

# Research for the Flow Profile In the Natural Gas Pipelines by Means of PIV

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**Abstract** the flow profile in the natural gas pipelines can be measured by means of the Particle Image Velocimetry( PIV) to research effects of typical flow profile on gas flow measurement accuracy. Then the measurement accuracy can be improved by compensation. But there is rarely public report about this kind of examples up to know. In this case of test, safety is very important ,for example ,zero leaking and explosion prevent should be take account. In this paper ,the PIV system is introduced in detail. The unique design and production of a visual pipeline-section, a positive pressure ventilating room and a high-pressure particle inject device are introduced. Meanwhile the software of PIV system also was represented including some special image processing algorithms and Topological Graph Theory Algorithms.

**Key Words:** PIV ; flow profile ; methods

## 1.Introduction

As particles which are mixed in flow can scatter light, PIV technology make use of this characteristic to record position of particles in flow filed. we can determine the flow velocity and other related parameters of particles by measuring the displacement of the particles at different time. PIV technology which is a combination of visual flow and measurement of flow parameter can quantize flow parameters. It is widely used in various fields. Compare to conventional methods of measurement, PIV have two advantages: 1.no disturbance in flow field; 2.can get various related parameters of flow field simultaneously. By using PIV technology, we can observe flow profile downstream of various disturbing fittings and straight pipeline, then

quantize these effect in order to compensate and improve accuracy of flow measurement. Because of those advantages, Chengdu Verification Branch of Natural Gas Flow Rate for National Crude Oil Large Flow rate Calibration Station (CVB) and Beijing Petroleum University carry on the research.

## 2.Configuration of PIV system

### 2.1 Hardware configuration

Hardware of the system include: a impulsive laser device, a synchronizer, a CCD pick-up head, a image card, a computer, and a particle induction device, figure 1 and 2 show the structure of system:

