PARTICLE IMAGE VELOCIMETRY: A NOVEL VELOCITY MEASURING TECHNIQUE

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ABSTRACT

This paper discusses both traditional flow measurement techniques and the novel PIV velocity measurement technique. The application and advantages of the PIV technique are also discussed. The PIV technique is capability of offering very high accuracy without the need of system calibration, offering fast response and high spatial resolution while remaining non-intrusive make attractive for use in corrosive and toxic environments.

INTRODUCTION

Flow measurements account for a high percentage of the process variables measured in the chemical processing industries. No other variable is more important to plant operation. Without flow measurements, plant material balances, quality control and even the operation of continuous processes would be almost impossible.

TRADITIONAL VELOCITY MEASUREMENTS

Many accurate and reliable methods are available for measuring a flow. Some are suitable for liquids only, others for gases/vapours and some are suitable for both. The type of conduit (closed or open) also restrict the choice of flow measuring devices.

The most common method of measuring flow is that of differential pressure, or head, method. The method utilises restriction elements (orifices, venturis, etc.) in a line to register a differential pressure from which the flow rate can be calculated. The differential pressure registered is normally proportional to the square root of the flow rate.

Most flow measurements are made under turbulent flow conditions ($Re>4000$). This is imposed because of economic considerations and not by requirement for the principle or accuracy. Large pipes and slower velocities would require much more expensive piping systems. Turbulent flow is thus the necessary requirement to meet the empirical relationships that have been developed over the years. Whenever these empirical relationships are being used, it is essential to determine whether the flow is turbulent or not. This fact is often overlooked and can give erroneous results with serious cost implications. In this paper traditional techniques are discussed in general to offer the basis of comparison with the PIV method. Traditional flow measurement techniques are well discussed in [1-3]

Closed Conduit: Liquid Flow Measurement

Several devices are available for measuring liquid flow rate in closed circuits. These include: full bore devices, insertion meters and clamp-on meters. Full bore meters are the orifice plates, venturis, magnetic meters (magmeters), V-elements, turbines, positive displacement meters, vortex-shedding and target meters. The insertion meters include magnetic and target meters, sonic and ultrasonic meters, Pitot tubes, swirl turbines and vortex shedding meters. The clamp-on meters are the sonic and ultra sonic meters (including Doppler's effect ones).

For liquid flow measurement in closed conduits, the venturis tubes are the recommended primary flow measurement devices. The most critical aspect of their application is the pressure sensing system used to record the differential pressure. These meters offer poor results at low flow rates due to the square root function cut-off. Erroneously high flow rates can be recorded for pulsating flows and where the tap lines are inadequately sloped, and if bleed valves are not provided, gas build-up can occur and this affects the accuracy of the meter.

Closed Conduit Gases Flow Measurement

There are many differential type meters for measuring gas flow rates. Technologies include: mechanical, differential pressure, vortex shedding and mass rate cooling. The common devices are the orifice plates, venturi tubes, averaging Pitot tubes, turbines, mass flow meters, vortex shedding, target meters and displacement meters. Pitot tube is the recommended device. Normally the tube is of the insertion type and can offer accuracy of 2% to 5% at full scale; with repeatability of 1% at full scale. The Pitot tube suffer from condensate formation, unequal pressure tap line lengths or elevations, wrong range of differential pressure transmitters (where used), insufficient straight-run piping and generally poor maintenance can affect their accuracy.

Open Channels

In open channels, flumes and weirs are the most commonly used flow-metres. Other meters include Kennsion nozzle and velocity-area meters(magnetic-probe, transmissive sonic and Doppler type).

PIV VELOCITY MEASUREMENT

PIV Recording

PIV is a velocity measuring technique which can instantaneously record velocity over a whole flow field. The technique relies on photographing small particles contained in and faithfully following the flow under investigation. Light from a laser source is normally expanded into a two-dimensional sheet and projected into the flow field. The laser beam is then pulsed (either by Q-switch or by a spinning mirror) so that successive images can be recorded on the film plane of a camera placed perpendicular to the expanded sheet of laser light. Fig. 1 shows the configuration for PIV recording.

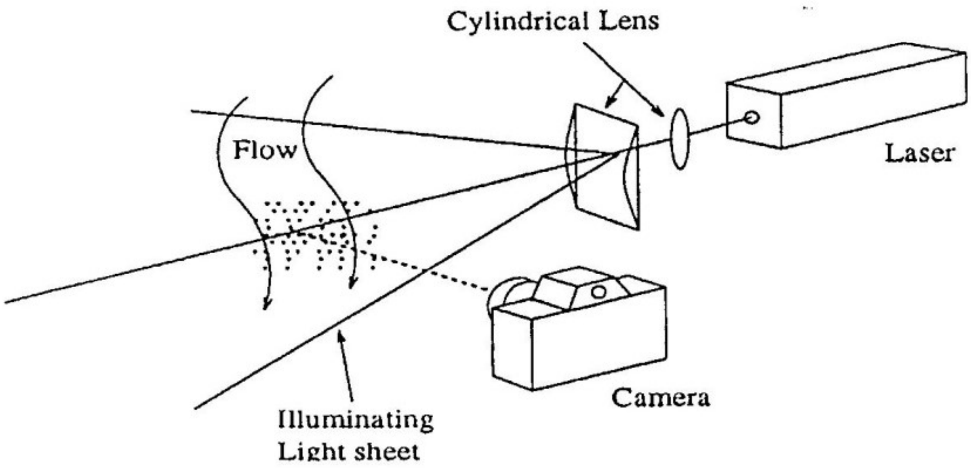

Fig. 1 PIV recording set-up

Laser, acronym for light amplification by simulated emission of radiation, is a light source which works by taking the light from one atom to stimulate the emission of more light from other atoms.

