EPTV has two major preferences.

First, still belonging to the class of pure PTV techniques, it inherently able to visualize with high spatial resolution not only locally uniform flows as PIV does, but also strongly non-uniform ones, including random flows such as Brownian motion.

Second, very high spatial resolution (approximately ten times higher than typical for correlation involving methods) in vector field can be achieved due to non-statistical nature of tracking processing.

5. ENHANCED PTV/T TECHNIQUE

The main idea is to use all the information available on the image of each individual particle to recover its size for further pair matching, namely position, spread parameter and total intensity.

In the image plain, the intensity I at the location (x,y) caused by irradiation from individual particle focused at the location(x_0,y_0) is well approximated by a two-dimensional Gaussian function (Adrian and Yao 1984):

$$I(x,y)=\frac{E}{2\pi\sigma^2}\exp\left\{-\frac{(x-x_0)^2+(y-y_0)^2}{2\sigma^2}\right\} \tag{1}$$

where E is the energy captured from the particle by the lens, and σ is the spread parameter which can be interpreted here as effective blur circle diameter being caused by lens diffraction and/or finite particle diameter. More particulary, using so called Gaussian particle image diameter d=4σ, the circle with intensity level at 13.5%), this diameter d can be well approximated by the formula (Adrian and Yao 1984; Subbarao 1988):

$$d=4\sigma=\left(M^2d_p^2+d_s^2+d_d^2\right)^{1/2} \tag{2}$$

where M is the magnification, as a function of actual particle diameter d_p , the diameter d_s of an Airy function, given by (Adrian 1991)

$$d_s=2.44(1+M)f^{\#}\lambda \tag{3}$$

where $f^{\%}$ is the f-number of the lens, and λ is the wavelength of light, and the defocusing diameter d_d , given by (Subbarao 1988)

$$d_d=kM_o\frac{f}{f^{\#}}\frac{|\Delta Z|}{Z} \tag{4}$$

where M_o=MZ/Z_o is the magnification of the lens focused on the object plane O at the depth Z_o , Z is the actual depth of the tracer particle P , ΔZ=Z-Z_o is the is the depth deviation of the particle P from the object plane $\boldsymbol{O}$, f is the focal length of the lens, and k is a constant of proportionality characteristic to a given camera and can be properly calibrated.

According the expression (2), the Gaussian image diameter in the sensor plane is well approximated by the diameter of the particle, the magnification, blur caused by defocus and the point response of the lens. Three important extremes should be clarified depending on the prevailing of one of three components in formula (2):

1). Geometric scattering range with thin planar illumination, when particle diameter is much more than wavelength without any defocusing.

2). Diffraction range with thin planar illumination, when defocusing effect still can be neglected.

3) Pure defocusing case, when last term in formula (2) is prevail compare with two others.

To simplify further analysis only first two extremes will be considered here which can form the basis of further generalisation if required and seem to be quite relevant for a wide range of applications with planar illumination, uniform along Z or Z-shaped, when defocusing can be neglected. As far as pure defocusing case, it is a subject of another separate consideration.

The energy of the incident light $W(Z)$ is typically a Gaussian profile in the case of the pulsed laser for “traditional” planar PIV:

$$W(Z)=W_0\exp[-8(Z-Z_0)^2/\Delta Z_o^2] \tag{5}$$

where W_0 is the maximum intensity along the Z-direction and light sheet thickness ΔZ_0 is defined by the $1/e^2$ intensity. In other cases, e.g. μ-PIV or other cases, sheet illumination source can be expressed by any measured or predicted function $W(Z)$ or even $W(X,Y,Z)$, if significant absorbtion/dispersion can occur. The conversed extreme to any Z-nonuniform illumination is provided by expression (5) with unlimited ΔZ_o, namely:

$$W(Z)=W_0=const \tag{6}$$

The most uncertain/random parameter in current consideration is the light intensity reflected by the tracer particle *P* having certain diameter *D*. According to Mie scattering theory, the energy captured by certain lens from a tracer particle with given diameter *D* can significantly fluctuate by the order of magnitude with diameter *D* change around 5-10% (see, e.g., Adrian 1991)

5.1 Particle Identification and Tracking Algorithms

The main idea behind current consideration is the use all the information available on the image of each individual particle to recover its size for further pair matching, namely position, spread parameter and total intensity.