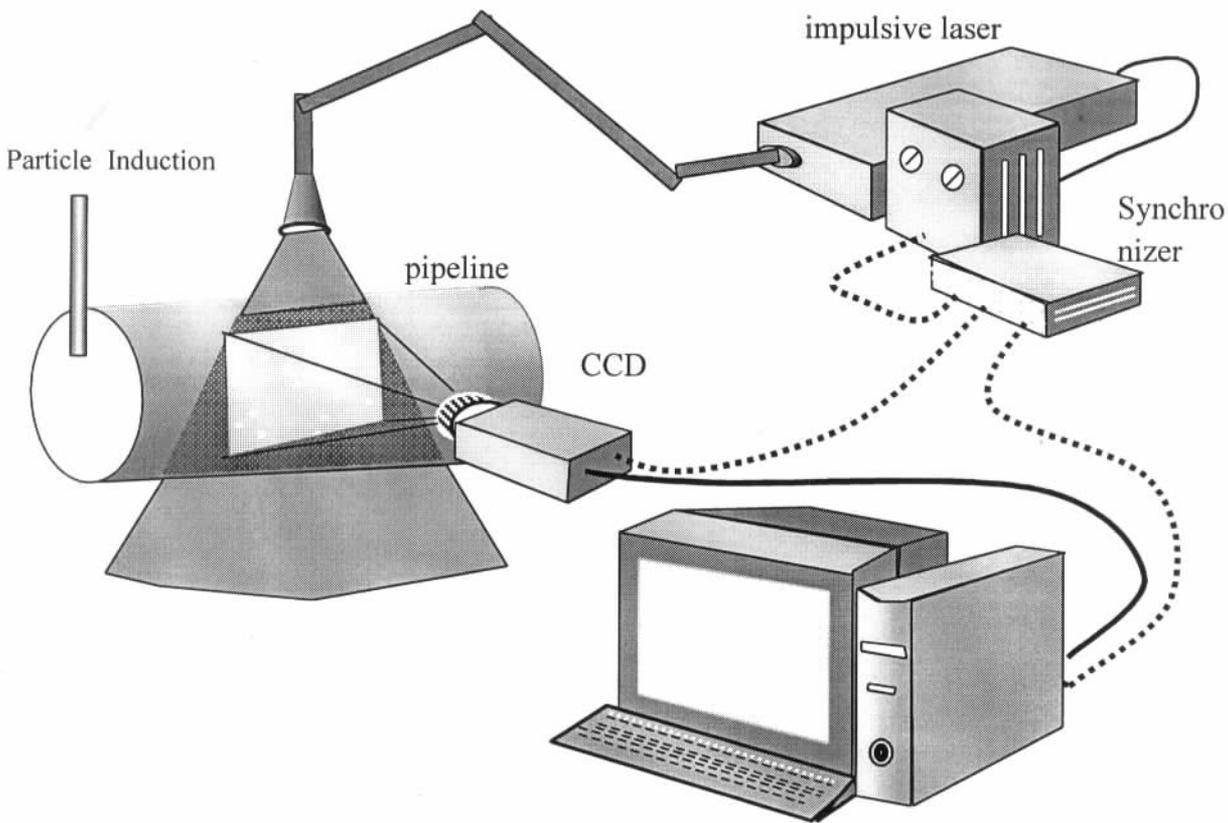
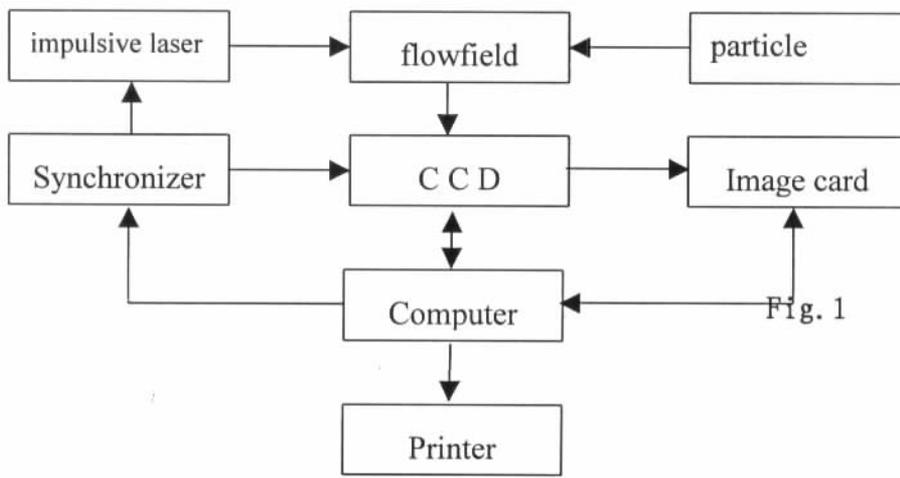


Fig. 2

Operating principle: Firstly, use particle induction device to inject particles into visual pipe, then, use CCD to continuously take photos of visual pipe which is highlighted by impulsive laser device, synchronizer here is used to ensure that impulsive laser device work

synchronistically with CCD. The pictures are sampled and analyzed by computer. Finally, we can get the useful information of flow field.

### 1.2 Software configuration

The software is consisted of two modules:

1) Image sampling and synchronous control module:  
Real-time monitor the flow field in pipeline, synchronistically trigger impulsive laser device and CCD, transport pictures which are captured by CCD to computer. Exposure interval of CCD is  $1\mu s \sim 100\mu s$ .

2) Picture analyzing module:

Pictures' preprocess include: set area of flow field, set fixed edge and free edge, digital filtering and enhancement of image, particle identifying, positioning and matching.

Further process include: velocity field interpolation, velocity profile( vertical or horizontal) calculating, stream line calculating, vorticity calculating etc.

## 2. Manufacture of visual pipe

### 2.1 Design

Visual pipe with size of  $130 \times 15$  is made of organic glass which light transmission ratio is 91%; It use flange and O ring to connect with other pipes, and its intensity exceed 1.0MPa.

### 2.2 Trail manufacture and pressure resistance test

We have done intensity test with medium of water under pressure of 4.0MPa, and done gas tight test with medium of air under pressure of 1.5Mpa. The pipe under those two test is no distortion and leak after 30 minute.

### 2.3 Simulated experiment

We have tested light transmission ratio of visual pipe and combustibility of natural gas under irradiation of laser. The results of the tests show that visual pipe cut the muster.

## 3. Positive draft

All devices without explosion proof should be placed in a gas tight room. The room's size is  $2000 \times 2000 \times 1800$ . It use air compressor to supply air into the room. The room is removable.