Amplification is provided by an active medium which can be fluid, solid or by semiconductors. Laser is commonly thought as giving a bright, highly coherent and highly monochromatic light. Some typical laser light sources are shown in Table 1.

Table 1: Some commonly available continuous wave laser

Type	Pumping System	Medium	Principle wave-length [nm]	Typical output [mW]
Argon	Electrical discharge	Gas	351.1 528.7 488.0	50-30 100-1000 500-5000
Helium - Neon	Electrical discharge	Gas mixture	632.8 1152.3 3391.2	1-50 1-10 1-10
Helium - Cadmium	Electrical discharge	Gas - vapour mixture	325.0 441.6	1-10 5-40
Tunable dye	Argon or Krypton ion laser	Solution of fluorescent dye and rhodamine dye	530-590 570-650	1000 1000
Neodymiu m - Yag	Optical with tungsten halogen or arc lamp	Crystal of Yttrium - Alumin-ium doped with Neodymiu m	1064	1000-10000

There is large literature on PIV and is still growing. Particular reference is made to [4-17] which cover the basic principles, early developments and application of the PIV technique, PIV data confidence criteria and equipment discussion.

The PIV technique has been employed in diverse research fields such as measurement of strain and planar, and surface displacement and tilt, e.g. in engines [4-6], in studies of particle ropes [7-11], measurement of velocity distributions [12-16], measurement under water waves [17-20], etc. There also has been extensive numerical work and computer simulation related to PIV and this coverage is growing. Some of this work is dealt with in [17, 21-23]

Retrieval of Flow Field Data

The velocity information on the film can be recovered by ascertaining the separation of the particle images. This can be done by either observing the film directly using a microscope or, more commonly, by interrogating each point on the film using a low powered laser beam (optical interrogation), or by digitising the whole doubly exposed image and storing the digital image in the computer memory for subsequent analysis. Within a small local region of the negative, over which the fluid velocity is approximately constant, the recorded flow will consist of two similar but displaced random patterns of resolved particle images. The spacing and orientation of successive particle images in the area of the interrogation are directly determined from the two-dimensional position of the signal peaks in the auto-correlation plane. The position of the centroid of the signal peak is directly correlated to the inter-particle image spacing on the negative; normally a micro computer is employed to find the location of these peaks. There are three techniques of producing the correlation function which are described below.

i) **Fully Optical method:** An optical processor is used to generate a two-dimensional squared auto-correlation function, which is later analyzed by computer.

ii **Optical-digital method:** Digitalization applied after an optical generation of the power spectrum, again numerical analysis completes the analysis.

iii) **Fully digital method:** Digitalization of the photograph, followed by numerical analysis based on an auto-correlation technique.

Optical method

Some of the processors used in optical processing include: non-linear optical media, electrically addressed spatial light modulators (EASLM) and optically addressed spatial light modulators (OASLM) [24]. These perform at the speed of light and thus, provide inherently fast, parallel processing. As the data associated with PIV images is always large, this method has a fundamental advantage over the other two. For example, generating a squared auto-correlation function takes only 10 ms (plus 20-40 ms for exposing a video) compared to about 1s by the digital method [24]. The system, however, still needs to digitise the auto-correlation to perform the peak finding. Another disadvantage is the requirement of a monochromatic and coherent light source to power the processor. It also has limited resolution [24-26], optical processing set-up is shown in Fig. 2

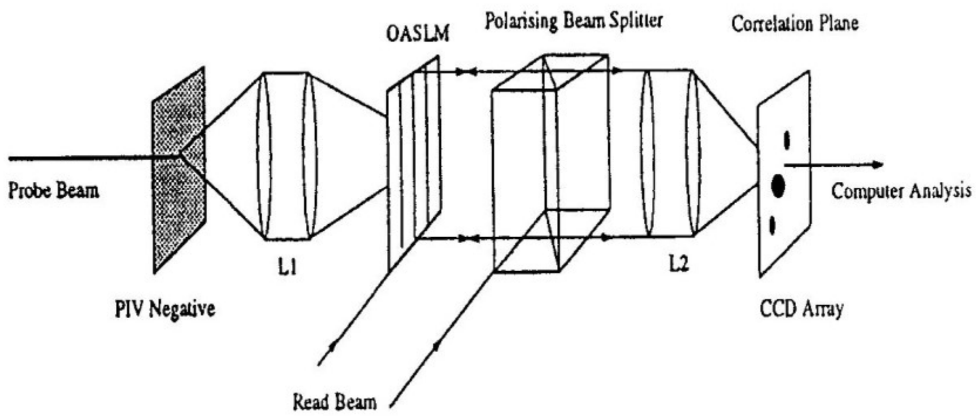

Fig. 2 Optical processing of PIV negative.