Before extracting all these parameters for each individual particle, an identification and localization process has to be performed on the recorded frames of overlapped particle images. The identification of particles from recorded images is a critical task and constitutes in itself a general problem in pattern recognition research. It seems that there is no universal method and specific approaches have to be considered for any particular application. Several authors have discussed this topic in different ways Carosone et al. (1995), Etoh et al. (1998), Guezennec and Kiritsis (1990)

Nevertheless, this task can become easier and the performances will be improved if the experimental conditions are taken into account optimizing proper choose. The Particle Mask Correlation (PMC) method is one of the methods for particle image extraction from a plane (Takehara et al., 1999). This method used in this work was initially developed for images obtained for classical PIV. In order to identify the central positions of tracer particles with higher accuracy level, a guassian particle mask (Etho T., and Takehara K. 1998) is used in the present study. If guassian mask is not applicable, another method based on the determination of the background noise analyzing the distribution of the gray levels and local intensity threshold by dividing the whole image in smaller regions followed by second thresholding to separate individual particles within each smaller region. In any case a double gaussian interpolation is then performed to get to the position at the sub-pixel accuracy.

Some important of the original particle information, however, is obscured in such a techniques, namely spread parameter and intensity. In this paper, a new computationally efficient method is proposed that takes advantage of the entire particle information recovery.

A particle identification and matching approach is used for the digital processing of the image pairs to produce the displacement field. To obtain velocity data with high spatial resolution, a novel processing algorithm was developed. First, particle size distribution and the relationship between the particle size and its image diameter and intensity are defined based on experimental setup. Second, separate image spots comprised of individual and overlapped particle images have been detected by a selected threshold method or theirs combination. Then, each spot is processed to acquire position, diameter and intensity of each particle followed by particle size recovery and appropriate accuracy estimate. Finally, individual particles pair identification is arrived at through most close particle size search.

5.2 Benchmark data for processing

Benchmark data comprises of qualitative (or quantitative, if available) particle size histogram behaviour and quantitative dependences of particle image intensity and particle image diameter from its real size.

5.2.1. Particle size distribution

A technique proposed in this work is based on the size *D* variety of tracer particles seeded into flow. Therefore the average particle diameter and the standard deviation are major input parameters for algorithms realized.

5.2.2.Particle iImage diameterand intensity versus particle size

In general, two particle image parameters can independently reflect its size, namely Gaussian diameter and total intensity. Therefore, two functions, based on experimental setup, should be assigned:

$$d = f_d(D) \tag{7}$$

where *D* is the particle size, *d* is the Gaussian diameter, and

$$E = f_E(D) \quad (8)$$

where E is the total light intensity captured by the lens from given particle.

5.3 Particle identification and data recovery algorithm

A three-step method is presented to identify individual particles and recover the Gaussian diameter d and total intensity E to obtain each particle size D by formula (5) for further size-based tracking procedure, it consists of:

1. Individual particle detection
2. Particle group segmentation
3. Particle data recovery, including size and intensity

5.3.1. Individual particle detection

Individual particle detection, required in any PTV technique, becomes a crucial step in particle size based tracking as compared with particle location based tracking because it is associated with additional difficulties caused by simultaneous recovery not only location, but also the Gaussian diameter d and the total intensity E for each identified particle.