## 4. Design and manufacture of particle induction device

Design and manufacture of particle induction device have many ways. We have two methods to induct particle into the pipe by using liquid particles:

① using atomizing nozzle to spray particles into pipe directly.

② using pump to induct vaporous glycerin into pipe. Also we can use pump to induct solid particles into pipe, in this way, we need special filter to recover solid particles.

## 5. Image sampling and analyzing

### 5.1 Image Digitalizing and sampling principle

The sampling principle is that size of particles in digital image should be more than four pixels.

### 5.2 Digital filtering and image enhancement

Digital filtering include spatial filtering and frequency filtering.

1) Spatial filtering

Assume expression of digital image is

$G(i, j)(i = 1, 2, \dots, M)(j = 1, 2, \dots, N)$ , expression of spatial filtering is:

$$\bar{G}(i, j) = \sum_{k, l \in \varepsilon(i, j)} G(k, l) H(i - k, j - l)$$

Where  $\varepsilon(i, j)$  is neighborhood of point  $(i, j)$ ,

$H(i, j)$  is the core of enhance operator. Here, we

introduce two typical operators:

a. Smoothing: smoothing operator is used to eliminate noise. The core of smoothing operator  $H_a$  is:

$$H_a = \frac{1}{5} \begin{bmatrix} 0 & 1 & 0 \\ 1 & 1 & 1 \\ 0 & 1 & 0 \end{bmatrix} \quad \text{or} \quad H_a = \frac{1}{8} \begin{bmatrix} 0 & 1 & 0 \\ 1 & 4 & 1 \\ 0 & 1 & 0 \end{bmatrix}$$

b. Sharpening: sharpening operator is used to enhance contrast of image, here are two common sharpening differential operator:

Digital Gradient

$$H_g(i, j) = \sqrt{(G(i+1, j) - G(i, j))^2 + (G(i, j+1) - G(i, j))^2}$$

## Digital Laplacian

$$H_L(i, j) = G(i, j) - \frac{1}{5}(G(i, j) + G(i+1, j) + G(i, j-1) + G(i, j+1))$$

) frequency filtering

ormally, discrete fourier transformation of digital gray function  $G(x, y)$  ( $i = 1, 2, \dots, M$ ) ( $j = 1, 2, \dots, N$ ) can be derived form following function:

$$G(x, y) = \sum_{i=1}^{\infty} \sum_{j=1}^{\infty} A_{ij} \cos \frac{2\pi i x}{L_x} \cos \frac{2\pi j y}{L_y} + B_{ij} \sin \frac{2\pi i x}{L_x} \sin \frac{2\pi j y}{L_y}$$

where  $G(x, y)$  belong to  $\{x \in [0, L_x], y \in [0, L_y]\}$ ,

and

$$\begin{cases} A_{ij} = \frac{1}{L_x L_y} \int_0^{L_x} \int_0^{L_y} G(x, y) \cos \frac{2\pi i x}{L_x} \cos \frac{2\pi j y}{L_y} dx dy \\ B_{ij} = \frac{1}{L_x L_y} \int_0^{L_x} \int_0^{L_y} G(x, y) \sin \frac{2\pi i x}{L_x} \sin \frac{2\pi j y}{L_y} dx dy \end{cases}$$

so, discrete fourier transformation can be expressed in following way:

$$\begin{cases} A(u, v) = \frac{4}{(M-1)(N-1)} \sum_i \sum_j G(i, j) \cos \frac{2\pi i(i-1)}{M-1} \cos \frac{2\pi j(j-1)}{N-1} \\ B(u, v) = \frac{4}{(M-1)(N-1)} \sum_i \sum_j G(i, j) \sin \frac{2\pi i(i-1)}{M-1} \sin \frac{2\pi j(j-1)}{N-1} \end{cases}$$

Now, we can do filtering calculation in frequency domain  $\{u \in [0, F_{Cx}], v \in [0, F_{Cy}]\}$ .

