Measurement of high-speed gas-droplet flow characteristics by pulse photography method

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Abstract. The subject of this work is the optical probe measurement system for the measure of droplets parameters in high-speed two-phase flow. A system with dark-field illumination including two pulse lasers as illumination sources is used for droplets registration. Rays from lasers intersect at the angle of 120° and form a measurement volume. When a droplet crosses the volume, it refracts a part of the light. Refracted rays pass through the optical system and create two highlights on the sensor. Distance between two highlights is equal to the droplet diameter. System for measurement of coarse droplets parameters in wet steam flow, based on the described method, is developed. Main components of the system are the optical probe and PC with software. The system allows determining the following parameters of droplets: size distribution (20–600 μm), velocity distribution (0.1–300 m/s), movement direction. The results of measurements of the system in two-phase flow are presented in this work. The system is successfully operated as part of the complex for investigation of two-phase flow parameters on the model turbine.

1. Introduction
Measurements of wet phase characteristics is an essential component of wet-steam flows investigation. Optical methods can be used for carrying out such type of measurements.

The subject of this work is the system for measure structural-kinematic parameters of high-speed two-phase flow in steam turbine.

Operation of this system is based on a pulsed photography method. The method allows measuring the follow parameters: droplets size distribution, droplets velocity distribution and droplets movement direction.

2. Particularities of investigated environment
Wet phase in wet-steam flow is amount to mix of two fractions: fine fraction (80–90% of mass) with droplet diameter 0.05-2 μm and a coarse fraction (10-20% of mass) with droplet diameter 10-1000 μm.

Velocity and movement direction of fine droplets correspond to these of main flow. However, velocity and movement direction of coarse droplets may differ significantly from those of the main flow.

Various methods (mainly optical methods) are used for measure parameters of fine fraction. There are many measurements results on the model and the full-scale turbines.
At contrast, the question about measurements of coarse fraction parameters is still open. There are not generally accepted results from measurements of size and velocity of erosion dangerous droplets.

Photography registration of moving droplets is one of the first methods used for investigation of two-phase flow disperse structure. The photo demonstrates the shape and size of droplets with high confidence. This property of photo is important when preliminary information about the droplets is absent.

Nevertheless, using this method for investigation of wet steam flow in a turbine can cause some difficulties:

- droplets velocity may be up to 300 m/s. Illumination source with very short pulses should be used for registration such values;
- stringent requirements are met for dimensions of a measurement device;
- there is not preliminary information about the droplets, which requires an expansion of measurement range;
- there is statistically less than one droplet in a measurement volume (figure 1), which requires large quantities of data in order to obtain a sufficient representative measurement.

![Figure 1. The expected concentration of droplets in the flow part of the turbines](image)

**Figure 1.** The expected concentration of droplets in the flow part of the turbines $n$ – number of droplets in measurement volume, $N$ – number of batches needed for registration of 1 droplet.

### 3. Illumination system

Choose a type of illumination system is an essential aspect of the realization of a pulse photography method.

Usually, the following illumination system is used for photoregistration: measurement volume is located between illumination source and registration device. In that case, an image of droplet looks like a black-out area on a light field.

This illumination system’s design is simple, but it has several significant disadvantages. The primary disadvantage is the uncertainty of the registered volume depth estimate, which influences the calculation of droplets concentration. Besides, the regime of multiple expose cannot be applied because of image contrast loosing.

Illumination system described in the inventor’s certificate [1] is different from mentioned above by illumination sources location off-axis of the registered system. Light from sources goes to the area of measurement (measurement volume) under angle $\beta$ to the optical axis of registered system. This system (so-called dark-field illumination system) is realized in the optical probe (videoprobe) described in this paper.
In that case, translucent spherical droplet plays the role of a small wide-angle lens when it crosses the measurement volume. Images of illumination sources as two bright highlights against the dark field are formed on registration plane.

Distance between the highlights is equal of droplet diameter if the value of angle $\beta$ is chosen correctly. Dependence of highlights location relative of droplet size on value angle $\beta$ and rays’ way in a droplet ($n = 1.33$) are demonstrated on figure 2. This dependence is presented both for reflected and refracted ray.

If $\beta = 50^0$, values of $h/r$ for reflected and refracted rays are equal. It means, two highlights pair (from opposite illumination sources) superimpose on one another. Highlight formed by the refracted ray is significantly brighter then highlight formed by the reflected ray.

Value of angle $\beta$ was chosen $60^0$, when the videoprobe was designed. In that case, the distance between highlights is equal to 0.98 droplet diameter.

Image of droplet with a diameter 1 mm is shown on figure 3. This image was made by the videoprobe. Highlights formed by refracted and reflected rays are clearly visible.

Dark-field illumination system has two advantages:

- using multiple exposure regime recording without picture contrast loss (regime of information storage); multiple exposure is amount to increase of measurement volume in corresponding numbers of times. This advantage is critical when droplets concentration is very low;
- scale constancy on measurement volume depth; distance between highlights centers is kept and does not depend on droplet location relative of the focal plane.
Optical probe for fractional analysis of coarsely dispersed gas-droplet flow based on this illumination system was designed in [2].

4. Videoprobe. Optical head

The main component of the videoprobe is an optical head containing all optical and electronic components (figure 4). This design is capable of short illumination pulse generation and high-resolution image acquisition.

Illumination sources are based on pulsed laser diodes with a central wavelength of 905 nm. In total there are 4 diodes in the videoprobe, two diode pairs are located on both sides of the videoprobe. These diodes provide illumination pulses with minimal duration of 30 ns and optical output power up to 90 W. In case of elevated image brightness, the pulse width can be increased up to 100 ns. High speed of applied diodes provides opportunity to acquire several batches of pulses for a single video frame. This results in ability to determine size of droplets being measured and at the same time their velocity and movement direction.

