

On specific features of investigation of fluid flows by photometric techniques

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Abstract. Specific features of investigation of the fluid flow structure in a pipeline by photometric techniques are considered. The applicability of the photometric techniques based on the Doppler effect to such studies is discussed. A new method for detecting defects on inner walls of a pipeline that involves the use of the laser radiation scattered from particles in a flowing fluid is suggested.

1. Introduction

Experimental and theoretical studies of flows of fluids and suspensions are among the most urgent problems of fundamental physics [1-3]. Such investigations are necessary for improvement of such devices as flowmeters, spectrometers, pulseoxymeters, life support systems, water-based cooling systems, etc. [3-4]. The data obtained in such studies can make important contributions into development of advanced devices and methods for measurements of physical parameters of flows [2, 5-7].

Of major complexity are the studies of flows of aggressive and hazardous media (e.g., benzene, heptane, or concentrated sulfuric acid) and also of biological solutions and medical suspensions where sterility conditions should be satisfied. Such measurements must be carried out by non-contact methods. For example, high-speed video cameras are successfully used for temperature measurements in plasma [8]; the techniques based on scattered laser radiation enable investigation of surface inhomogeneity [1, 2], etc.

The fluid flow velocity in a transparent pipeline can be measured by the technique based on the Doppler effect. From the measured flow velocity one can find the shape and nature of the flow (laminar or turbulent), but this method has not found a wide use for studying fluid flows and measuring the flow rate. One of specific features of this photometric technique is that in order to measure a fluid flow velocity with an error of not more than 1%, the sizes of the particles from which the laser radiation is scattered must be not less than λ [1, 3, 5-7]. To achieve this, various chemical components or particle are added to water and other media in many experiments. However, such additives cannot be used in studies of hazardous liquids or suspensions in chemical or pharmaceutical industries, and for this reason the structure of the flows of these media in pipes is examined by NMR spectrometers [3, 4].

At present, the problem of detecting internal defects in pipelines by a non-contact method is of vital importance for life-support systems and production of artificial blood vessels. This is also significant for manufacturing biological solutions and medical suspensions because an accumulation of a



substance and a subsequent formation of a foreign particle occur in the zone of the defect. The detachment of this particle can lead to undesirable consequences. NMR techniques are unable to reveal defects in a flowing liquid. One of possible solutions to this problem may be the use of photometric techniques.

2. The method

The experimental setup which was used for investigation of the fluid flow velocity in the pipeline with circular cross-section is presented in figure 1.

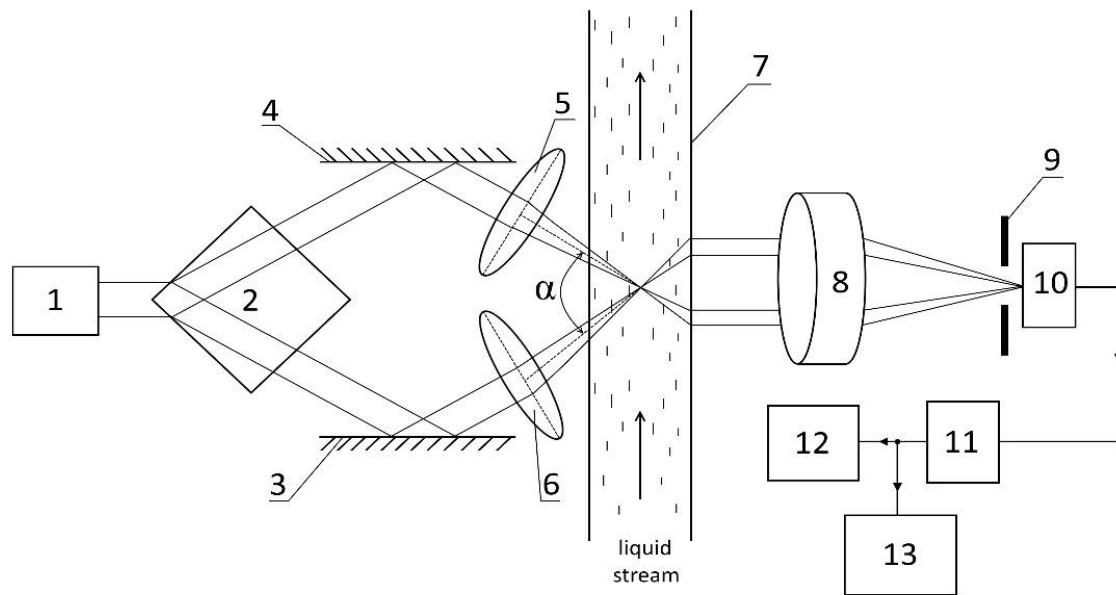


Figure 1. Scheme of differential optical Doppler velocity meter: 1 – optical quantum generator (laser), 2 – rhomb-shaped prism, 3 and 4 – mirrors, 5 and 6 – focusing lenses, 7 – glass pipeline, 8 – object glass, 9 – diaphragm with adjustable aperture, 10 – photoreceiver, 11 – wideband amplifier, 12 – spectrum analyzer, 13 – oscilloscope.