Ideally, each of sequent PIT frames consists of bright particle spots on a dark background. Simplest single (global) or multiple (local) threshold segmentation (instead of binarization) followed by least-square Gaussian fit (instead of centroid calculation) is obvious well an established standard solution for such a case. However, this method is applicable only if the majority of individual particle images can be easily segmented by threshold into sharp enough Gaussian-shaped spots. In practice, this is rarely the case even for sparse seeding due to a variety of factors, including background intensity noise caused by radiating flow domain itself, e.g. reflection from boundaries, camera random dark noise, others background nonuniformity sources, and, finally, particle images overlapping for high image density. Recently a few methods have been established and proofed for with particle location based PTV to improve identified particle yield. None of them can not be directly applied to recover the Gaussian diameter d and the total intensity E together with particle location because they inherently use some image preprocessing which disturb d and/or E. Nevertheless, two of them, the Particle Mask Correlation (PMC) method (Takehara et al., 1999) and the Dynamic Threshold Binarization (DTB) method (Ohmi and Li, 2000) have been chosen and tested to locate particles preliminary for further processing.

5.3.2. Particle group segmentation

For each particle, its nearest neighbor is judged belonging to the same group if the ratio of minimal from two peak intensities to the minimal pixel intensity on the line between peaks is more than threshold of 0.13. In such a manner, the image is segmented into group images of individual or several overlapped particles. Each group image is processed further separately.

5.3.3. Particle data recovery algorithm

An essential part of presented technique is an algorithm for recovery all particle data, namely position, Gaussian diameter and intensity, from particle group image.

5.4 Particle tracking algorithm

Input data for particle tracking are discrete particle data x_i , y_i , D_i , δD_i recovered from first image for n particles and x_j , y_j , D_j , δD_j recovered from second image for m particles, where δD is the size recovery error estimate.

Simplest algorithm is quite similar to traditional PTV by a simple nearest neighbors search, using particle size D instead of distance, and it is applicable when δD is much less than $\Delta D/n$ and $\Delta D/m$, where ΔD is the particle size range.

More advanced algorithm implies match probability definition for each candidate j within the search range $|D_j – D_i|<\varepsilon$ based on δD_i , δD_j and known particle size distribution, match probability sorting followed by velocity field postprocessing to iteratively replace spurious vector by next candidate until velocity field satisfy certain spuriousless criteria.

5.5 Flowchart of the super-resolution EPTV/T method

The flowchart shown in Fig.2 summarizes the aforementioned procedures, namely: 1) Forming benchmark data for processing from experimental setup, particle size distribution and relation between particle size *D* and its image parameters such as Gaussian diameter *d* and total intensity *E* captured by the lens, 2) Individual particle detection, 3) Particle group segmentation, 4) Particle size and intensity recovery, 5) Size and/or intensity based particle tracking.

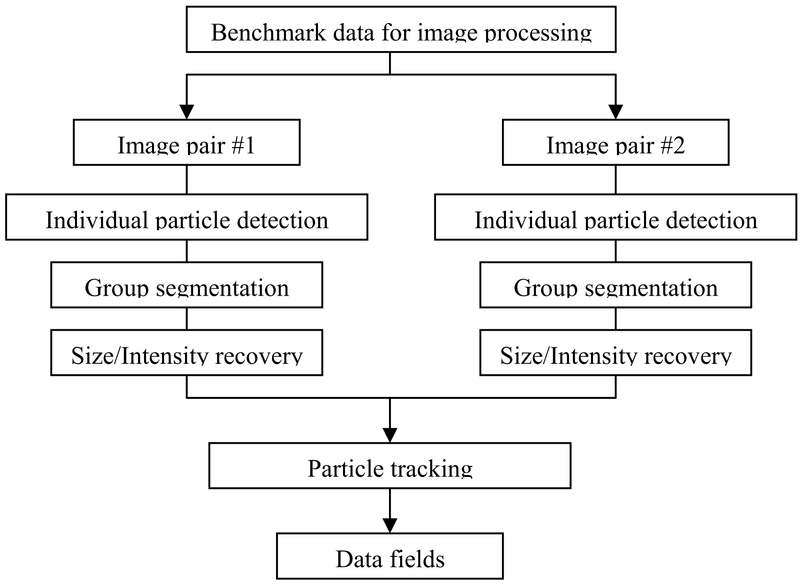


Fig. 2. The schematic of velocity and temperature based particle tracking algorithm

6. TECHNIQUE LIMITATIONS AND TECHNICAL IMPLEMENTATION

Theoretically, the temperature of each tracer can be recovered from either absolute image spot intensity or relative spot intensities taken at two different wavelengths. The first mentioned way is quite obvious in terms of technical implementation and conventional PIT hardware can be used without any modification. In the present section of the paper the second way of temperature recovery is implied to imagine required technical modification as compared with conventional PIT hardware arrangement.