## 5.3 Particle Searching

Its common methods include Gray Threshold Level and Gradient Threshold Level:

1) Gray Threshold Level Method

Determine a gray value as a threshold level, if gray value in image smaller than threshold level then this point is surrounding, or else is particle's image. The common method to determine the Gray Threshold Level is make statistic histogram of gray value in image, then according to particle's density in flowfield  $G_V$  to

determine the Gray Threshold Level  $G_T$ , we often use

following relation:

$$P(G(i, j) > G_T) = C_V \frac{2}{3} C_d$$

where  $G_d$  is a constant which is relevant to dispersion of laser on particles. Gray Threshold Level is heavily affected by noise.

2) Gradient Threshold Level Method

Determine a gradient value as a threshold level, if gradient value in image larger than threshold level then this point is particle's image. Determination of Gradient Threshold Level can refer to determination of Gray Threshold Level. The advantage of Gradient Threshold Level is less effect of noise.

As long as we find first point(i.e. Pixel), we assume it as a point of particle's edge, and then we continuously find its adjacent points until all points come into being a close figure. Because the edge of points is accidented, we have different method to find concave edge and convex edge.

## 5.4 Particle matching

Mathematic lifting manipulation

$$\text{Assume: } F = \{f_1, f_2, \dots, f_m\} \quad S = \{s_1, s_2, \dots, s_m\}$$

find a mapping:  $M : F \Leftrightarrow S$

1) Probabilistic method

Theory—do probability distribution function of particles' displacement and direction in neighbouring areas of certain particle, we regard value and direction which make probability distribution function reach maximum value as particle's displacement and direction.

2) Correlation Analysis Method

Theory—define a correlation function between one particle and its adjacent point in certain neighbouring areas:

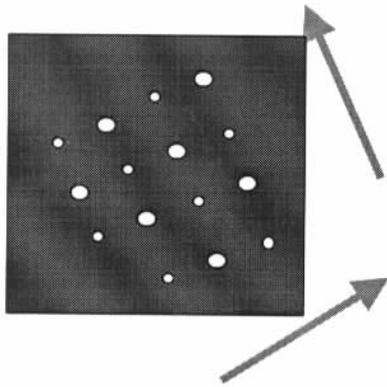
$$R_{op}(\delta x, \delta y) = \frac{\iint_{\Delta} G(x, y) \cdot G(x + \delta x, y + \delta y) dx dy}{\iint_{\Delta} G(x, y) dx dy \cdot \iint_{\Delta} G(x + \delta x, y + \delta y) dx dy}$$

Where  $G$  is function of grey value, then we regard its adjacent particle which makes correlation function reach maximum value as its corresponding image at

next exposure time, so we can get velocity of particle:

$$u = \frac{\delta x}{\Delta t} \quad v = \frac{\delta y}{\Delta t}$$

Those two methods are based on an assumption that particles are within a small flow field in which velocity and direction are the same at two adjacent exposure time. But when flow field change acutely, neighbouring areas that reach the requirement of those two methods will larger than that we assumed in correlation function, i.e. velocity and direction in this flow field are not the same at two adjacent exposure time. In another way, number of particles in assumed flow field can not reach the requirement of correlation analysis. Furthermore, error of match will easily occur when particles arrange symmetrically in flow field. The following figure illustrate this status:



### 3) Topological Graph Theory Method

This method is based on Point Set Topological Mapping and Graph Theory—Topological Graph Theory Method. This method is suitable in confused flow field, such as circumfluence after column and ball valve, step stream etc. Its advantages are in follow ways:

- higher accuracy and lower error of match;
- suitable for acute flowfield;
- faster calculation speed.

Now we introduce its theory and arithmetic:

#### (1) Theory of Topological Mapping and Flow Type Judgment

we can get two collections  $F$  and  $S$  in two PIV pictures which were got at adjacent exposure time:

$$F_1 = \{f_1, f_2, \dots, f_n\} \subset F$$

$$S_1 = \{s_1, s_2, \dots, s_n\} \subset S$$

If there is a relation  $M$  that makes points in  $F(f_i \in F)$  and points in  $S(s_i \in S)$  has an one to one correspondence, vice versa, we call it Mapping. It's expressed as  $M : F \Leftrightarrow S$ .

There is a large number of particles in picture, so we introduce subset of mapping.

Assume:  $F_1 \subset F, S_1 \subset S$ , if  $M_1$  exist between  $F_1$  and  $S_1$ , i.e.  $M_1 : F_1 \Leftrightarrow S_1$ , then we call  $M_1$  is a subset of mapping.