Optical-digital interrogation (Young's fringe method)

This is a traditional method [12-16, 24-32]. A doubly exposed photograph is optically Fourier transformed by a lens to form Young's fringes on the closed circuit digital (CCD) camera located in a focal plane of the lens. The resulting Young's fringes power spectrum is captured by CCD camera, and the information is sent to a microcomputer via a frame store. During processing, the digitised signal from the CCD is Furrier transformed again by a microcomputer to form the auto-correlation plane, as shown in Fig. 3. The Young's fringe method is suitable particularly for high density seeding.

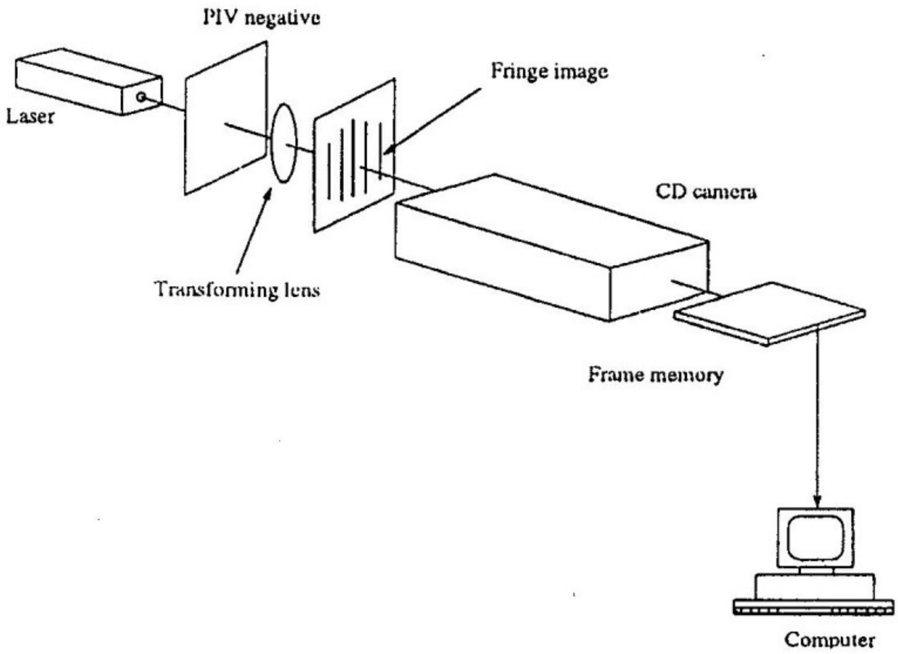

Fig. 3 Optical-digital (Young's fringe) method

Digital interrogation

In this method, the whole, doubly exposed image is digitised making it available in the memory of a computer. The advantage of the digital method is that it allows for adaptive variation of the interrogation area to optimize spatial resolution and to achieve a wide dynamic range. It can also potentially select particle images from a given intensity range within the whole digitised image so as to analyze certain ranges of particles without interference between signals (suitable in two-phase flows) [21, 33-34]. Other advantage of the full digital processing includes the method does not require the use of coherent light source. It also offers flexibility and capability of carrying out extra processing such as corrections for lens distortion or other perspective distortion, particle counting, detection of flow boundaries, subtraction of background images, aligning of successive frames, etc. Digital processing, however, is fundamentally many orders of magnitude slower than optical processing.

COMPARISON OF PIV AND TRADITIONAL FLOW METHODS

All traditional flow measurement techniques are point referenced. This is a limitation, especially where a complete velocity profile of a region is required. This is where PIV superiority and appeal excels. The length scale offered by PIV can not be matched by the traditional flow measurement techniques. The velocity and length scale in boundary layers, for example, can not be measured by the traditional flow measuring techniques; apart from the hot wire method which, unfortunately, can also cause obstructions in the flow filed, giving results that are not necessarily representative.

CONCLUSIONS

In can be concluded that the PIV measurement method offer high accuracy and high resolution (length scales) in flow measurement. Advantages of the PIV technique include: high accuracy without the need of system calibration, fast response and high spatial resolution. The PIV technique is also a non-intrusive making it attractive for use in corrosive and toxic environments. The need for a transparent medium, optical access and use of scattering particles are the main demerits. The laser light source of decent power and the signal processing equipment are often expensive and can thus inhibit wide applications of the PIV technique.

Laser light, especially high powered ones, pose serious safety conditions. The equipment for signal processing is still expensive. There are, however, certain areas where the PIV technique has, and will continue to offer scientists and engineers information of flow characteristics un-thought of in the traditional flow measurement era.

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