A differential type measuring scheme allowed us to exclude the condition of coincidence of directions of the wave number vectors of laser radiation k_0 and k_s in measurements of velocity with an accuracy of no more than 1% [7]. After laser beam splitting into two uniform beams (by a beam splitter rhomb-shaped prism (2) in figure 1) both coherent beams are passed through the optical elements and are focused on a flowing fluid in the glass pipeline (7) to be studied. The scattered light passes through an object glass (8) and is detected by a photomultiplier (10). The wave fronts of the scattered laser beams in our method are always parallel.

One more feature of the differential circuit presented here is the independence of the spectral width of beats on the object glass aperture. The lower limit of the measuring range is determined by the bandwidth of laser radiation and the upper limit is dictated by the photoreceiver bandwidth (if we use a photomultiplier, the bandwidth is up to 300 MHz)

To calculate the flow velocity v by the Doppler method, classical equations may be used [6, 7]:

$$\Delta f_D = v \cdot \frac{2n}{\lambda} \cdot \sin\left(\frac{\beta}{2}\right) \cdot \cos \varphi, \quad (1)$$

where β is the angle between the directions of incident and scattered waves, φ is the angle between the difference vector $\mathbf{k}_s$ and velocity vector, and Δf_D is the Doppler frequency shift.

In our case the wave number vectors of scattered light which are detected by the photoreceiver are coplanar (a specific feature of the differential circuit). Therefore, equation (1) may be written as

$$\Delta f_D = \frac{2v}{\lambda} \cdot \sin\left(\frac{\alpha}{2}\right) \quad (2)$$

where v is the flow velocity, and α is the angle between laser incident beams.

It is evident from (2) that the upper measuring range boundary of v for a specified λ is determined by angle α . For example, the experimental results showed that in the case $\lambda = 630$ nm and $\alpha = 20^\circ$, the maximal flow velocity which can be measured was 5 m/s

In addition, we used the transfer matrix method for calculating the transformation of the laser Gaussian beam and the beam waste shift ΔX_p during the beam successive passage through two different interfaces (air - glass and glass - fluid) and also the coordinate of the beam intersection point X_p . In the meridional plane ΔX_p is given by the following relationship:

$$\Delta X_p = \frac{(n_2^2 - 1) \sin^2 \alpha / 2}{n_2 (1 - \sin^2 \alpha / 2)^{3/2}} \cdot X_k + \frac{(n_1^2 - n_2^2) \sin^2 \alpha / 2}{n_2 (n_1^2 - \sin^2 \alpha / 2)^{3/2}} \cdot L_p \quad (3)$$

where n_1 and n_2 are the refractive indexes of the material of pipeline and flowing fluid, X_k is the distance from the outer pipeline wall in the laser radiation propagation direction to the point where the beams would intersect after the lenses (Figure 1) if no pipe with a flowing fluid were present in their path, and L_p is the pipe wall thickness.

Expression (3) was calculated for the following method of setting of the measuring optical system. The setting was carried out by the maximum value of Δf_D which corresponded to the highest velocity in the pipeline. Regardless of the regime of fluid flow, the flow velocity is maximum at the center of the pipeline. The point at which the beams would intersect after the lenses was determined in the absence of the pipeline with the flowing fluid. The point of location of the pipeline was found and X_k was determined.

Then ΔX_p was calculated. ΔX_p had to be lower than $d/4$ (where d is the inner pipe diameter), otherwise it was difficult to set the system to measuring the maximum v . After this the pipeline moved along the X axis which coincided with the propagation direction of radiation emerging from 1 (see Fig. 1). The distance X_k in this case increased or decreased until the maximum in Δf_D appeared. After setting a new value of X_k was determined and ΔX_p which was compared with the difference $(L_p + d/2) - X_k$ was calculated. The discrepancy between these values was less than 2%, all the inaccuracies in measuring the distances being taken into account. The result obtained allowed us to accurately determine the position of the point in the pipeline at which the measurements of v were performed. The error in measurements of flow velocity v was less than 1%.