Accordingly, even though  $M_1$ , it has many one-one relations, here we introduce basic rules for Particle Matching.

#### (2) Theory of topological mapping

Assume  $F_1 \subset F, S_1 \subset S, M_1 : F_1 \Leftrightarrow S_1$ , every point

$f_k$  in polygon  $f_1, f_2, \dots, f_i \subset F_1 (i > 3)$  has only

one image  $s_k$ , vice versa. This mapping of  $M_1$  is a

basic topological mapping. Its physical meaning is that a close figure's image is a close figure too in topological mapping. Theory of topological mapping is a essential element for judgment of matched mapping but not adequate. Here, we give some auxiliary conditions:

##### a. Geometry Fixed Criterion

Assume:  $F_1 = \{f_1, f_2, \dots, f_m\} \subset F$

$$S_1 = \{s_1, s_2, \dots, s_m\} \subset S$$

and  $M_1 : F_1 \Leftrightarrow S_1$  exist, if

$$D_g = \frac{\sum_{i,j=1}^m |\overline{f_i f_j} - \overline{s_i s_j}|^2}{\sqrt{\sum_{i,j=1}^m |\overline{f_i f_j}|^2 \sum_{i,j=1}^m |\overline{s_i s_j}|^2}} = 0$$

we call  $M_1$  is a matched mapping under Geometry

Fixed Criterion. It's expressed as  $M_g$ . Geometry

Fixed Criterion describe flow's translate and rotation.

b. Incompressible Criterion

Assume:  $F_1 = \{f_1, f_2, \dots, f_m\} \subset F$

$$S_1 = \{s_1, s_2, \dots, s_m\} \subset S$$

and  $M_1 : F_1 \Leftrightarrow S_1$ , if

$$D_h = \frac{\sum_{i,j,k=1}^m |\Delta f_i f_j f_k - \Delta s_i s_j s_k|^2}{\sqrt{\sum_{i,j,k=1}^m (\Delta f_i f_j f_k)^2 \sum_{i,j,k=1}^m (\Delta s_i s_j s_k)^2}} = 0$$

we call  $M_1$  is a matched mapping under

Incompressible Criterion. It's expressed as  $M_1$ .

Incompressible Criterion describe flow's translate, rotation and angular distortion.

c. Isotropic Criterion

Assume:  $F_1 = \{f_1, f_2, \dots, f_m\} \subset F$

$$S_1 = \{s_1, s_2, \dots, s_m\} \subset S$$

and  $M_1 : F_1 \Leftrightarrow S_1$ , if

$$D_h = \frac{\sum_{i,j=1}^m |\overline{f_i f_j} - \alpha \overline{s_i s_j}|^2}{\sqrt{\sum_{i,j=1}^m |\overline{f_i f_j}|^2 \sum_{i,j=1}^m |\overline{s_i s_j}|^2}} = 0$$

where  $\alpha = \frac{\sum_{i,j=1}^m |\overline{f_i f_j}|}{\sum_{i,j=1}^m |\overline{s_i s_j}|}$ , we call  $M_1$  is a matched

mapping under Isotropic Criterion. It's expressed as

$M_1$ . Incompressible Criterion describe flow's translate, rotation, angular distortion and its isotropic change of volume. This model can describe compressible flow's motion.

### 5.5 Velocity measurement error

1) The diameter of a particle should be more than 2 pixel. When diameter of a particle is more than 3 pixel and the space between particles is more than 5 pixel, the average displacement measurement error is less than 3% ; when space between particles is more than 8 pixel, the average displacement measurement error is less than 2% ; when space between particles is more than 12 pixel, the average displacement measurement error is less than 1%. Those errors can be regarded as error of the flow velocity measurement in PIV.

2) The effect of particles' diameter and ellipticity, space between particles on velocity measurement is within a range of 1% ;

3) Normally, error of single point is within 3 times of average error .

### 6. Peroration

In the now days, PIV is a advanced technology which is used to research natural gas in pipeline. Since CVB have started research in 2001, we have already accomplished many antecedent jobs such as material collection, visual pipe's design、manufacture and intensity test, design and manufacture of Positive Draft House, integration of PIV system, software developing etc. The further study of effect of flow profiles on flow measurement will be carried out.