Two-color enhanced PTV technique can be applied to seeded flows in an assumption of accurately measurable radiation intensity, captured from individual tracer, associated with tracer's temperature, regardless the nature of tracer's radiation, inherent or laser induced. A variety of solid/liquid tracer particles or distinguishable groups of molecules (e.g. injected into hot flow in the form of liquid evaporating droplets) can be used depending on certain application and technical implementation.

Principal technique limitation is caused by the amount of light captured by lens from individual tracer, which should be enough to satisfy mentioned above assumption. For laser induced radiation, laser pulse power allows to achieve almost nanosecond image exposure in the majority of cases. The worst case, but still very attractive for some scientific and industrial applications, in this sense is realized when inherent radiation is used. Therefore below appropriate limitations are evaluated.

6.1 Planck's radiation intensity of a tracer

Using inherent radiation instead external laser illumination technique results in a limitation for the temperature which can be still measured at acceptable accuracy. Let us estimate the level of radiation energy emitted from single particle. In terms of time resolution it means that the minimal possible exposure time to detect tracer particle by film or CCD sensor is restricted.

The heated-up single tracer particle in gaseous or liquid flow can be considered as radiating gray body. Its spectral intensity approximately satisfies Planck's distribution law, i.e. the radiant energy emitted from total surface of spherical particle at the wavelength λ is given by:

$$B_{\lambda}(T) = \frac{2hc^2}{\lambda^5} \frac{4\pi r^2}{e^{\frac{hc}{\lambda KT}} - 1} \tag{9}$$

where $B_{\lambda}(T)$ - radiation intensity of the "blackbody" particle at the monochromatic wavelength λ, W; h - Planck's constant, J c; K - Boltzman constant, J/K; c - light velocity constant, m/c; T - temperature of particle, K; r – radius of particle, m.

For real surface of solid particle the expression (9) can be written as:

$$E_{\lambda}(T) = B_{\lambda}(T) e_{\lambda} (1 - \alpha_{\lambda}) d\lambda \,. \tag{10}$$

where e_{λ} - emissivity of surface of particle, α_{λ} - gas absorption coefficient (can be neglected in optically thin mediums); $d\lambda$ - wavelength range.

Temperature of a tracer particle can be easily obtained from the ratio of radiation intensities by simplified formula (9) at the two different basic wavelengths λ_1 and λ_2:

$$T_p \approx \left(\frac{1}{\lambda_2} - \frac{1}{\lambda_1} \right) \frac{C_2}{\ln\left(\frac{E_{\lambda_1}}{E_{\lambda_2}} \frac{\lambda_1^5}{\lambda_2^5} \frac{d\lambda_2}{d\lambda_1} \frac{e_{\lambda_2}}{e_{\lambda_1}} \frac{\alpha_{\lambda_2}}{\alpha_{\lambda_1}} \right)}, \tag{11}$$

where $E_{\lambda_1}, E_{\lambda_2}$ - measured radiation intensities of a tracer particle at the respective wavelengths and C_2 = 1.4388-e7 nm K.

In view of Planck's function behavior, temperature range and spectral sensitivity of the most of modern CCD-sensors, it's reasonable to consider spectral range of the technique in red and near infrared areas of spectrum (wavelength more than 700 nm) where according with Wien law the thermal radiation has a increasing of intensity in the temperatures range under consideration.