In the case a defect was formed on the inner surface of the pipeline, the flow velocity profile changed in the pipeline cross-section (above the defect formation zone) as compared with the profile of v in other sections of the pipeline. In the case of laminar fluid flow, the flow velocity profile remained unvaried along the entire length of the pipeline [9, 10]. Figure 2 shows a section of the pipeline with the defect in the form of protrusion (the most commonly encountered defects on the inner walls of pipelines). Comparison of the measured velocity profiles were performed in two sections 1 and 2.

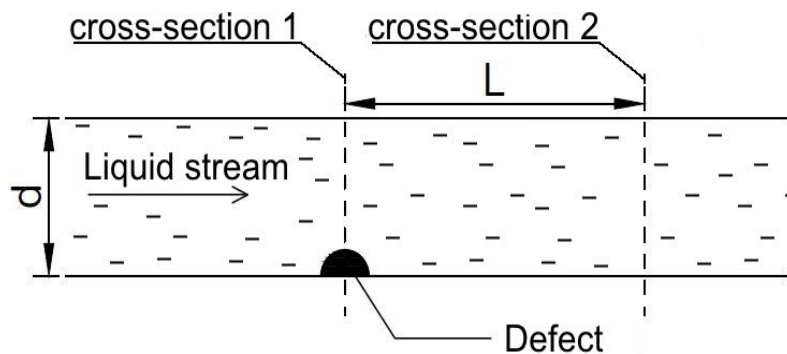


Figure 2 Pipeline with a flowing fluid

3. Results and discussion

Figure 3 shows, as an example, the measured flowing fluid velocities in two sections of the pipeline spaced at $L = 20$ cm (Figure 1 (a)). In the experiment, the tap water with an additive in the form of iron-3 oxidized in water (particle size of 1 - 3 microns) was used.

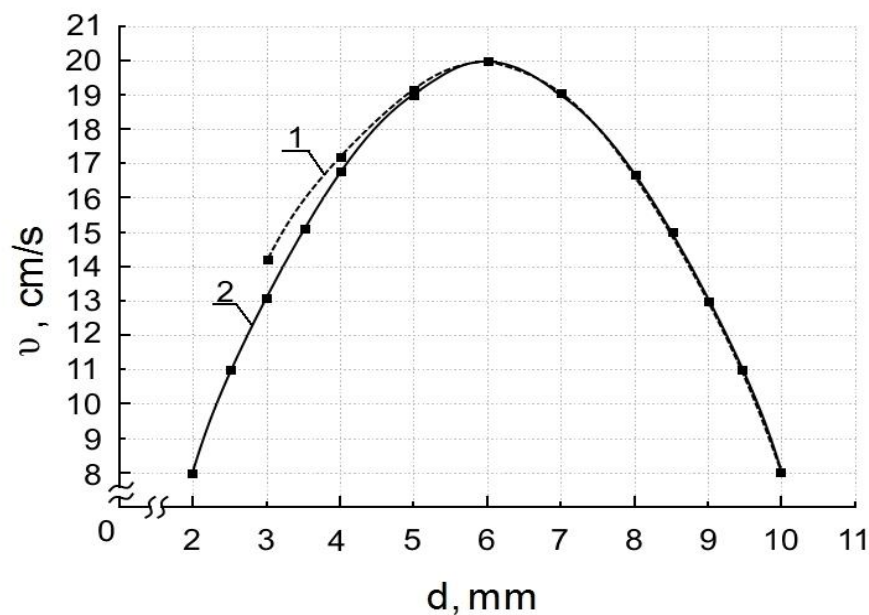


Figure 3 Flow velocity v distribution over the pipeline cross section (d – diameter). Curve 1 is for cross-section 1, curve 2 is for cross section 2.

The experimental results confirmed that it was possible to establish the presence of internal defects in the form of protrusions in the pipelines with the diameters d more than 4 mm by the method involving measurements of velocity changes. If the internal defect in the pipeline was in the form of a crack, it was difficult to detect it by measuring the flow velocity because a vortex zone was formed in the vicinity of the crack near the pipeline wall.

The flow velocity changed only slightly in this zone. In order to reveal defects of this type in pipelines, we developed the following method. The camera recorded a speckle pattern of the scattered laser radiation from the fluid flow. The changes in the speckle pattern shape arising due to eddy currents in the defect zone during the flow of the fluid had specific features from which the presence of the defects could be revealed.

Conclusion

The experimental results have shown that the method we propose is much more efficient and reliable than the detection of defects on the inner pipeline walls by optical techniques without the use of a flowing fluid.

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