An image sensor is a 5-megapixel monochrome CMOS with a pixel pitch of 2.2 µm. In order to improve image capture performance for pulsed illumination mode, the sensor operates in global reset release (GRR) mode [3].

Video signal and setup commands for illumination pulse generator and image sensor are transmitted over USB interface via a high-speed controller integrated into the electronic board. Precision generation of control pulses for the illumination source is implemented by the programmable logic (FPGA).

Configuration of the optical head is shown on figure 4. Rays go through guiding prisms and form measurement volume. Droplet refracts part of light when it crosses the volume. Refracted rays pass through optical system and form an image of the droplet as two bright highlights on matrix.

![Optical scheme](a) Optical scheme

![3D model of an optical head](b) 3D model of an optical head

Figure 4. Optical head. 1 – guiding prisms, 2 – laser diodes, 3 – objective, 4 – matrix, 5 – the electronic board.

Measurement volume can be separate into two areas (figure 5):

- two-side lighting area, all droplet parameters (size, velocity, movement direction) can be detected if the droplet is in this area;
- one-side lighting area, only velocity and movement direction can be detected if droplet is in this area.
Figure 5. Scheme of measurement volume forming. 1 – rays from illumination sources, 2 – view field of objective, 3 – measurement volume, 4 – focal plane, 5 – one-side lighting areas.

Value of measurement volume should be known for calculation of droplets concentration in a flow. Since the measurements of droplets size are carried out in a wide range, dependence of value of measurement volume on the droplet size (figure 6) should be considered for calculation of the concentration.

Figure 6. Dependence of value of measurement volume on the droplet diameter.

5. System for measuring structural-kinematic parameters of high-speed two-phase flow
System for measuring of droplets parameters in wet-steam flow in turbine (figure 7) consists of the follow parts:

- videoprobe;
- control PC with installed software for image acquisition and data processing;
- system for air blowing and cooling;
- traverse system for moving the probe in the turbine;
- power supply.
The system measures the follow parameters:

- droplets diameter: 20 – 600 µm;
- velocity: 0.1 – 300 m/s;
- movement direction: ±45° relative to the angle of videoprobe installation.

Assembled videoprobe is made as optical head installed on a bar with diameter 20 mm (figure 8). Electronic and power cables, and channels for air delivery lay in the bar. Elements of traverse system (step motors) are installed on the bar (figure 8).

Constant air blowing of power-on videoprobe is performed for two reasons:

- optical elements protection from contamination and water film. Guiding prisms and protection glass have slits for air outlet for this purpose;
- electronic elements cooling. The temperature inside of the videoprobe should be less than 60°C according to operation conditions. Resistance-temperature is used for temperature control. Value of temperature is displayed in a window of image acquisition software and recorded in the output data file.

Specific software was developed for videoprobe operation. It consists of two components:

- image acquisition software;
data processing software.

Image acquisition software controls illumination sources and image sensor, and also enables video stream and single-frame capture. Video stream is stored in a specially developed format, without image compression involved in capture process. Each output frame contains image sensor and illumination sources parameters.

The software is capable of adjusting image sensor readout parameters and of increasing frame rate by decreasing the number of sensor pixels being read. This can be achieved by limiting image area or image resolution.

While illumination pulses are generated, multiple images of objects are exposed on the photosensitive area of image sensor.

In order to increase droplets detection probability, several batches of image pulses are generated for each frame. At the end of exposure image readout is started. An example of timing diagram is shown in figure 9. There are 2 frames with 3 batches of illumination pulses and 4 pulses in each batch for the demonstrated example.

![Figure 9. Videoprobe timing diagram example.](image9)

Described illumination design renders image of each droplet as a sequence of highlights pairs (figure 10), which can be analyzed to determine droplet parameters: size, velocity and movement direction.

![Figure 10. Moving droplet image example.](image10)

Data processing software was developed for droplet parameter estimation. Droplets diameter $D$ is estimated by distance between highlights.

Droplets velocity: $V = \Delta L / \tau$, $\tau$ - pulse period, $\Delta L$ – the distance between pairs of highlights. As a result of processing the acquired data, the following information is retrieved:
- droplets size distribution;
- droplets velocity distribution;
- droplets movement direction.

6. Examples of measurements results
Described measurement system is applied in NPO CKTI for various problem solving. For example, results of droplets in spray nozzle parameters measurements are presented on figure 11.

Figure 11. Results of droplets in spray nozzle parameters measurements. $D$ – droplet diameter, $\mu$m, $D_0$ – average droplets diameter, $\mu$m, $N$ – number of droplets, $N_S$ - total number of droplets, $v$ – droplet velocity, m/s.

Moreover, the measured parameters of droplets in the steam turbine are shown on figure 12.
Figure 12. Results of measurements of parameters of droplets in the model steam turbine. $D$ – droplet diameter, $\mu$m, $D_0$ – average droplets diameter, $\mu$m, $N$ – number of droplets, $N_{\Sigma}$ – total number of droplets, $v$ – droplet velocity, m/s.

Measurements by the described system allow getting correlation between all measured parameters (figure 13).
Figure 13. Example of measurements result on a model turbine (relation between diameter, velocity and movement direction).

7. Conclusions
The system for measurement of high-speed erosion dangerous droplets parameters in wet-steam flow is designed. Operation principle of the system is based on the pulse photography method.

The system allows getting droplets size distribution, droplets velocity distribution and movement direction of droplets in the flow.

Specific software for recording photo and video files and processing them was developed. This software based on modern image recognition methods.

References
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