From corpuscular point of view the minimal exposure time Δt can be evaluated from the relation

$$\Delta t = \frac{N_{ph} \varepsilon_{\lambda}}{E_{\lambda}(T) \tau_{\lambda} \varphi_{\lambda} F_s} \tag{12}$$

where $\varepsilon_{\lambda} = hc/\lambda$ - energy of light quantum; $E_{\lambda}(T)$ is irradiation energy emitted by heated particle; φ_{λ} - integral spectral sensitivity of the CCD array; N_{ph} - a number of detected photons needed for stable signal; τ_{λ} - integral spectral transmission characteristic of the band-pass optical filter; F_s - coefficient of a simple optical system depending on solid angle, lens aperture and distance to object.

For example, the following values can be taken for estimation. Solid angle coefficient F_s can be evaluated as $1.56 \cdot 10^{-2}$ for lens-to-object distance 0.2 m and lens aperture 0.05 m. Integral half-width of band pass filters is assumed 5 nm at radiant transmission coefficient 0.5. To date the best modern high-speed cameras have quantum output about 50-85% in near infrared area and the readout noise reaches value of 20 electrons. Thus, the sensor with image intensifiers needs about 1200 "blackbody" photons on single sensor's cell to provide acceptable good signal-to-noise ratio (about 30 dB). Dependence of the minimal exposure time of detection of a particle having diameter around 10 μm is presented on figure 3 which shows that a single small tracer particle heated above 1000 K can be satisfactorily detected with exposure time more than 2-50 ms. The particle size, focal number of optical system, wavelengths and band-pass filters can be chosen so as increase time resolution (to microseconds values).

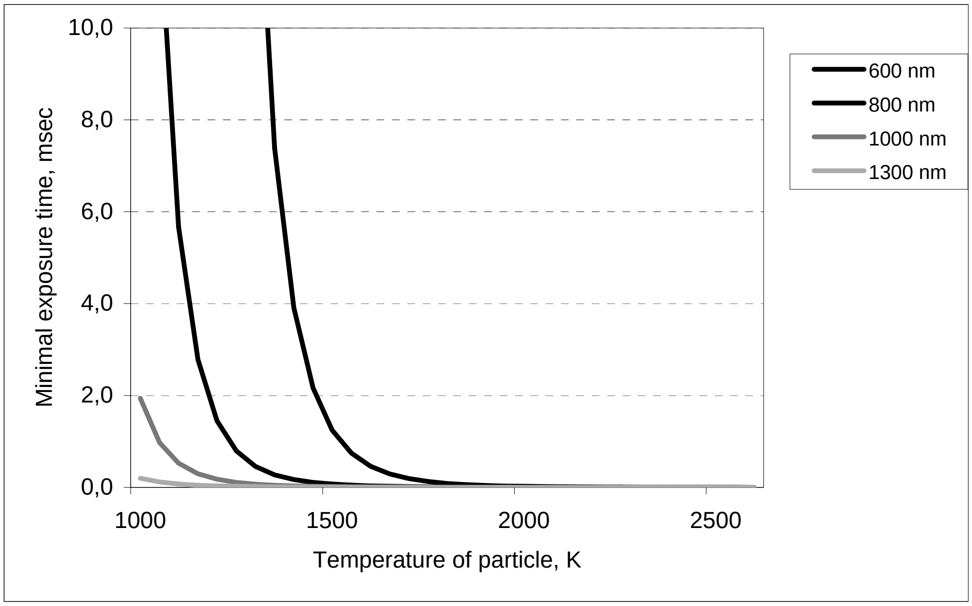


Fig. 3. Required exposure time vs. tracer temperature

6.2 Simpliest Technical implementation

A scheme of the typical optical system arrangement for temperature/velocity measurements is shown in figure 4. Such optical system can be easily realized on the basis of contemporary 3-CCD architecture. To date the commercially available CCD sensors are capable of detecting light beyond the visible wavelength out to 1100 nm. Optional narrow band filters can be placed in front of the arrays to select specific wavebands. These trim filters can be replaced in the field or at the factory allowing optimization for specific application. In some applications, there is an interest in acquiring simultaneous images from separations of light based on criteria other than wavelength, for example, percentage wave separation or polarization filtering. In that case one or both of the dichroic coatings on the prism can be replaced with broadband beam splitter or polarization separation coating. At present multispectral CCD cameras for different kind of applications become commercially available.

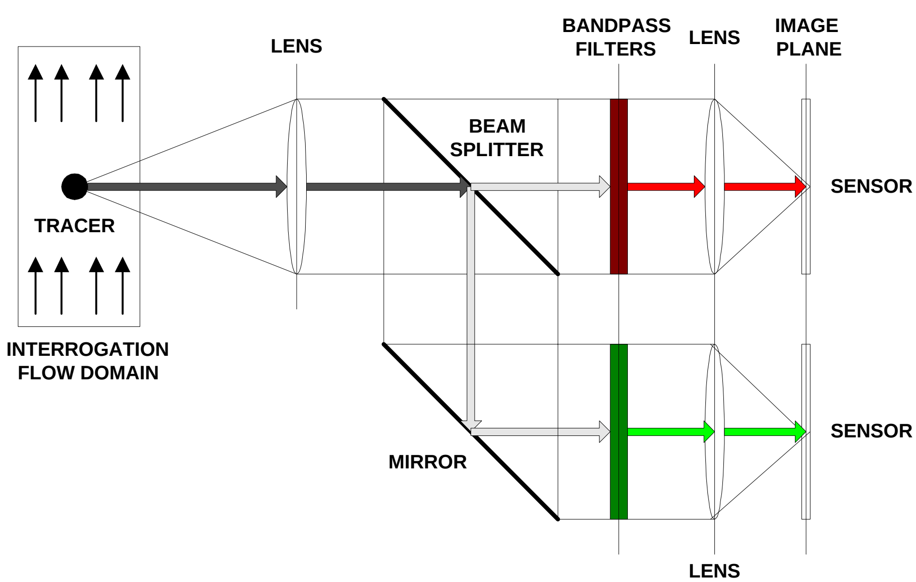


Fig. 4. Schematic layout of two-color PTV/T system

6.3 Preffered composite filter embodiment

The expanding of the idea of the two-wavelengths technique is that effect of particle image blurring in image plane can be used for simplification of the optical system arrangement. Actually, there is no need to arrange two separate optical channels as shown above on figure 5. Placing a special two-wavelengths composite bandpass filter on the optical path the light emitted from particle will be splitted on two wavelengths. General view of an optical system with composite two-wavelength filter is presented on the figure 6. In this way of arrangement the particle spot formed on image plane of sensor will consist of two "colored" regions. Computing separately left and right components of each spot, intensities ratio as far as centroid position can be recovered from an instant image.

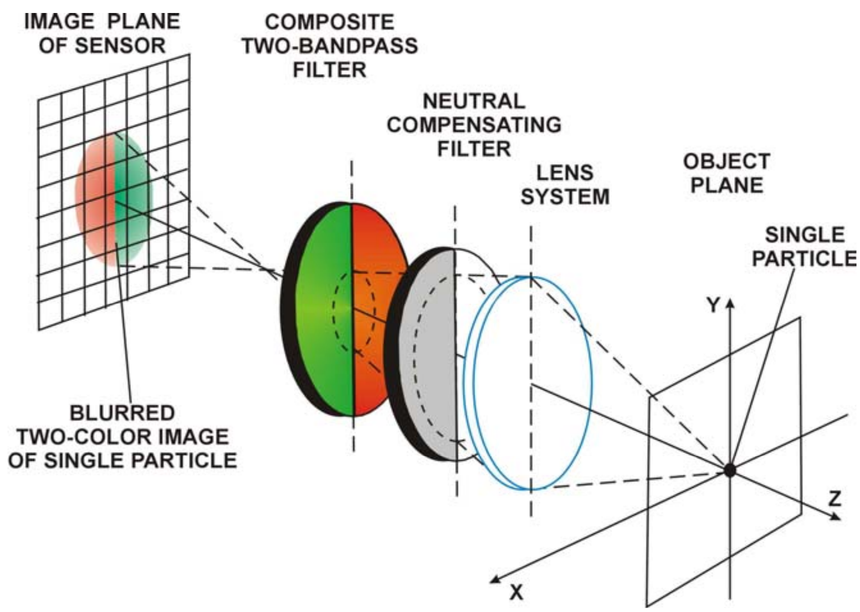


Fig. 5. Single sensor system with composite two-wavelengths filter

7. DEMONSTRATIONAL EXPERIMENTS

7.1 Computer simulated flow patterns

A series of numerical simulations has been carried out to evaluate technique performances. As a basis the standard PIV images and data (Okamoto et al. 2000) from VSJ have been used to realize particles distribution in some jet flow. Two sequential frames were selected from respective PIV series for flow imaging at two different point of time. The input temperature function was also employed to describe temperature distribution within interrogation volume. From original standard PIV data file, which respect to particles distribution at a point of time, two images were additionally computer generated, one image for each sensor of two-channel optical system. Images of particles represented on these images have the same locations (x, y - coordinates), but different intensity levels imitating wavelength filtering. An example of technique application is shown on the figure 1 (see **ABSTRACT**, the first page of this paper). Simulated velocity and temperature fields of 2489 vectors have been captured imitating noisy 8-bit 256x256 sensors. 2245 vectors are recovered with high accuracy.

7.2 Experiments with modeled flow patterns captured by real cameras

Further technique evaluation and demonstration uses real cameras to capture modeled flow patterns.
General experimental setup is shown on the figure 6.

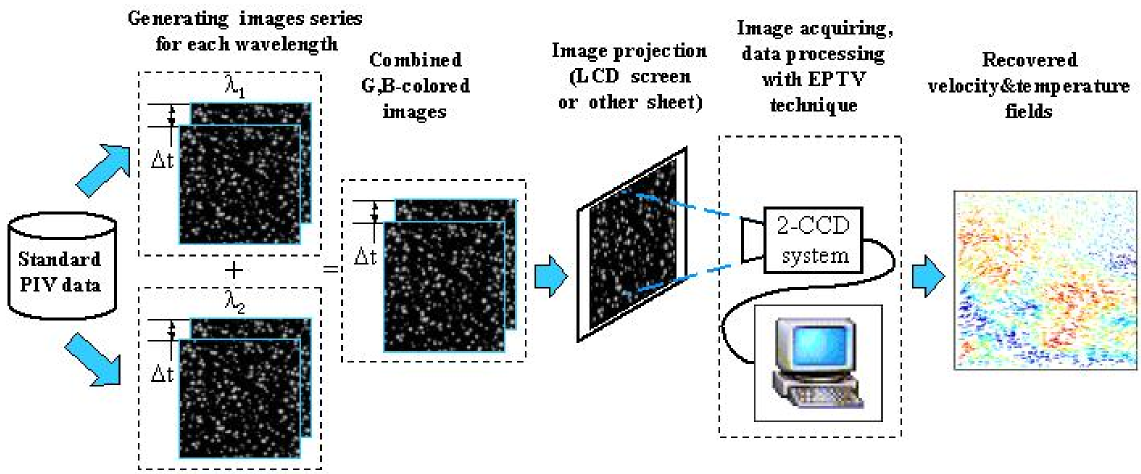


Fig. 6. Schematic of computer simulation, image capturing, and processing system for simultaneous temperature and velocity fields recovery

8. SUMMARY AND CONCLUSIONS

A new technique for simultaneous determination of temperature and velocity flow fields by enhanced two-color PTV technique has been introduced, described and evaluated.

Feasibility, limitations and most attractive embodiments of the technique as applying primarily to high-temperature flows using commercially available visible and near-infrared CCD sensors are evaluated. Numerical experiments for preferred embodiments demonstrate super-resolution features of this technique.

A series of demonstrational numerical experiments confirms the feasibility of practical implementation of this technique. It seems to be quite attractive alternative to more sophisticated technologies for a number of particular applications most of all due to much less expensive implementation and simple calibration providing acceptable accuracy with sub-pixel spatial resolution.

Further development, comparative investigations and application of this technique to real flows are expected.

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